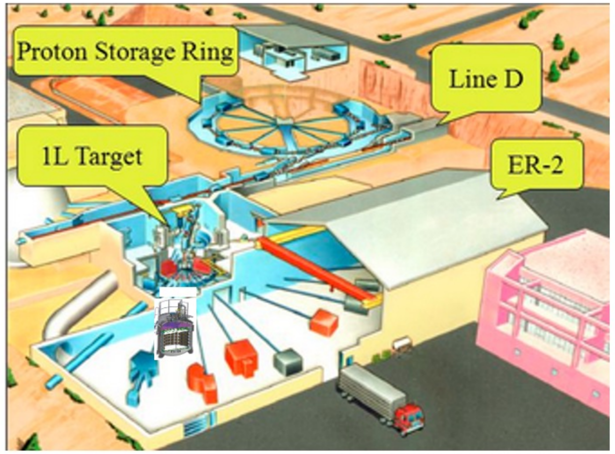
Probing the Dark Sector with Accelerators: New Opportunities!

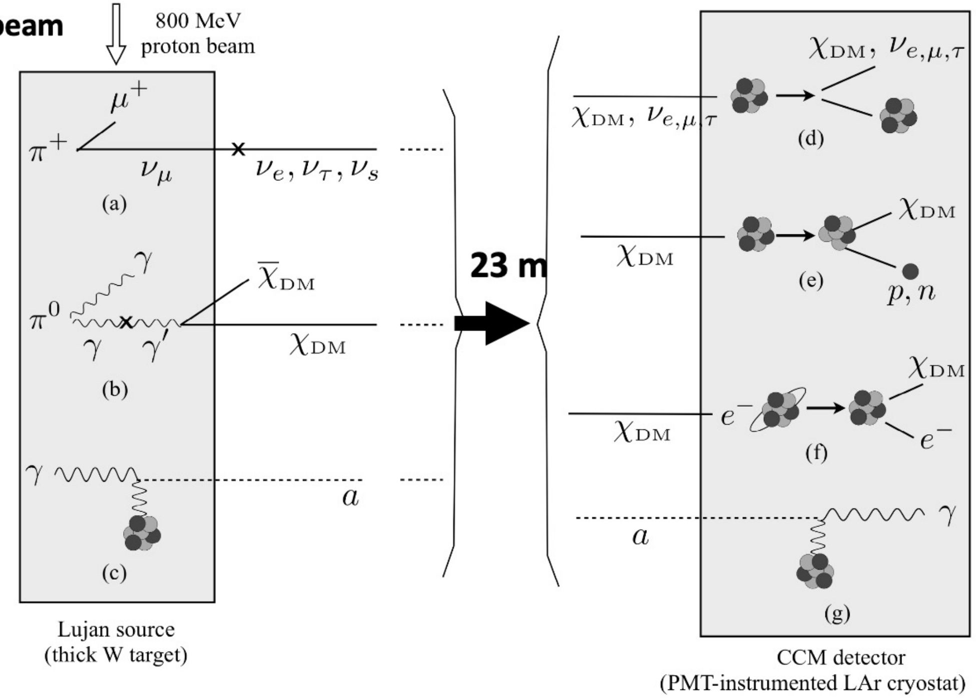
NAPAC 2022

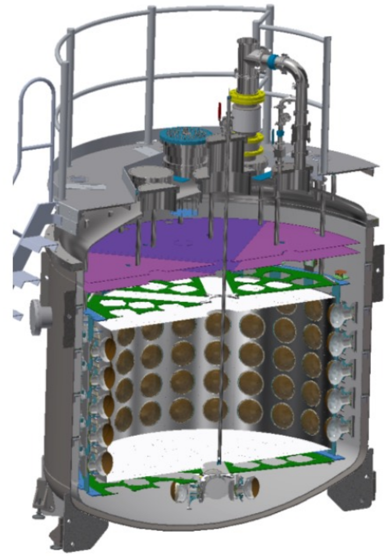
by R. G. Van de Water (LANL, P-2)

800 MeV protons, 100kW, 275 nanosecond pulsed beam



LANSCE-PSR-Lujan Target: Prolific source of charged/ neutral pions and photons that produce neutrinos and potential dark sector particles.





CCM: 10-ton Liquid Argon (LAr) detector instrumented with 200 8” Photo-multiplier tubes, veto region, shielding, fast electronics.

LA-UR-21-30818

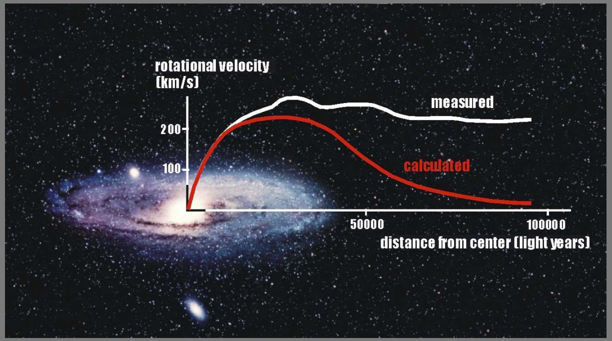
Outline

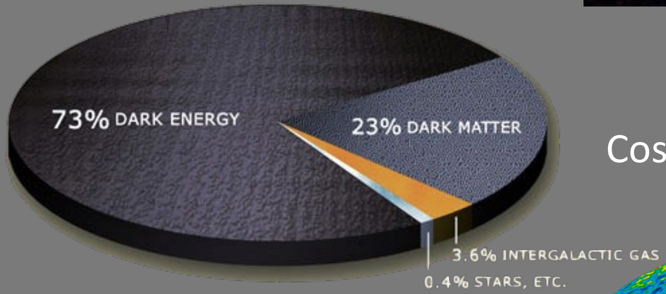
- Physics Motivation – Accelerators are ideal for probing the dark sector
- Example: The Coherent Captain Mills at LANSCE Experiment
  - LANSCE/Lujan beam and target
  - Production/detection of dark sector particles
  - Search strategies, CCM detector, physics reach
  - PSR upgrades
- Global effort and future dedicated facilities.
- Summary

Dark Matter/Sector, One of the Biggest Known Unknowns

Gravitational Lensing

Galaxy Rotation Curves

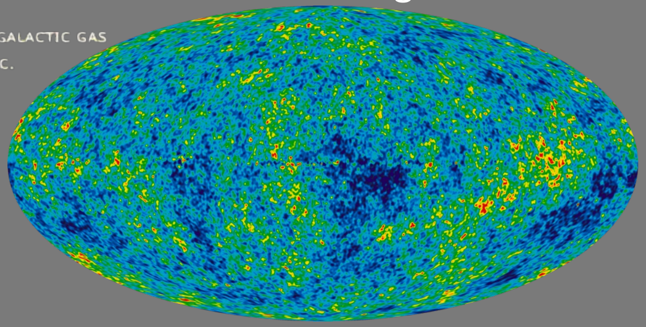




What we know about DM:

- gravitational
- slow moving (cold)
- passes though itself (collisionless)
- does not emit light (dark)
- non or weakly interacting with (anti)matter

Cosmic Microwave Background Clustering



- Standard Model particles only ~4% of total energy density
- Dark Matter (or dark sector) one of the few empirical hints of new physics
- Less known about Dark Energy??

Where to Search for DM: Dark Matter in the Early Universe and Relic Density Assumptions

Dark Matter

What we know:
Equation of state
$\rho_{DM} \sim \rho_{SM}$
Interacts through gravity
10^{-20} eV $< m_{DM} <$ 10^{68} eV

↓

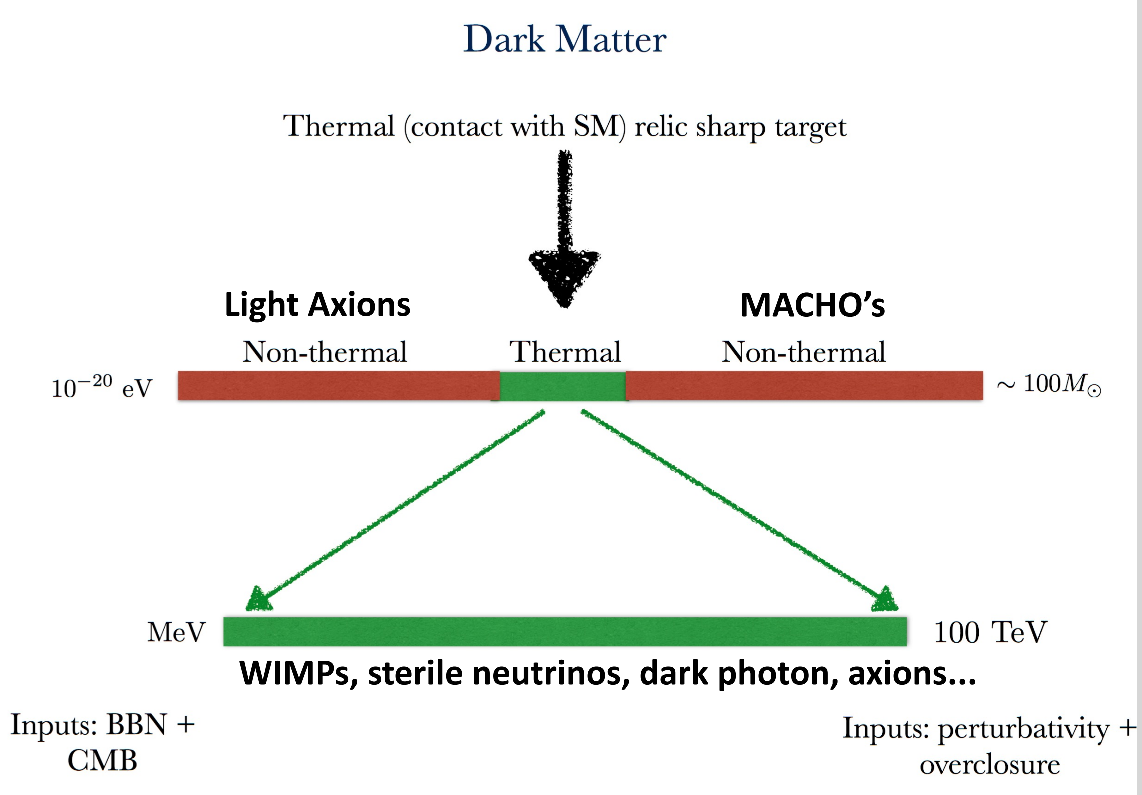
Hypothesis:
It couples to SM through 'sizable' non-gravitational interactions

↓ (consequence)

Thermal equilibrium with SM
Abundance through freeze-out

Energy density today
$\rho_{DM} = n_{DM} M_{DM} \approx 0.3$ GeV/cm^3

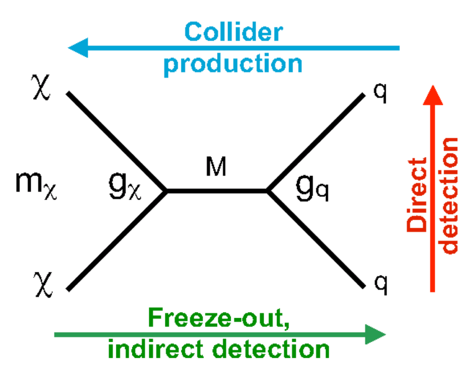
Thermal Assumption



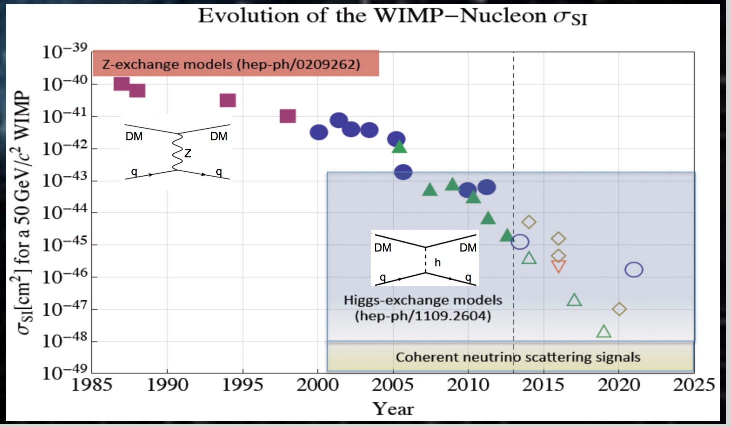
Relic DM density depends on DM mass and interaction cross section with the SM.

Traditional Search for DM: Float in space and wait for it to hit you, DM low rate and velocity!!

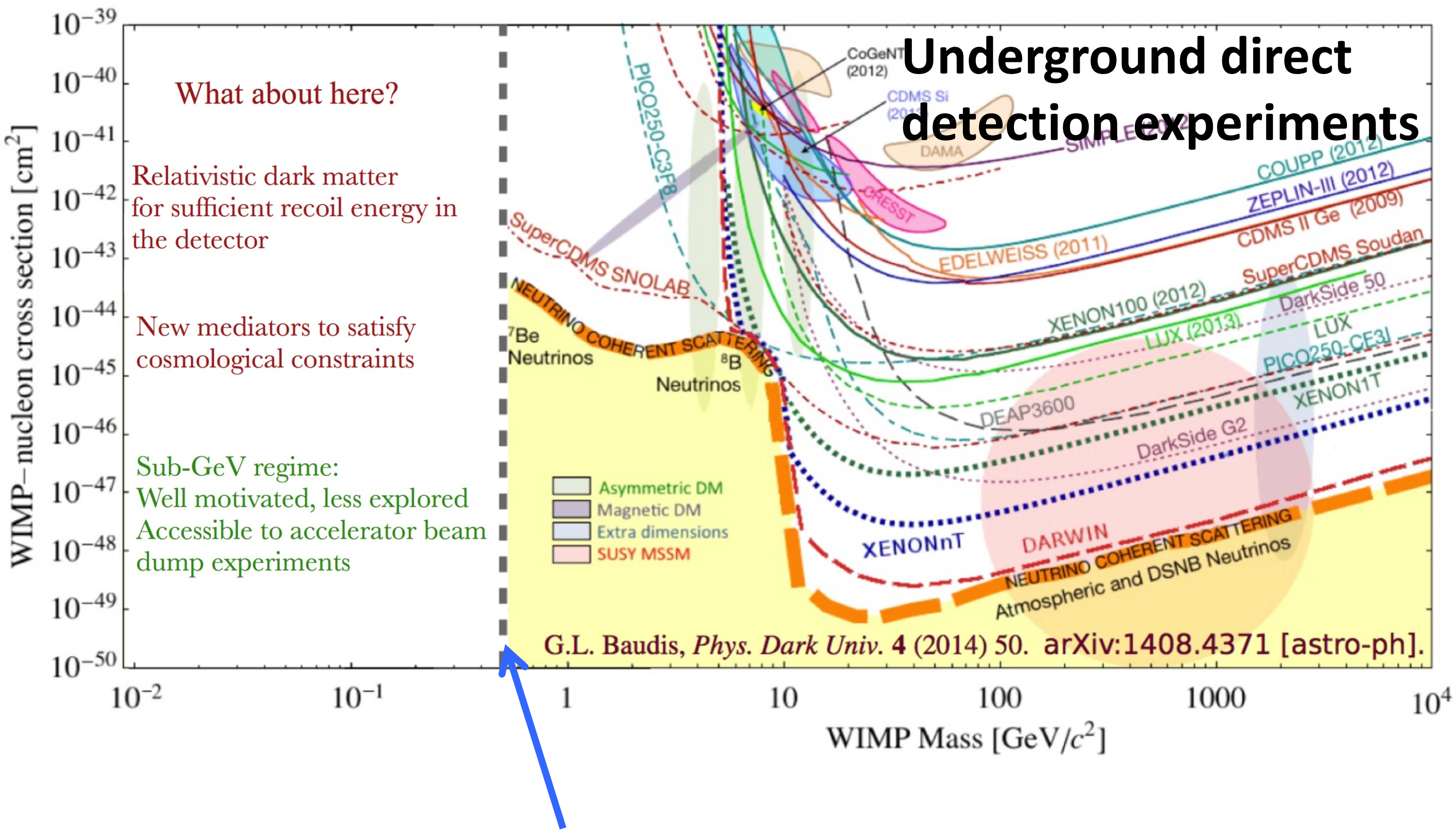
- V ~ 220 km/s (~10^{-3} c)



- Low recoil energies (~keV)

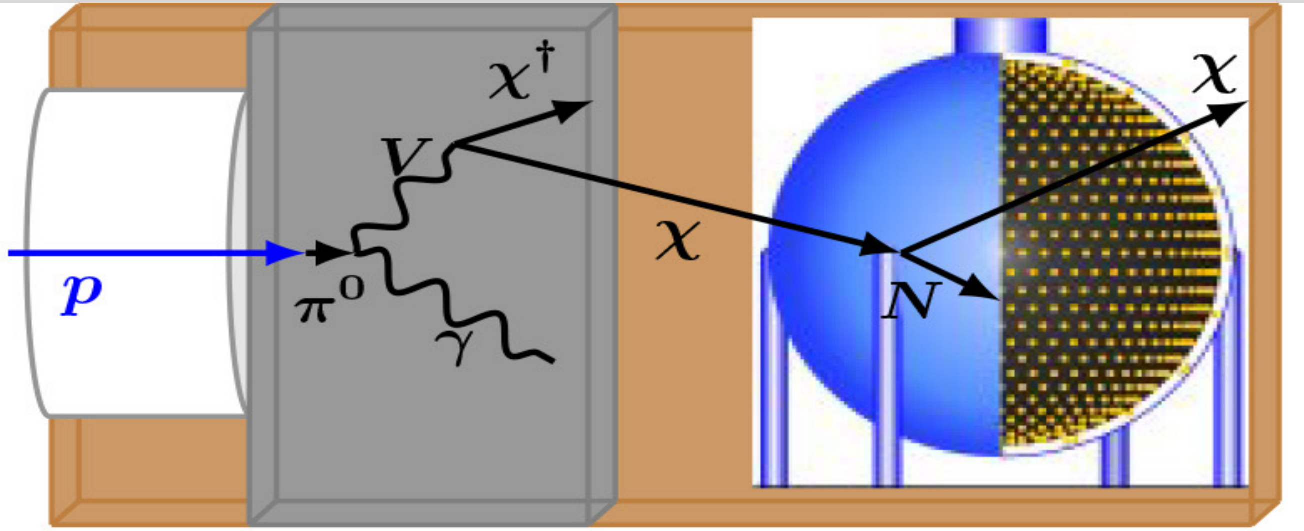


Experimental Motivation for Accelerator sub-GeV Dark Matter Searches



- Direct detection ~GeV mass threshold limit due to slow moving galactic halo DM.
- **Access sub-GeV threshold with accelerator boosted DM. Method has experienced much recent theoretical and experimental activity.**

New Method: Produce DM with accelerator and detect with large near detectors. Sounds like a neutrino experiment!



MiniBooNE@FNAL
Phys. Rev. D 98, 112004 (2018)

- **Protons: high energy (> GeV) and high intensity (> 10 kW)** at FNAL, LANL, SNS, etc
- Searches also with electron machines Jlab, SLAC, etc.

- Protons directly on beam dump produce **copious number of neutral particles** (π^0, eta, etc) which couple to dark matter.
- Boosted Dark Matter passes though dirt and interacts in detector.

- Large and sensitive detector required for high rates and good background rejection.
- **Final state particle energies ~MeV**

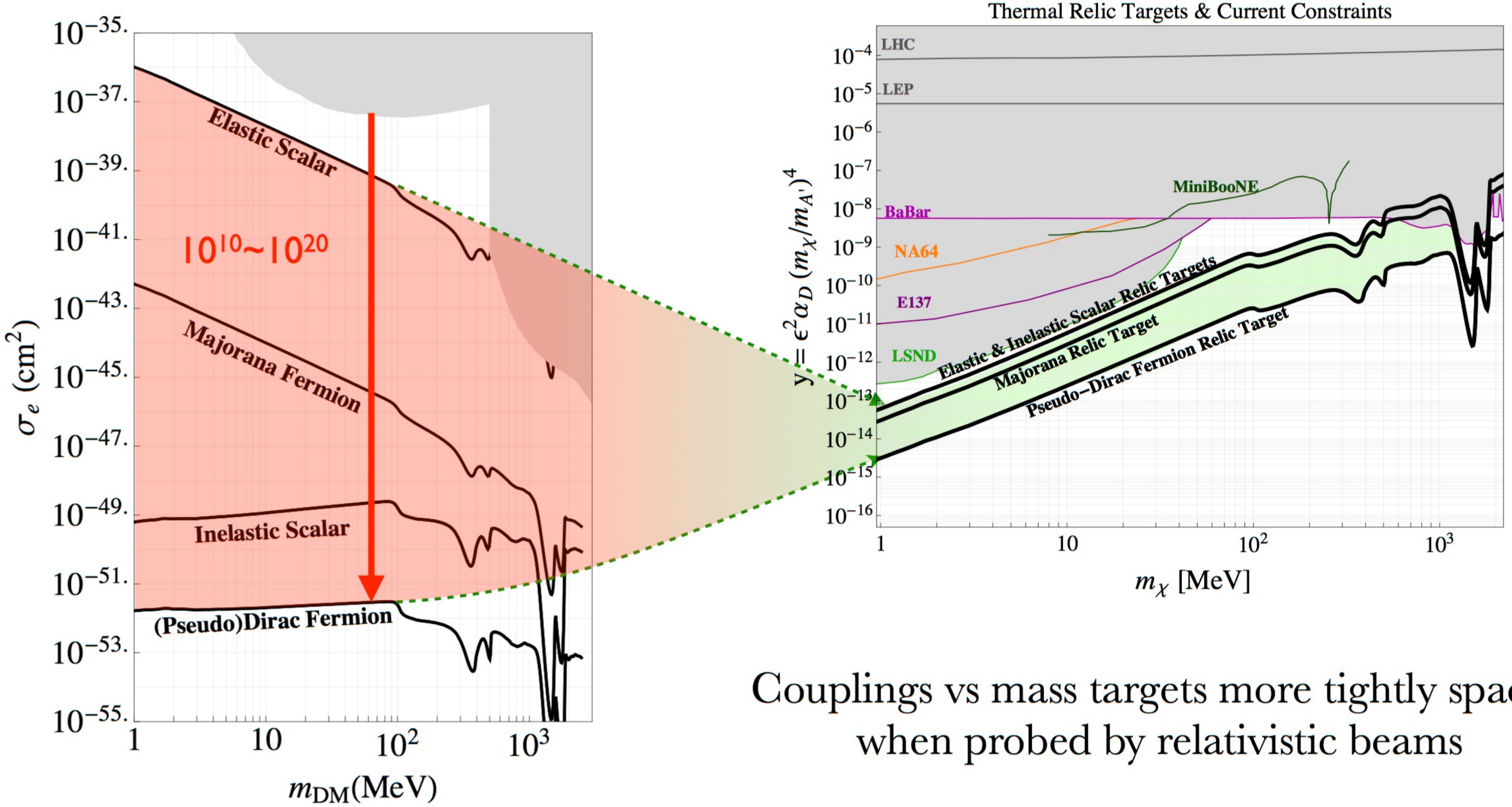
Motivation for sub-GeV DM Search: Probing Relic Density Limits

Boosted accelerator Dark Matter improves reach testing relic density limits

The Thermal Target

Halo DM ‘beam’: non-relativistic probe

Accelerator DM beam: relativistic DM



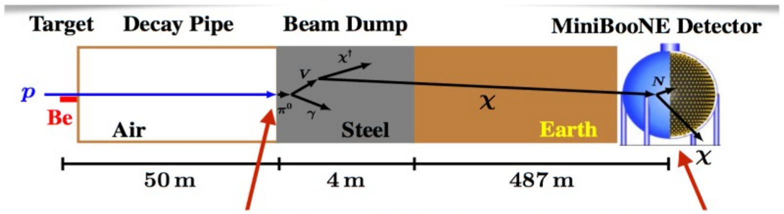
Couplings vs mass targets more tightly spaced when probed by relativistic beams

Sensitive to **any** thermal relic

Closing in on well defined goal post!

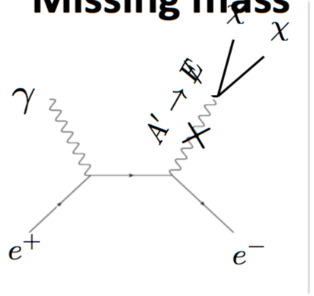
Many Techniques to Search for Accelerator Produced Dark Sector Particles

Proton / electron beam dump



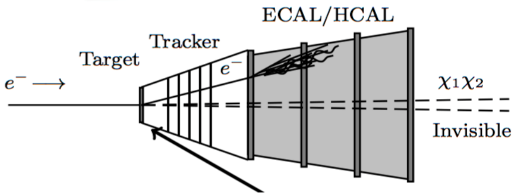
Probes DM interaction twice

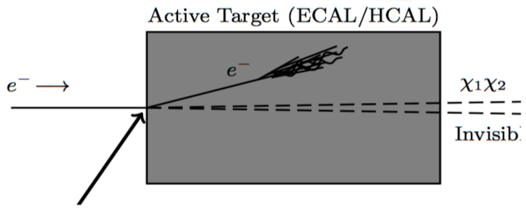
Missing mass



Resonance signal, rate gives coupling information

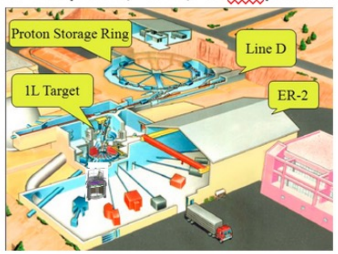
Missing energy / missing momentum



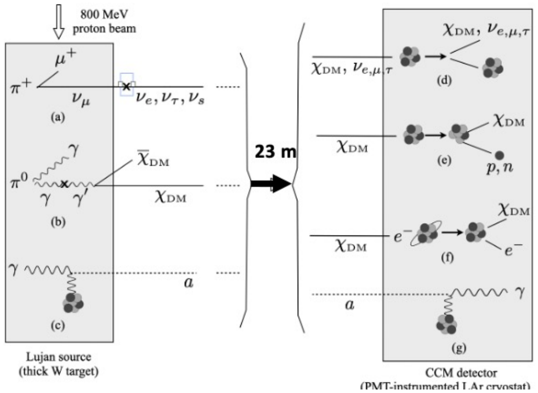


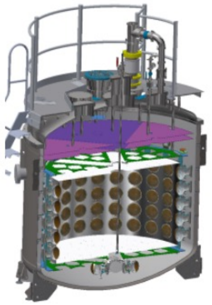
Best yield scaling with luminosity

800 MeV protons, 100kW, 290 nsec pulsed beam



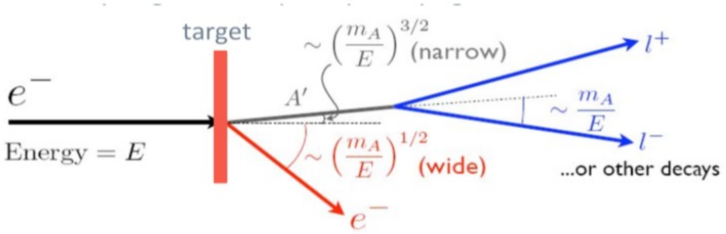
LANSCE-PSR-Lujan Target: Prolific source of charged/neutral pion's and photons that produce neutrinos and potential dark sector particles.





CCM strategy: Directly produce and detect dark sector particles and probe new physics

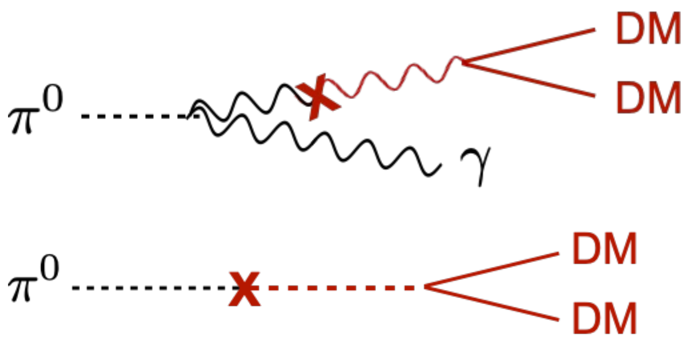
Searches for the mediator



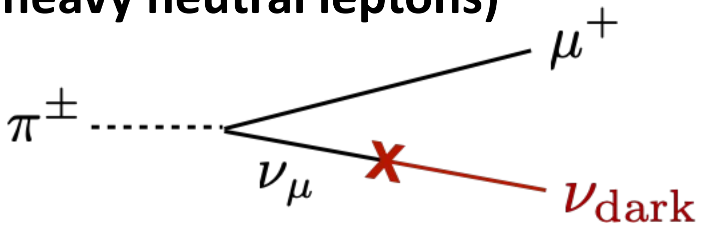
Complementary to DM searches

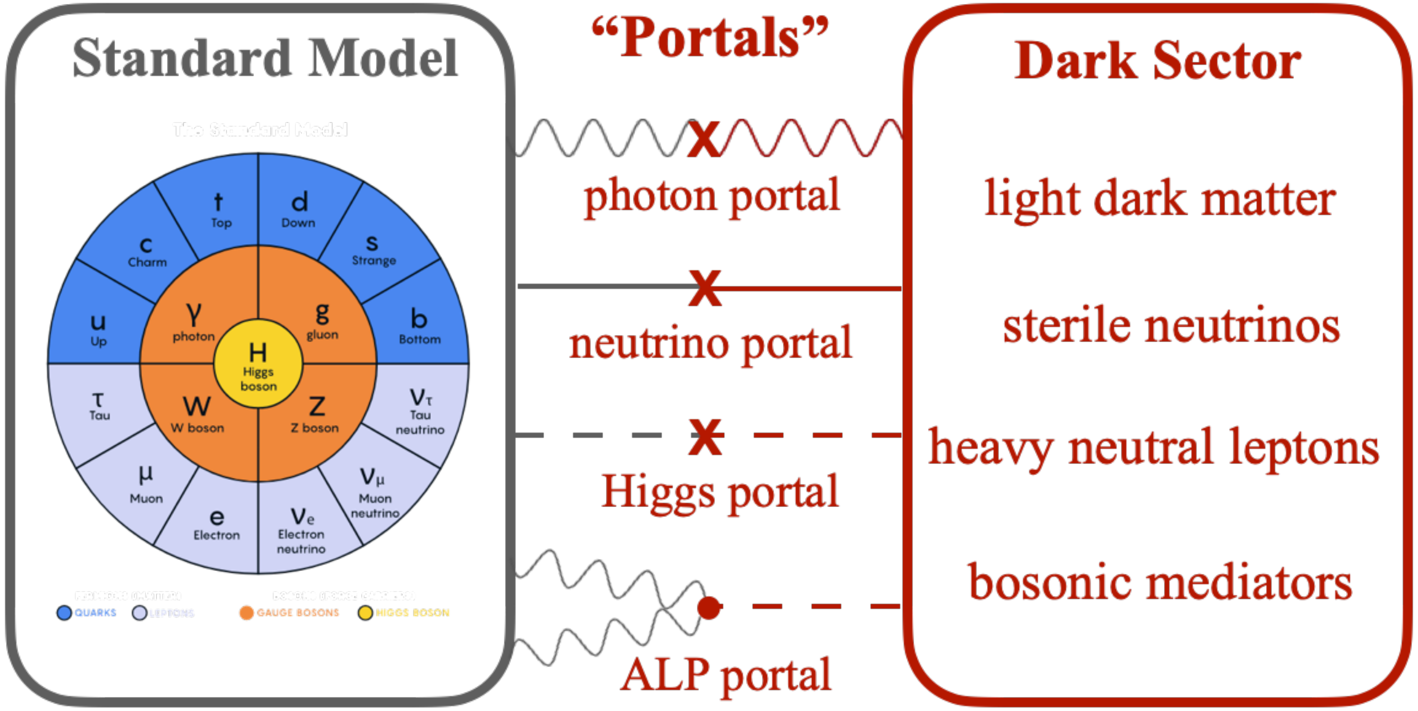
Intense/recent theoretical efforts developing a rich and evolving set of Dark Sector models: DS is maybe not so simple as a single WIMP particle!

- **Dark matter production and detection via vector and (pseudo-)scalar portals**



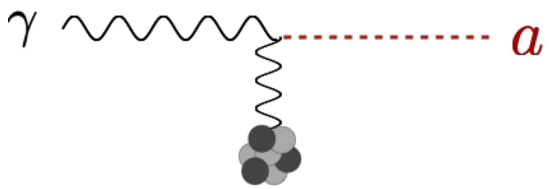
- **Neutrino Portals (sterile neutrinos, heavy neutral leptons)**

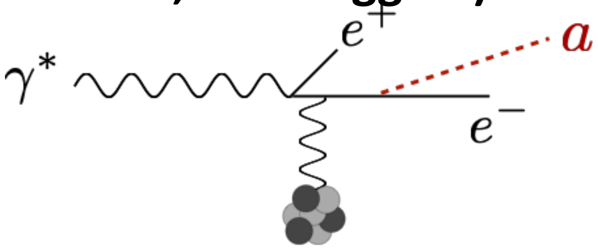




Intense proton/electron colliders and beam dumps can probe all these portals

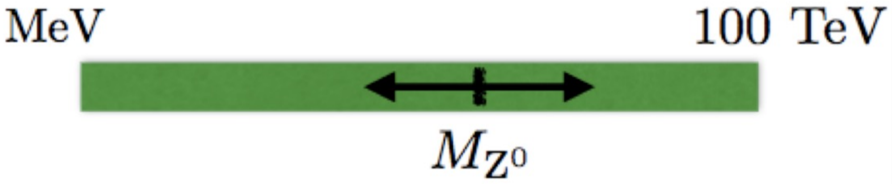
- **Dark Sector Mediators (ALPs, dark vectors, dark higgses)**



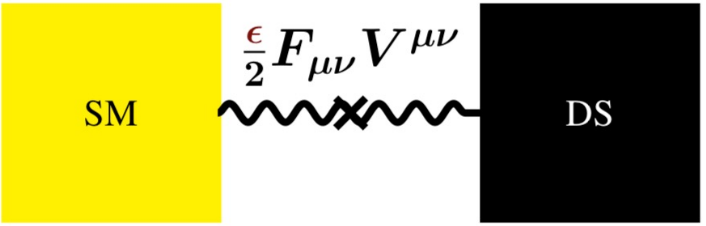


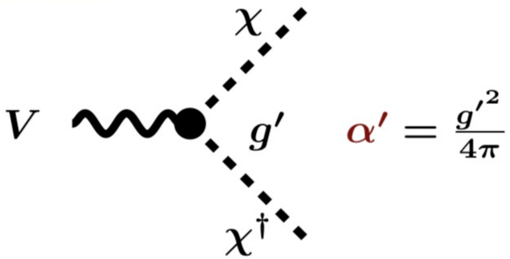
Example Benchmark Dark Sector Model: Vector Portal Dark Photon

Standard WIMP

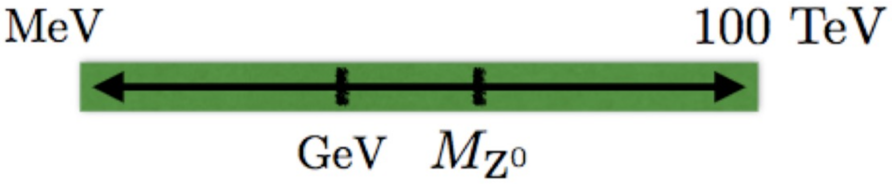


- Assumes mediator is the Z boson
- Strong constraints from cosmology, astrophysics, and particle physics





New Light Mediator



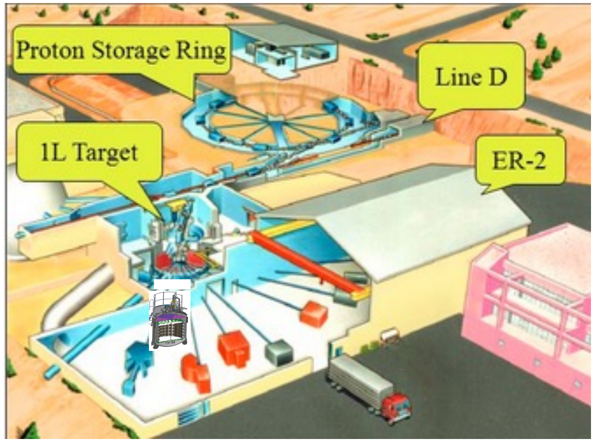
- Does not assume mediator is the Z boson
- Simplest model assumes mediator is a vector (dark photon)
  - 4 free parameters
    - Mass of the dark photon m_V
    - Mass of the dark matter m_χ
    - Mixing angle between SM and dark sector ε
    - Coupling between dark photon and dark matter α_D

Pospelov, Ritz, Phys.Lett.B **671 (2009)**

Dark Sector Searches at LANSCE with the Coherent CAPTAIN-Mills (CCM) Experiment

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

800 MeV protons, 100kW, 290 nsec pulsed beam



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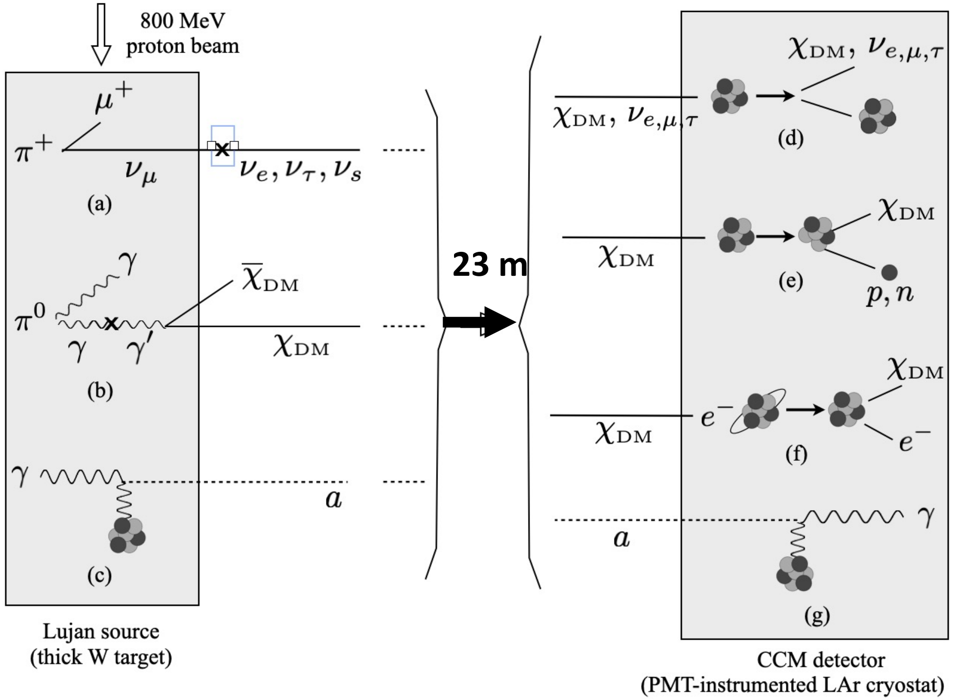
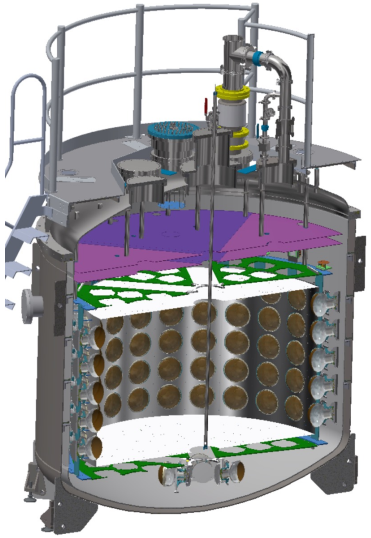




CCM: 10-ton Liquid Argon (LAr) detector instrumented with 200 8" Photo-multiplier tubes, veto region, shielding, fast electronics.

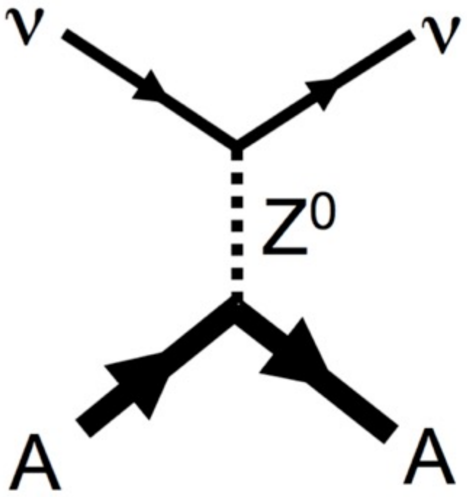
Planned Scope (LANL LDRD):

- Build a LAr low threshold, fast detector (CCM200) at Lujan and detect Coherent Neutrino Nucleus Scattering (CEvNS) with the goal of measuring coherent cross sections and searching for sterile neutrino oscillations at the LSND/MiniBooNE mass scale.

Expanded Scope (HEP Dark Matter New Initiative - DMNI):

- Goal to search for new dark sector particles (dark matter, ALPs, etc) with a three-year run. Enhanced shielding and detector upgrades would significantly improve CCM reach, test dark sector model explanation of MiniBooNE excess.

LANSCE Intense Pulsed Proton Source Search for the Dark Sector
The Coherent CAPTAIN-Mills Experiment



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CAPTAIN = "Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos"

The University of Edinburgh

Embry-Riddle Aeronautical University

Massachusetts Institute of Technology

Columbia University in the City of New York

UNM

Fermilab

UF University of Florida

Los Alamos National Laboratory EST. 1943

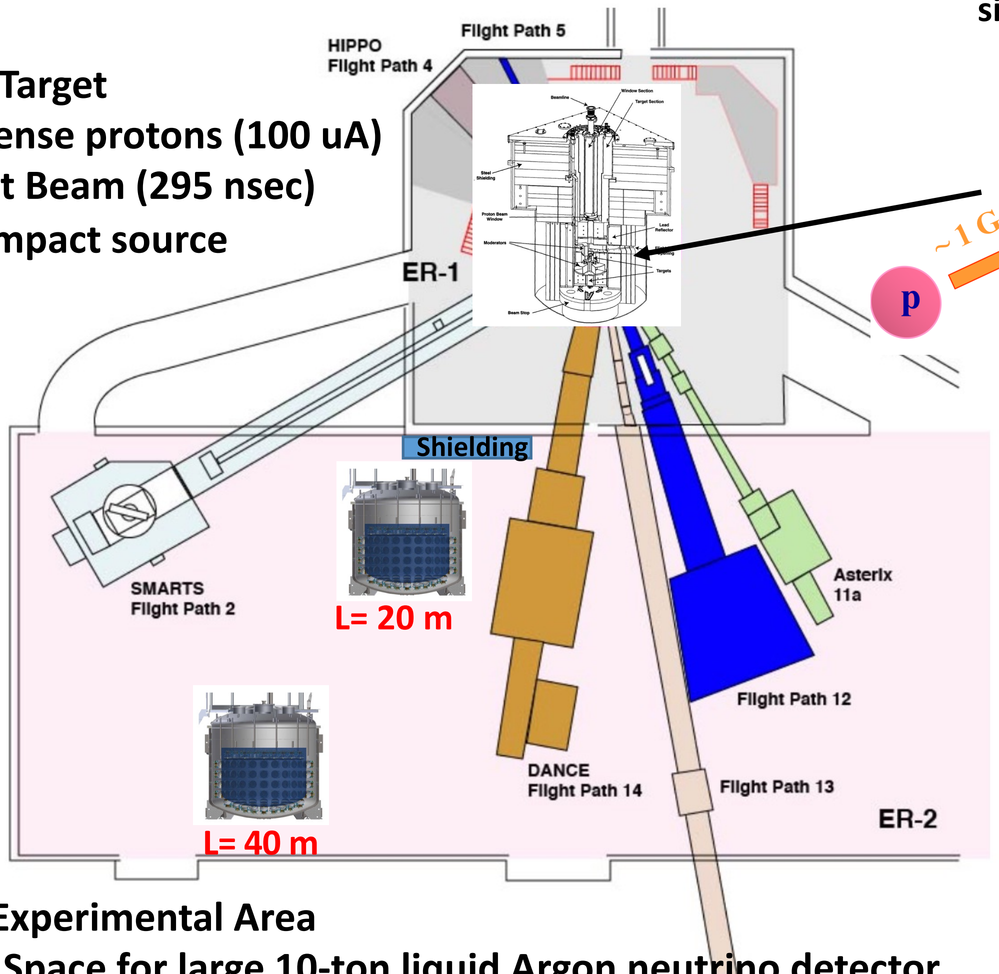
ATM

Universidad Nacional Autónoma de México

LANL Institutional Support

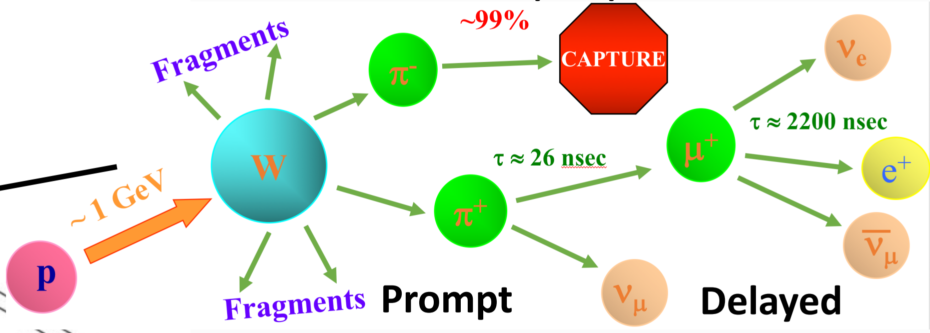
LANSCE-Lujan Facility a unique place to perform significant and timely test of Sterile Neutrinos and Dark Matter

Lujan Target
- Intense protons (100 uA)
- Fast Beam (295 nsec)
- Compact source



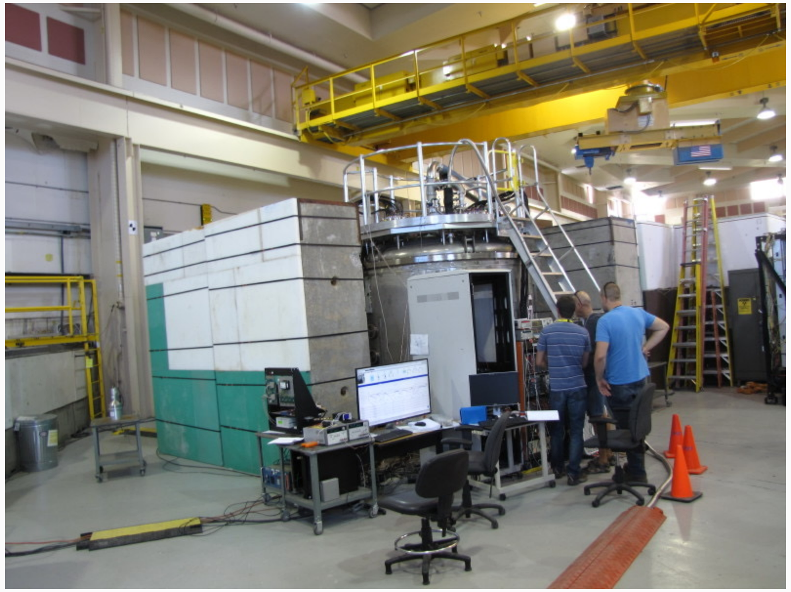
Lujan Experimental Area
- Space for large 10-ton liquid Argon neutrino detector.
- Can run detector in multiple locations – background studies
- Room to deploy shielding, large overhead crane, power, etc

Intense source muon neutrinos: target MCNP simulation flux 4.74x10^5 nu/cm^2/s at 20 m



copious amounts of π^0, γ, e, n, p also produced.

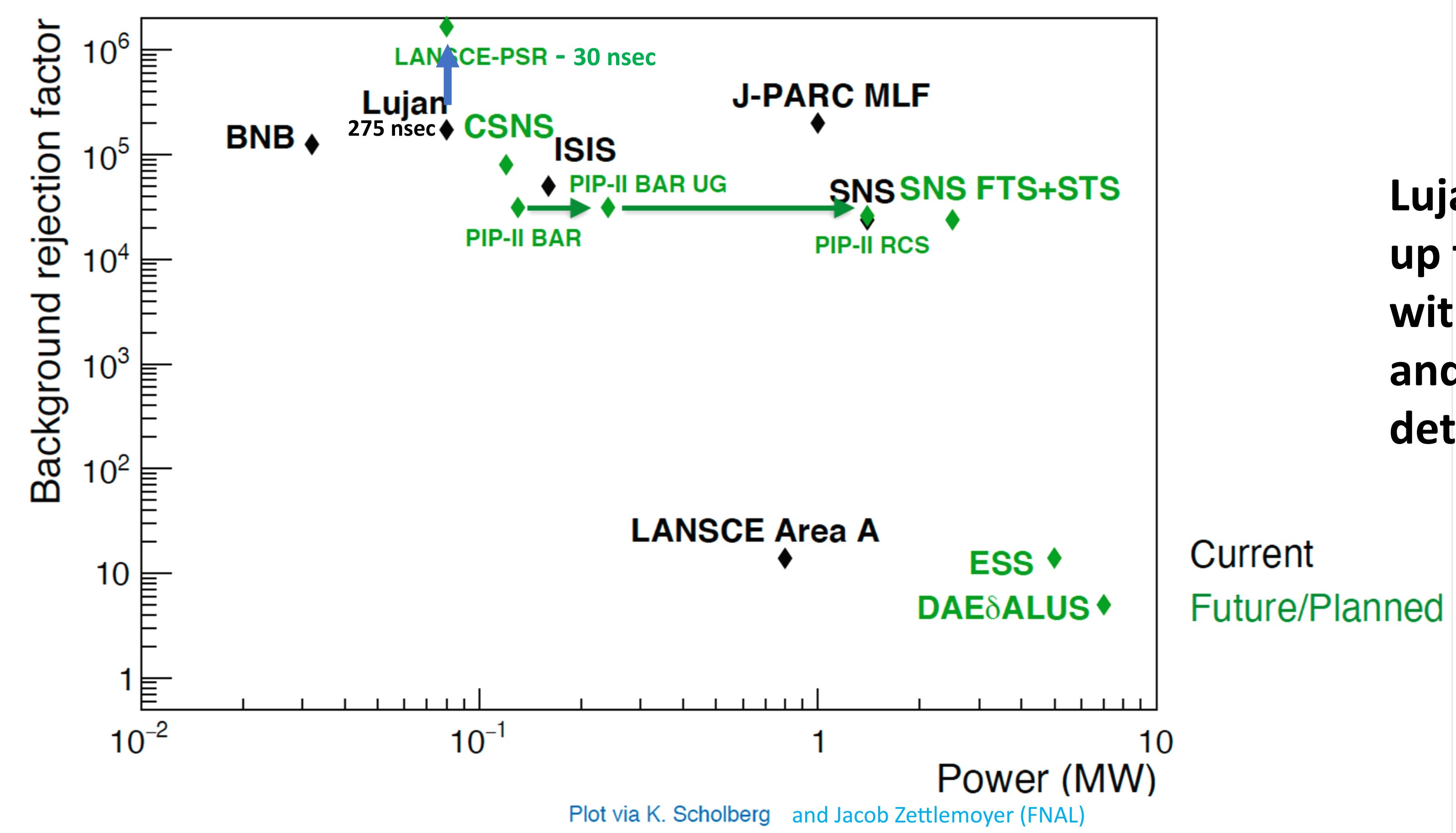
CCM120 beam and calibration run 2019 (L=20 m)



Lujan is a Competitive and Unique Neutrino/Dark Matter Source
Low duty factor critical for background rejection

LANL Institutional Support

Typical beam delivery of 7.5x10^{21} POT/year



Lujan/CCM makes up for less power with large, sensitive, and fast 10 -ton LAr detector!

- **Neutrino/DM experiments require high Instantaneous Power (IP) – measure of Signal/Background (S/B):** SNS (FWHM 350 nsec @ 60 Hz)= 0.060 kJ/nsec; Lujan(FWHM 138 nsec @ 20 Hz)= 0.031 kJ/nsec
- AOT working towards < 200 nsec beam, increasing IP and S/B by > 50% or more.
  - Result in significant increase in CCM sensitivity to dark sector searches.

Lujan Tungsten Target

(Neutron production well understood and modeled - AOT)

Nuclear Instruments and Methods in Physics Research A 594 (2008) 373–381

Nuclear Instruments and Methods in Physics Research A 632 (2011) 101–108

Complex target tuned for neutron production

Beamlines controlled by Hg window

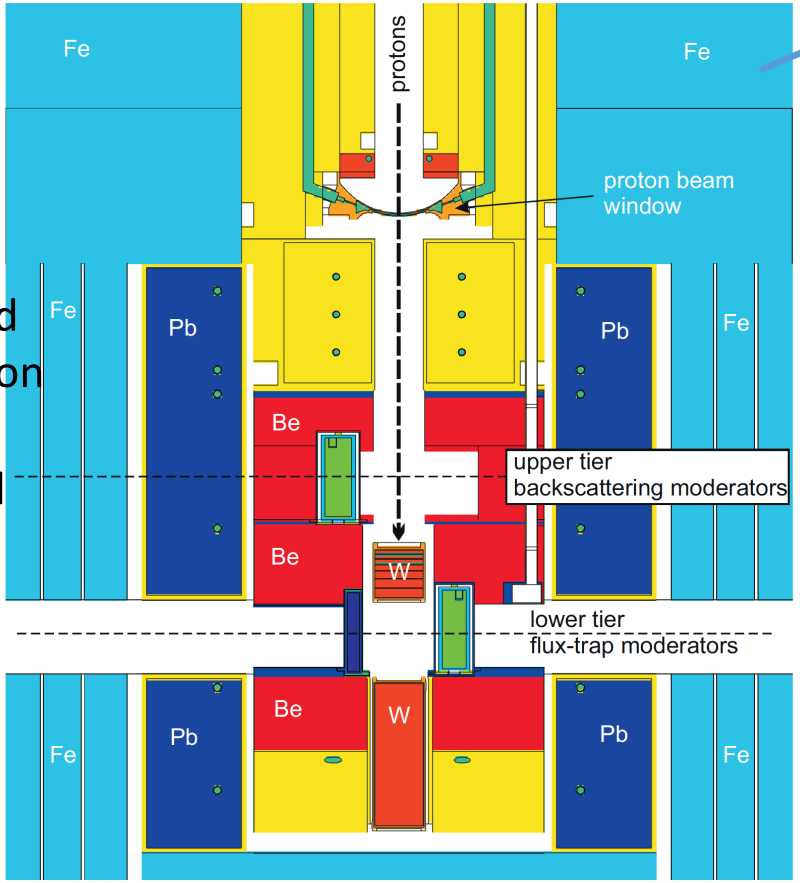
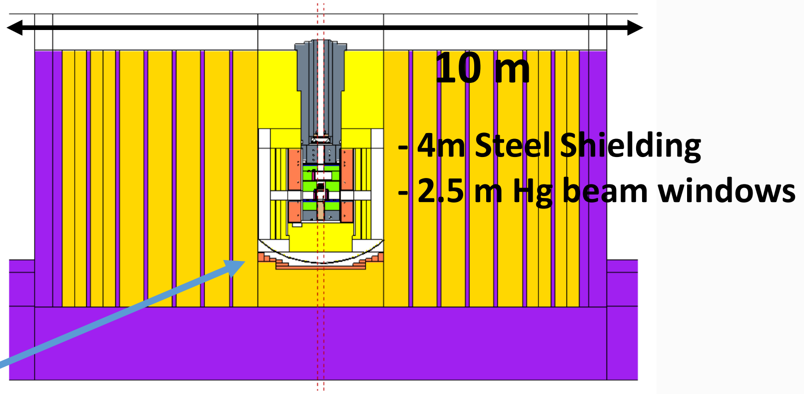
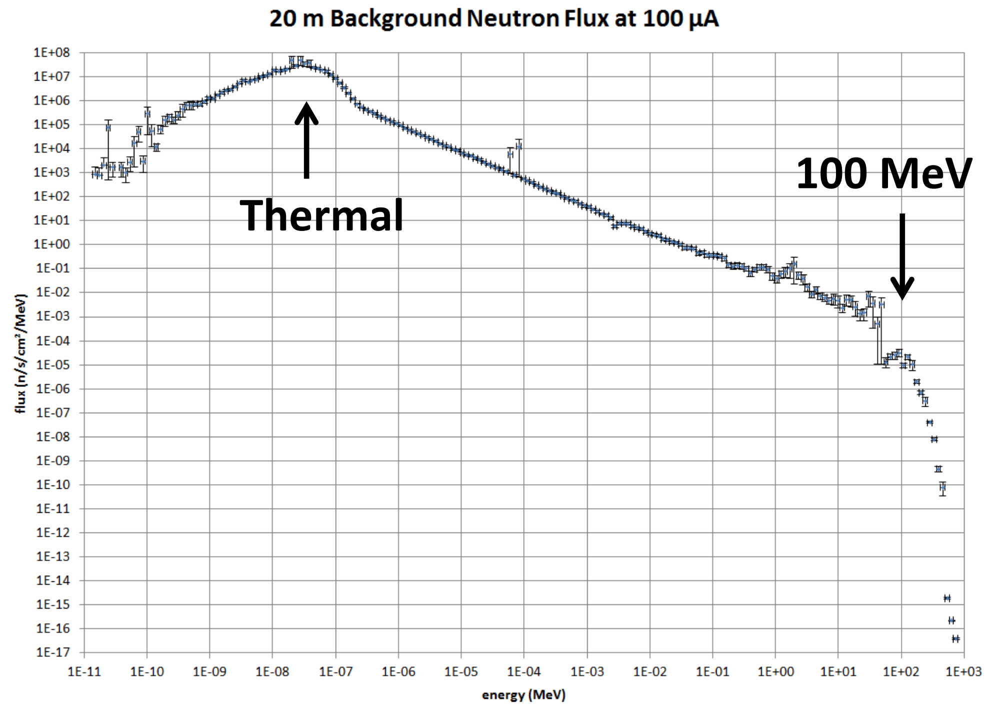


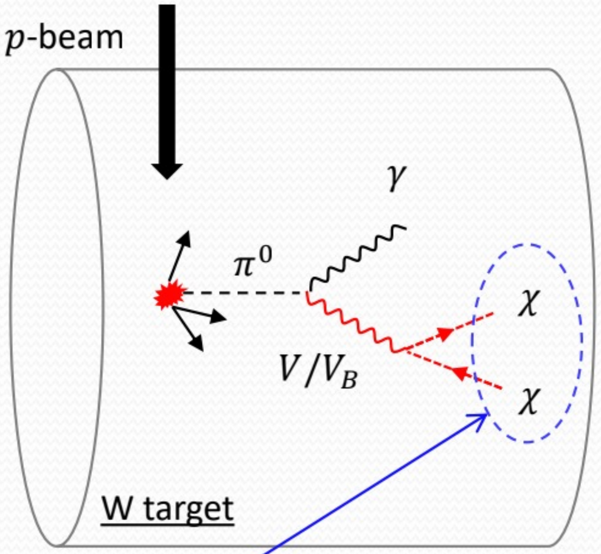
Fig. 1. Elevation view of the Lujan Center's TMRS geometry used in our calculations. The main components are labeled: split tungsten target (W), beryllium reflector (Be), lead reflector–shield (Pb), and the steel reflector–shield (Fe).



- Extensive shielding around target
- Simulations has confirmed hand calculated neutrino flux of ~4.74×10^5 nu/cm^2/s at 20 m
- MCNP simulation of target and ambient neutron flux

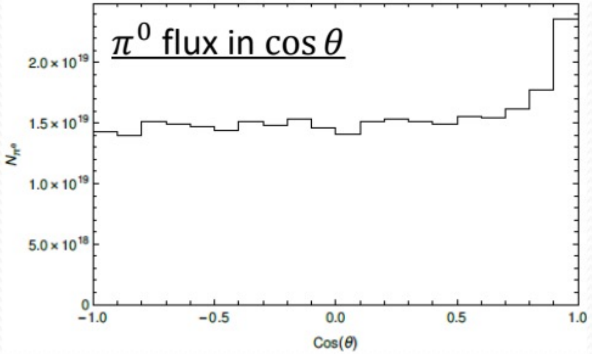


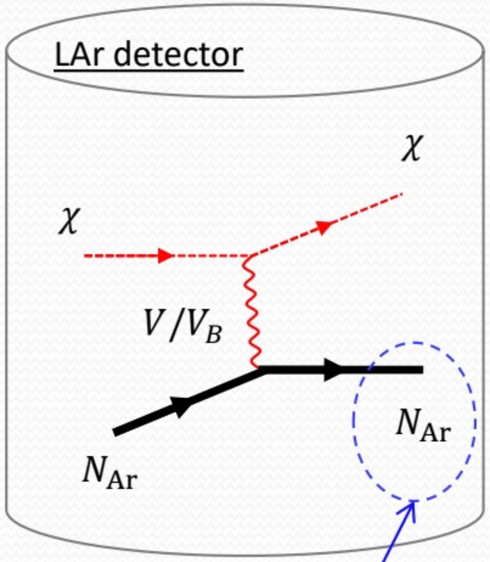
Production & Detection of Dark Matter at CCM



π^0-induced DM flux widespread in angle

$N_{\pi^0} = 0.115$/POT



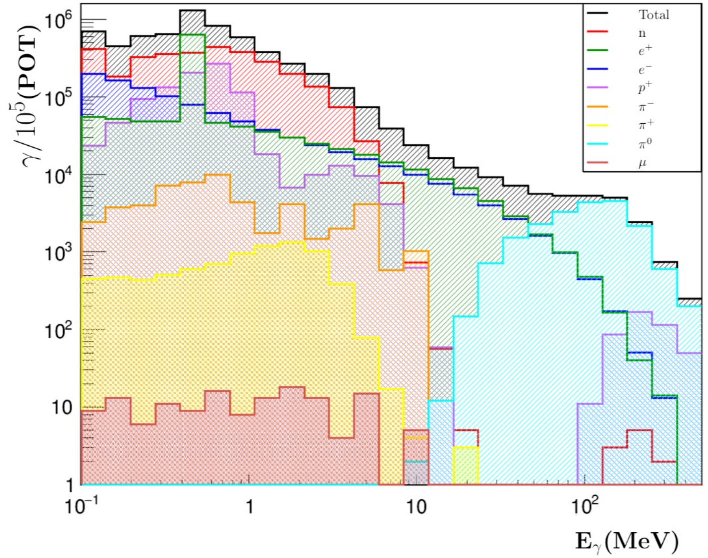


Coherent scatter final state 1 - 100's keV

Observing a coherent scattering off an Ar nucleus

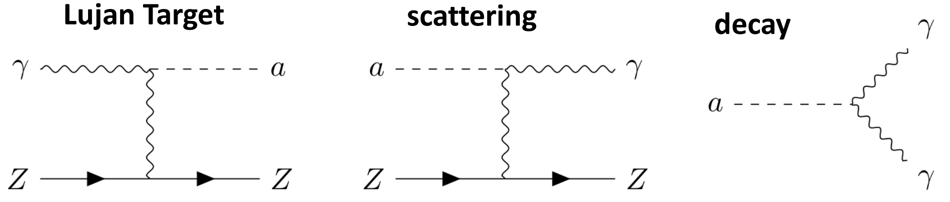
Axion Like Particles (ALPs) from Photon and Electron Production

Prolific Photon/electron Production in Lujan Target

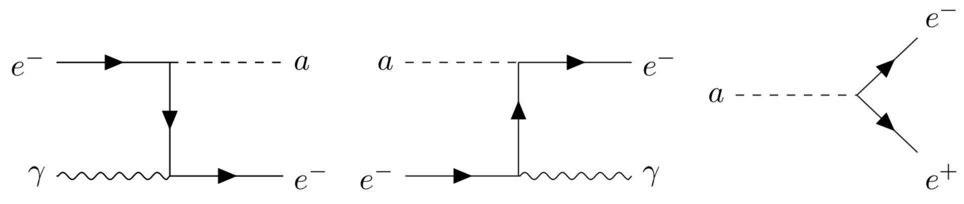


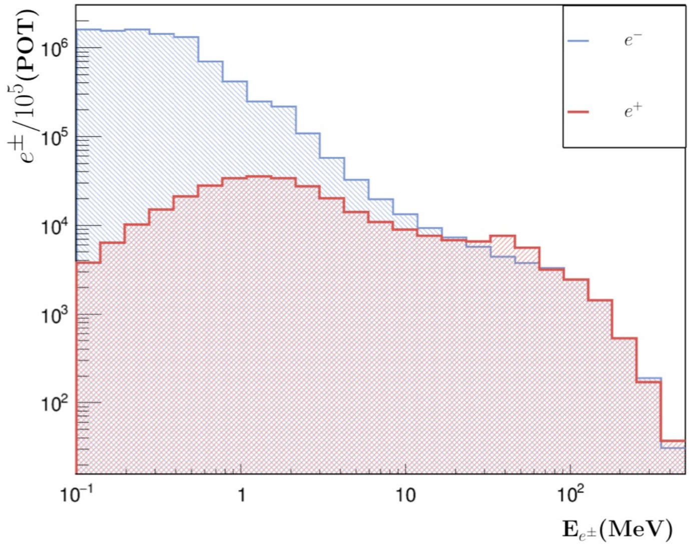
ALP (a) Primakov production and inverse-Primakov scattering

Production in Lujan Target | **Detection via scattering** | **Detection via decay**



Final state scatter 0.1 – 10's MeV



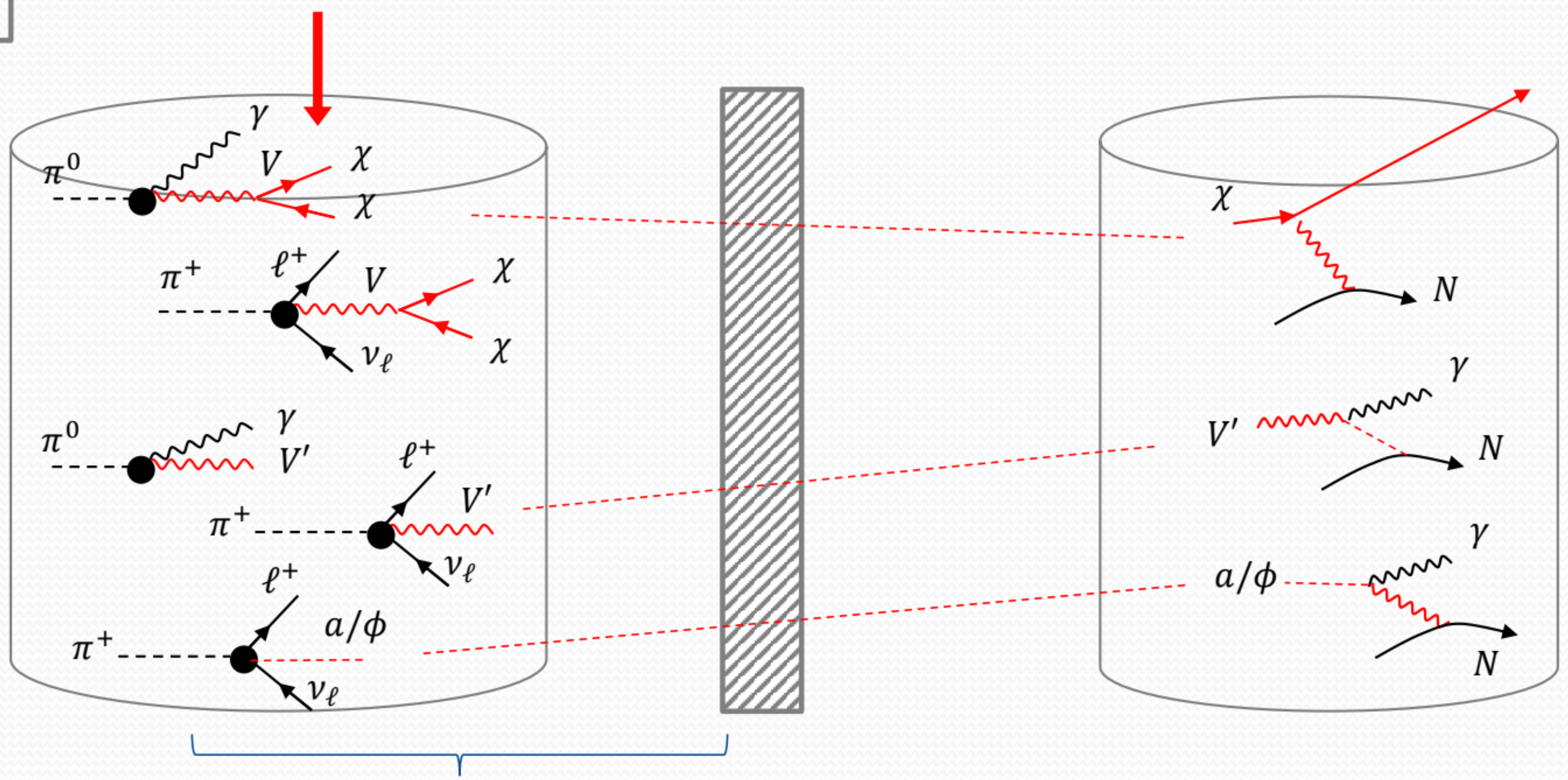


"Axion-Like Particles at Coherent CAPTAIN-Mills"
arXiv: 2112.09979

Testing Dark-Sector Scenarios for the MiniBooNE Excess at CCM (arXiv 2110.11944, accepted PRL)

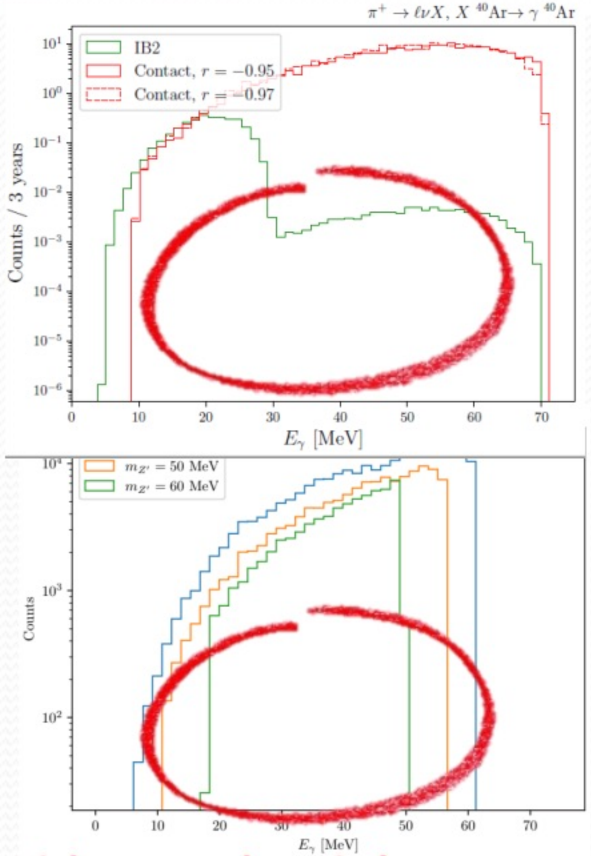
Connecting to CCM: hadronic currents

CCM



Isotropic flux of dark-sector particles

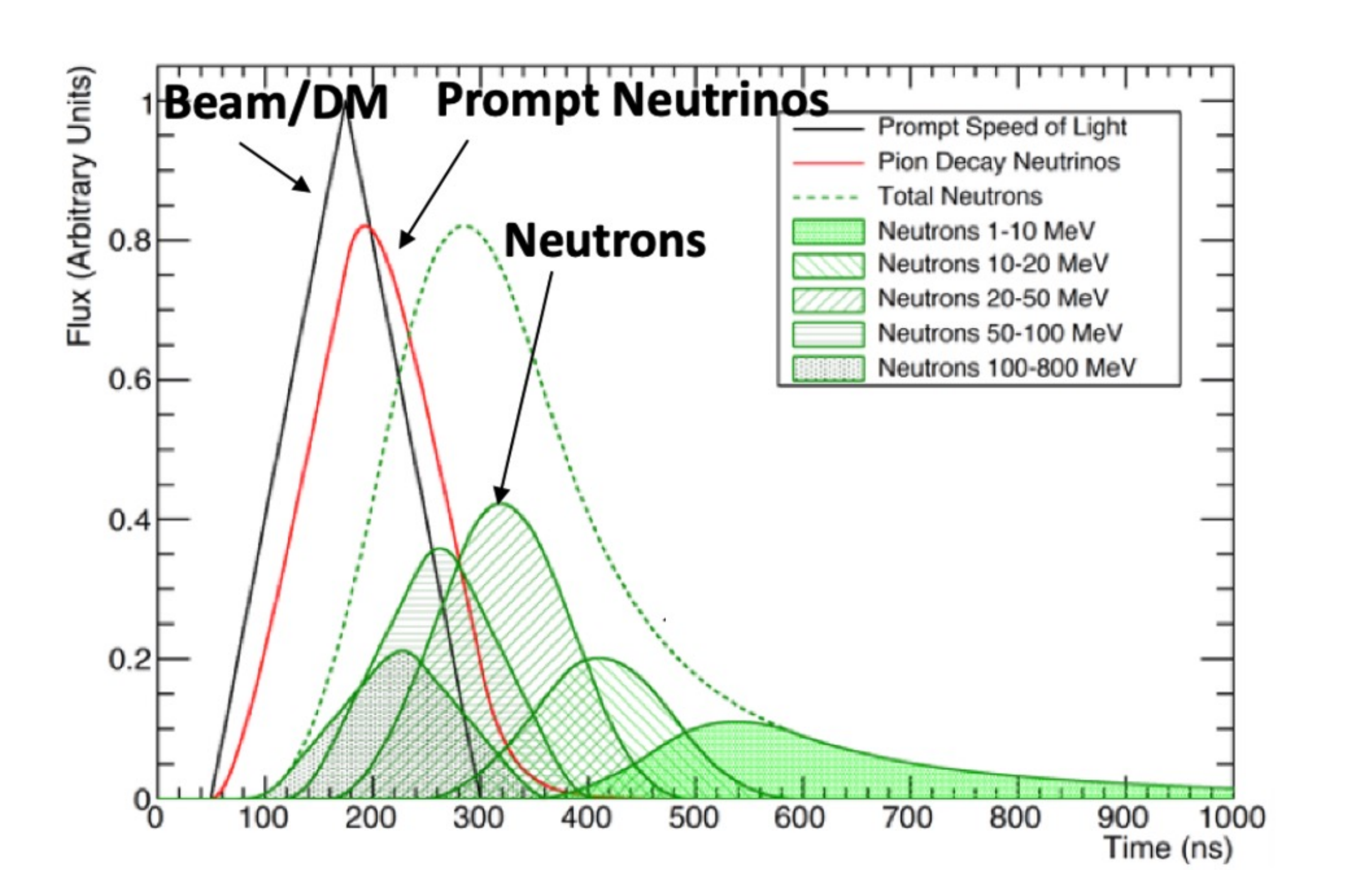
EM Signal > 10 MeV



High-energy deposits!

Cf. Observation of the $\chi \to \chi'$ (as well as $\nu \to N_R$) upscattering signals is very limited.

Key Requirement: Fast (~nsec) Beam and Detector Timing to Remove Beam Neutrons



- Extensive 5m of steel and 3m concrete slows down neutrons
- Speed of light neutrinos and dark sector particles show up ~200 nsec earlier.

CCM120 Analysis: Beam Related Background Free Region

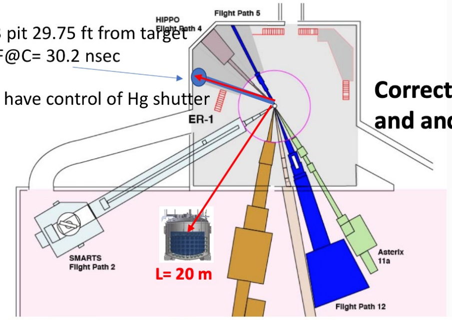
Critical to measure beam T0 using proton on target gamma-flash

Fast EJ-301 n/γ detector placed in FP3 pit

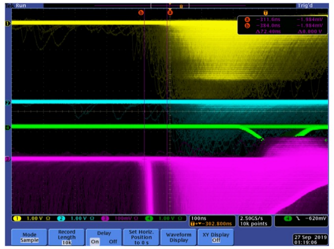
Cabled into CCM detector electronics

FP3 pit 29.75 ft from target
TOF@C= 30.2 nsec

We have control of Hg shutter



Correct for path length differences and and cable/PMT delays.



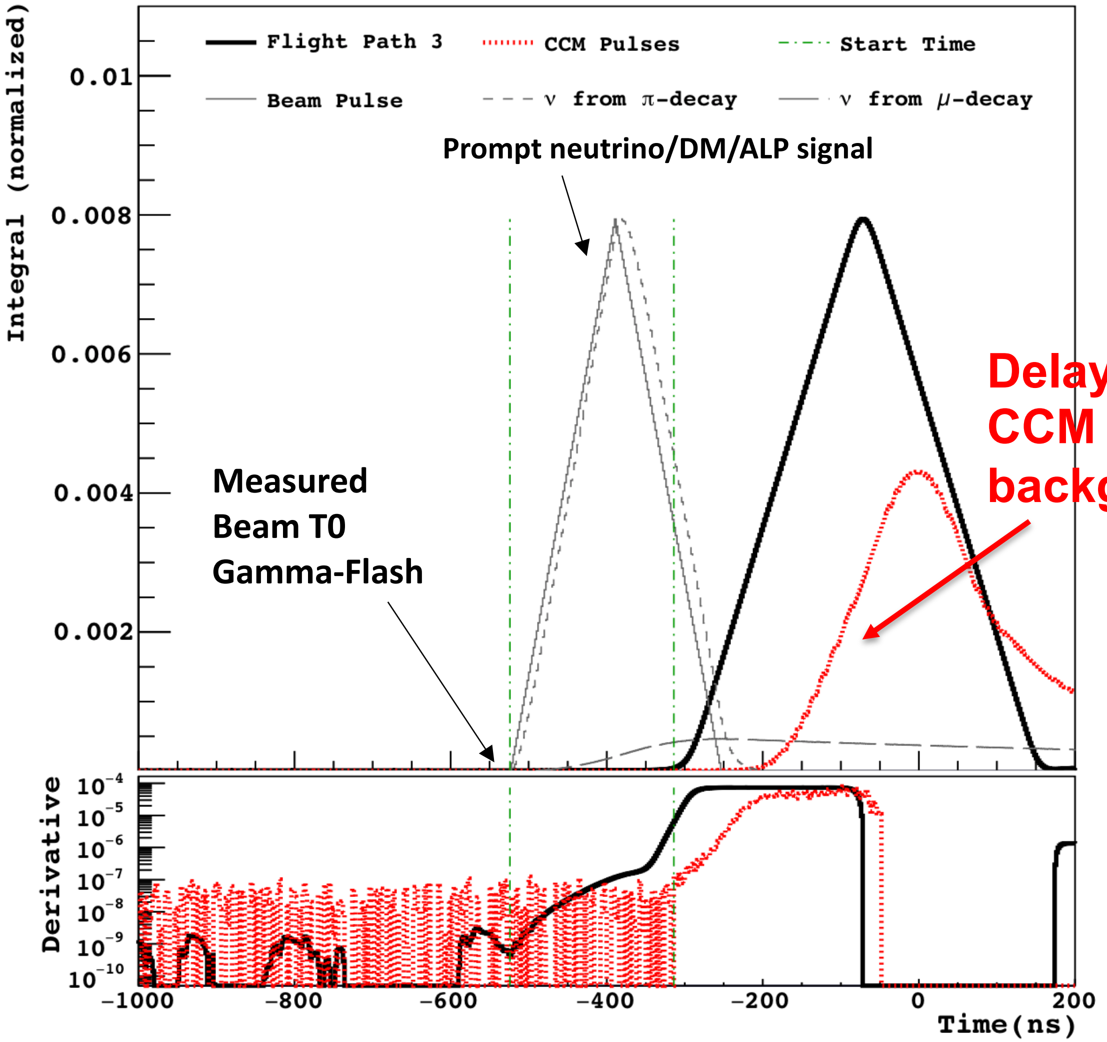
CCM EJ-301 @20m no shielding

CCM EJ-301 @20m behind shielding wall (steel + poly + concrete)

Beam Current Coil trigger

FP3 EJ-301 Shutter Open and Closed, 6" lead shielding

21

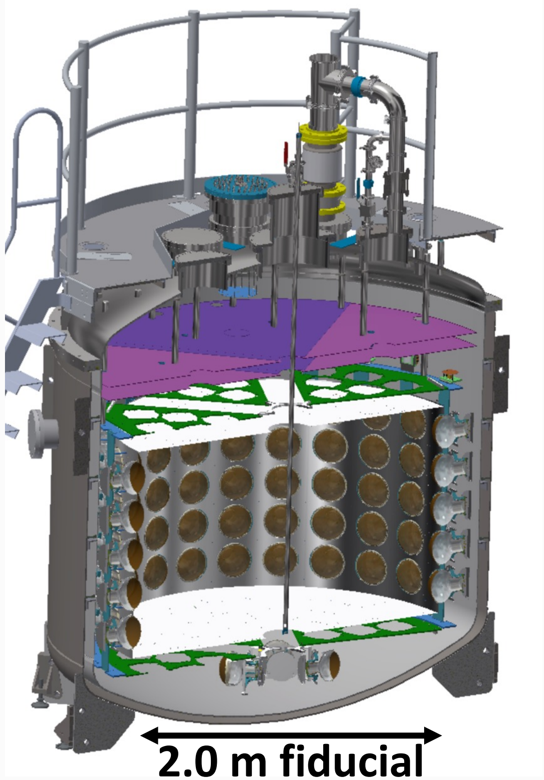


- ~200 nsec prompt time window maximally sensitive to dark sector physics
- The shorter the beam spill the larger the separation of signal and backgrounds

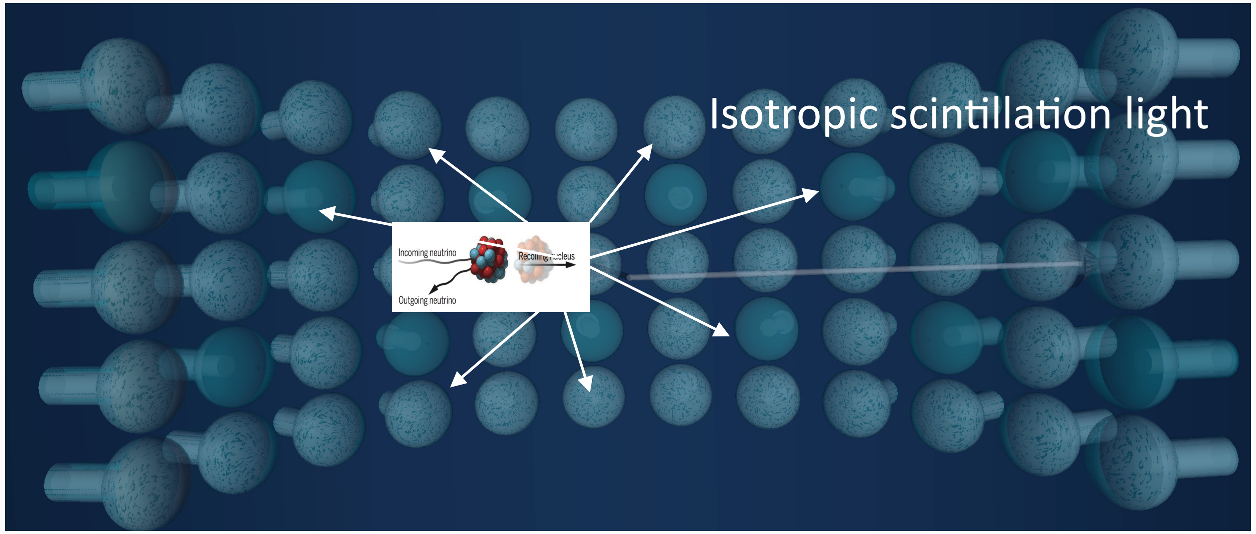
Tyler Thornton (LANL)

Detecting Coherent Neutrinos, DM and Axions: Maximizing Scintillation Light Detection!

- **200 R5912 PMT's 50% photocathode coverage.**
- **Wavelength shifting TPB foils rest of coverage. Provides optical barrier with veto region**



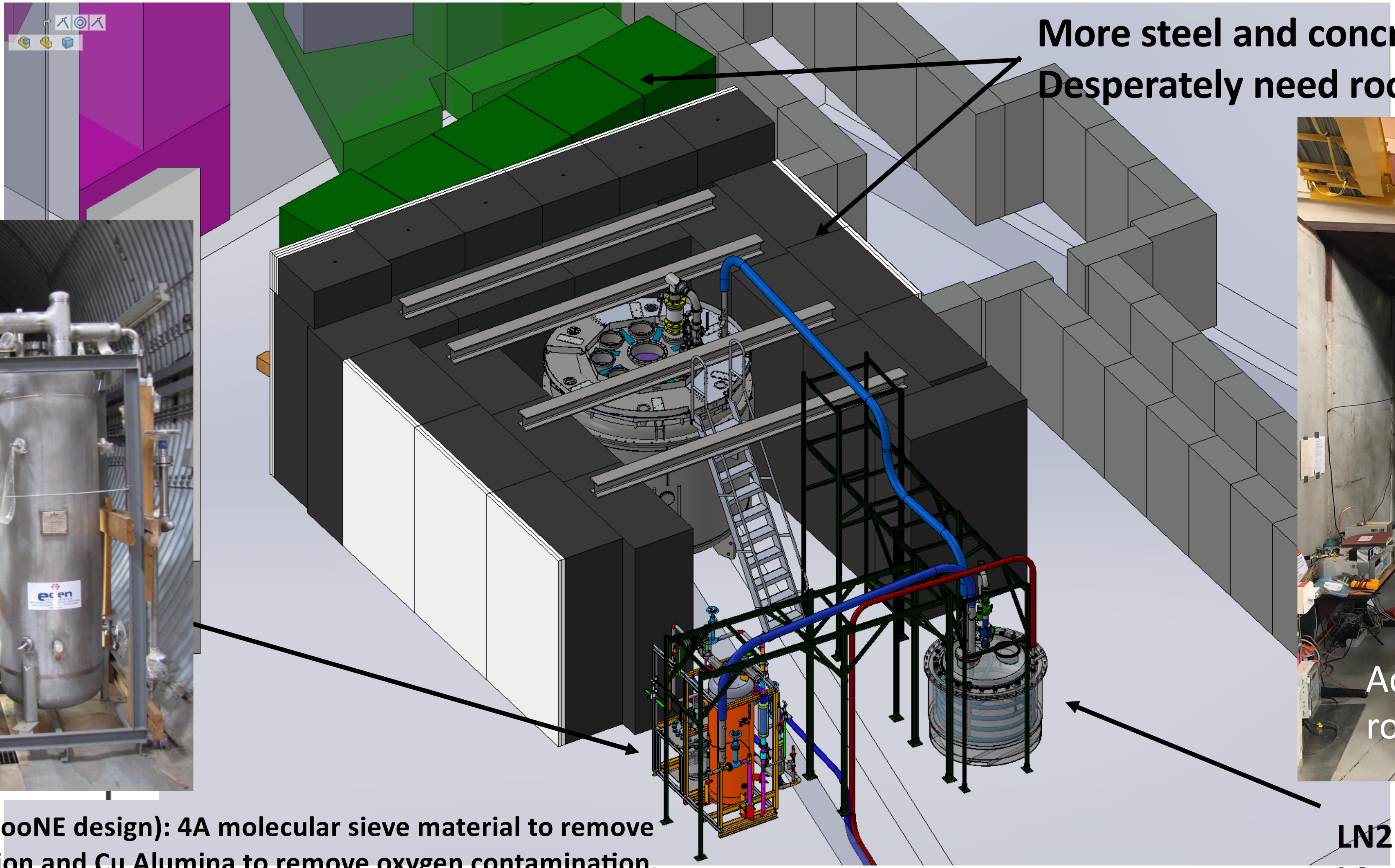
GEANT + Optical Model Input Detector Simulation



Simulations predict ~1 PhotoElectron/keVnr – singlet light

- **Liquid Argon scintillates at 128 nm with 40,000 photon/MeV, or 40 photons/keV.**
    - Fast 6 nsec (singlet) and slower ~1.6 usec (triplet) time constants.
    - TPB wavelength shifting coating on PMT's and foils to convert 128 nm photons to visible light.
- GEANT4 simulation predicts 10-20 keV detection threshold.
- 5 tons LAr fiducial volume, 5 tons LAr instrumented with 40 1" veto PMT's (2-3 radiation lengths)
- Event reconstruction resolution: time ~1 nsec, position ~20 cm, and energy ~20%.
- Large energy dynamic range from ~10 keV to 100 MeV – excellent photon and electron efficiency

CCM200 Layout at Lujan (23 m from target)
Begin Beam Running Oct 2021



More steel and concrete shielding added.
Desperately need roof shielding.

Filter skid (MicroBooNE design): 4A molecular sieve material to remove water contamination and Cu Alumina to remove oxygen contamination. LAr recirculation turn over time of ~three hours (see backup slide 50)

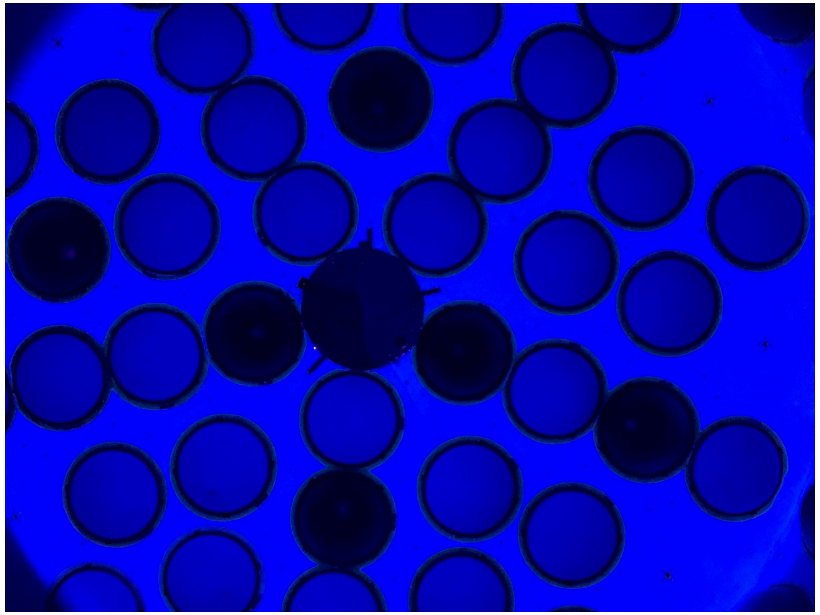
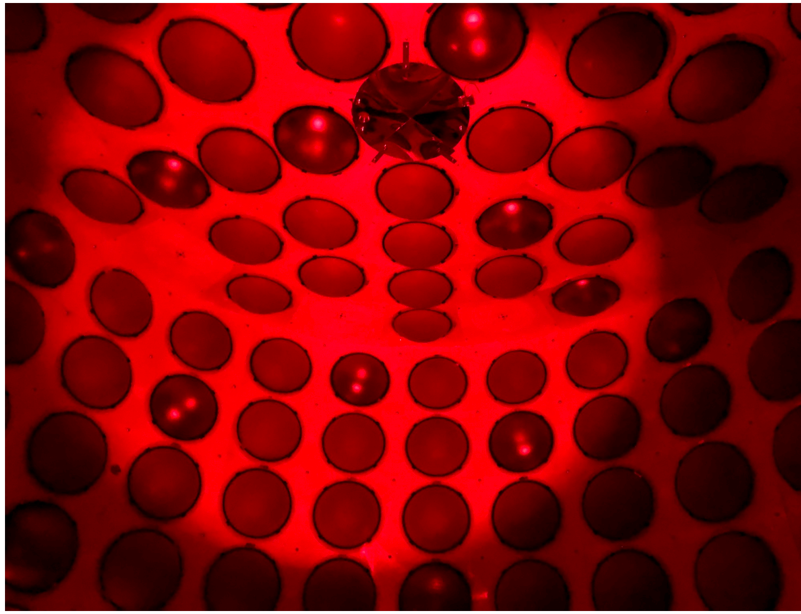
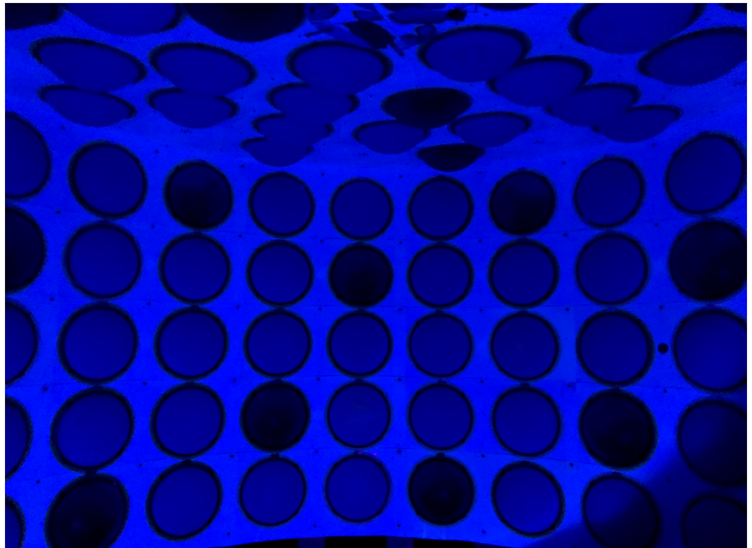
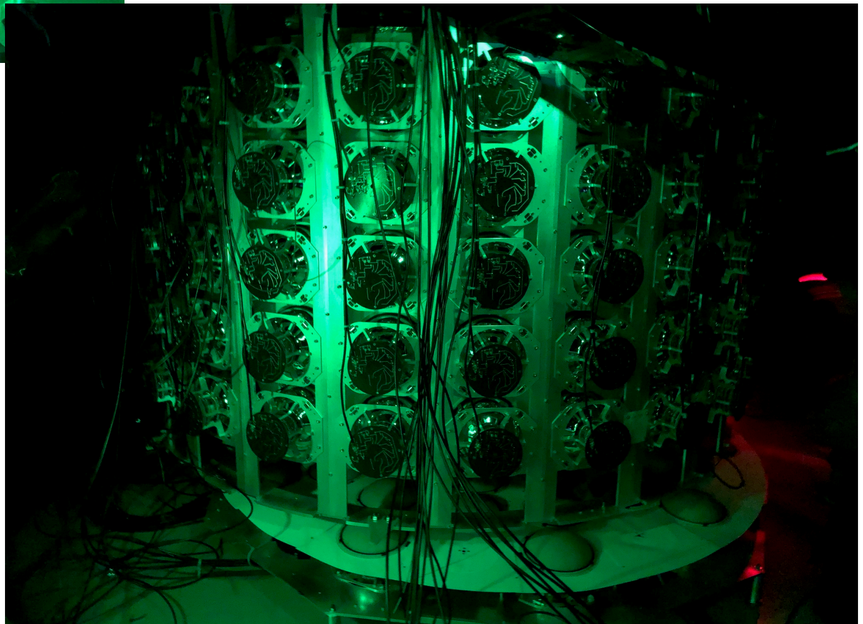
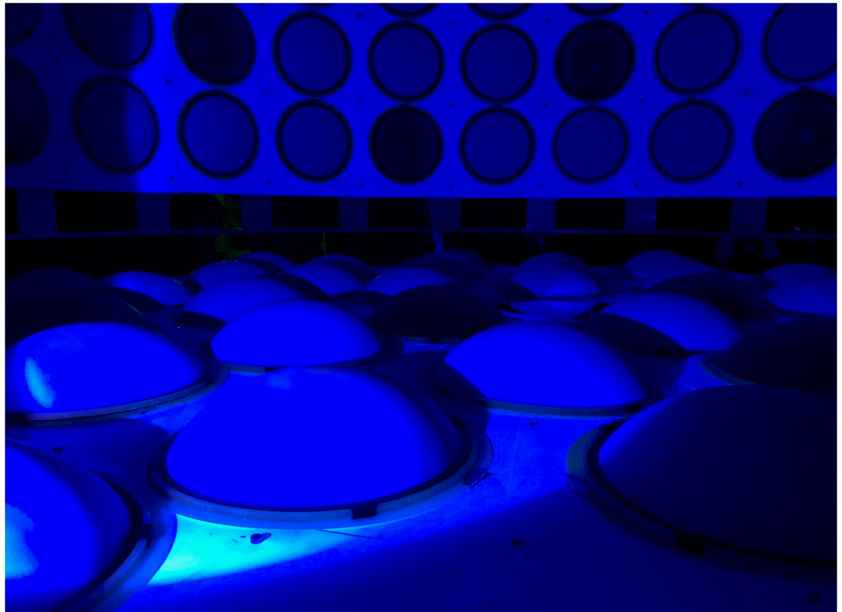
LN2 heat exchanger to reduce LAr losses (especially important if we use isotopically pure U/G LAr in the future).

CCM200 successfully constructed during COVID, begun running early Oct 2021

Huge effort by installation team (left to right):
TJ Schaub (UNM)
Mayank Tripathi (UFlorida)
Will Thompson (P-2 PostBac)
Ed Dunton (ColumbiaU)

Los Alamos
NATIONAL LABORATORY
EST. 1943

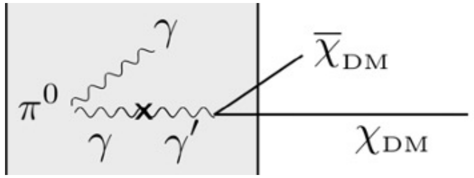
More Cool Pics of CCM200….

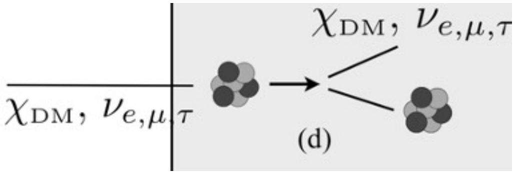
Vector Portal Dark Matter: CCM120 Results and Expected CCM200 Sensitivity

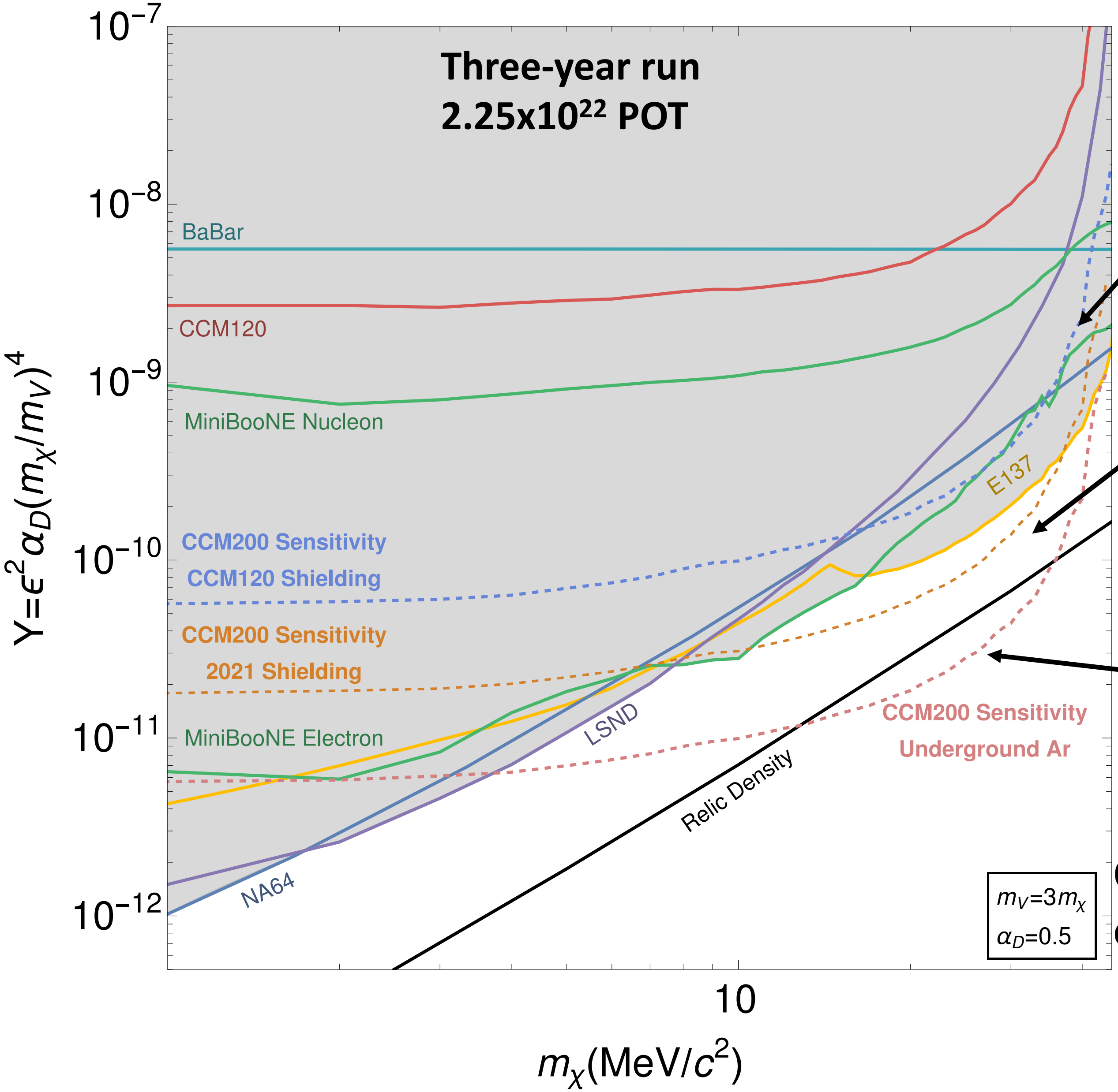
Phys. Rev. D 106, 012001, "First Dark Matter Search Results From Coherent CAPTAIN-Mills"

Source



Coherent Detection





CCM200 with clean LAr two orders of magnitude improvement over CCM120

Begin to probe new parameter space around 20 MeV with shielding

Reducing Ar39 by two orders of magnitude probes scalar relic density

CCM and MB-FullN are the only nucleon scattering limits

CCM200 only

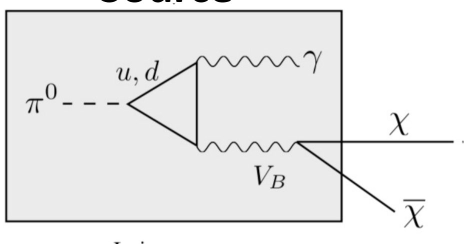
CCM200 + 2021 shielding Phase I

CCM200 + 2021 shielding + isotopically pure LAr Phase II

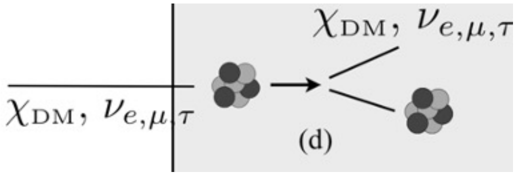
Leptophobic Dark Matter: CCM120 Results and Expected CCM200 Sensitivity

Physical Review Letters Vol. 129, No. 2 (2022), "First Leptophobic Dark Matter Search from Coherent CAPTAIN-Mills"

Source



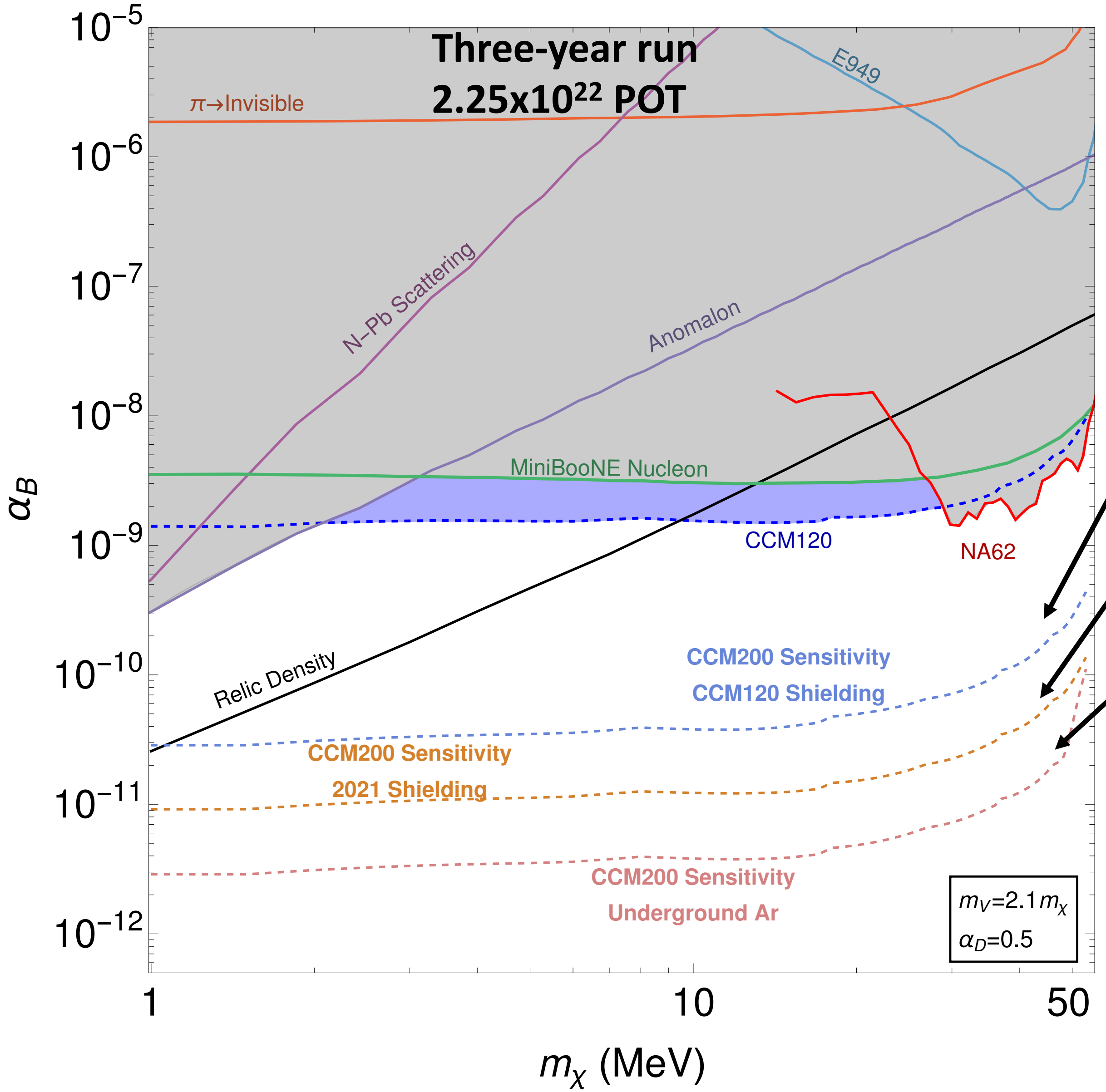
Coherent Detection



CCM200 only

CCM200 + 2021 shielding Phase I

CCM200 + 2021 shielding + isotopically pure LAr Phase II



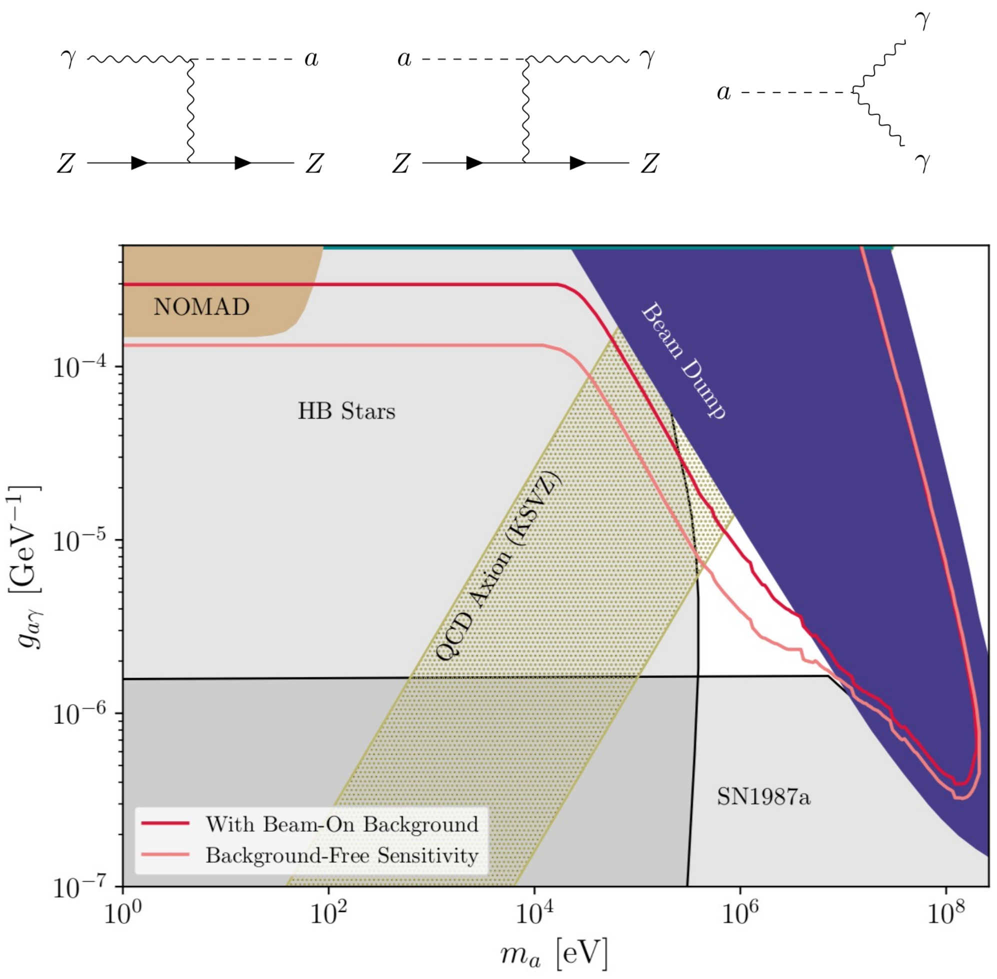
CCM200 with clean LAr two orders of magnitude improvement over CCM120

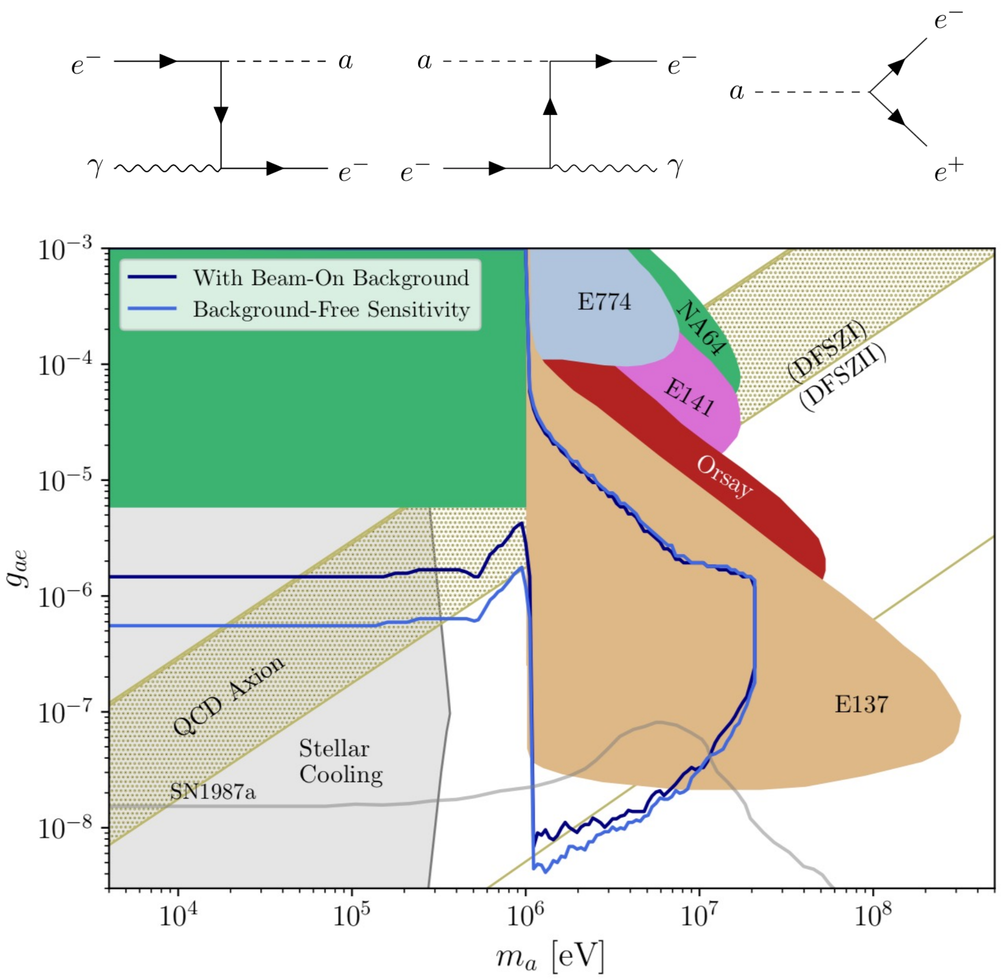
Completely cover relic density limits.

Reducing Ar39 by two orders of magnitude

CCM and MB-FullN are the only nucleon scattering limits

CCM ALP Searches: Testing Cosmic Triangle/Rectangle and QCD Axion





Dutta, Thompson (Texas A&M)

- CCM will probe proton beam dump kinematic region > 1 MeV (electro-magnetic)
- Final sensitivity should lie between projected backgrounds and background-free

Coupling of DM and Axions to Charged Meson Decays Fits to MiniBooNE Excess (arXiv 2110.11944)

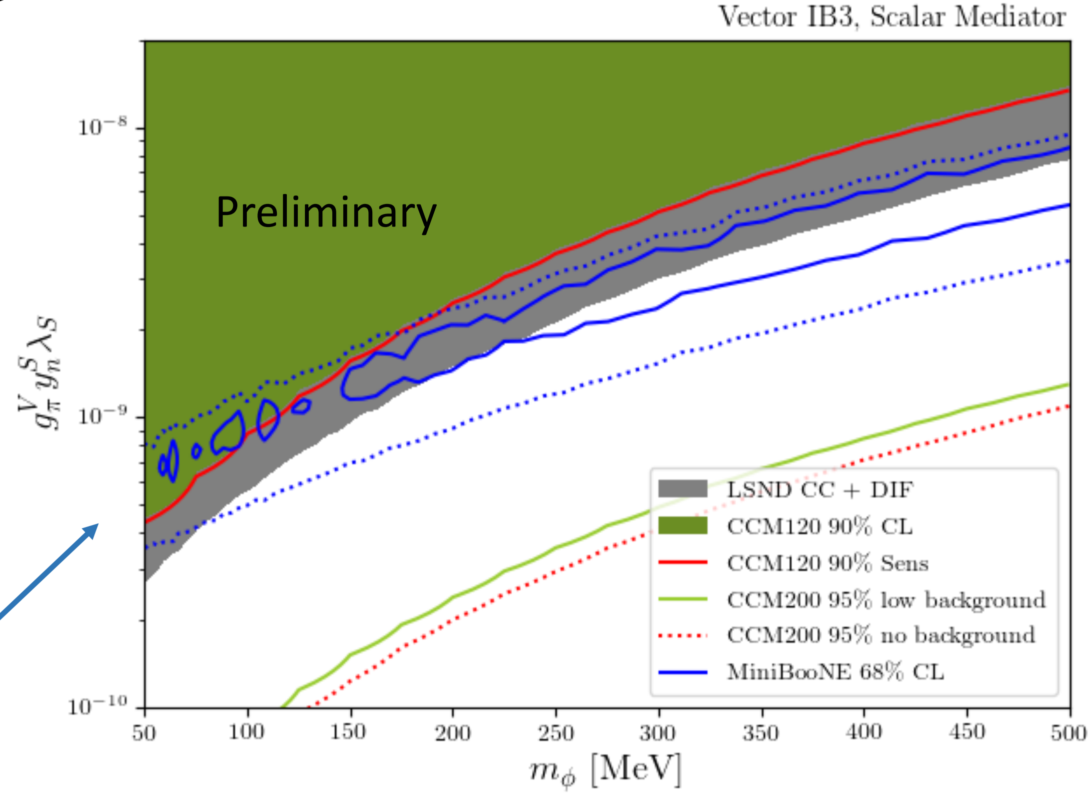
Vector-portal dark matter			
Scenario	$(m_{V_1}, m_{V_2}, m_\chi, m_{\chi'})$	$\epsilon_1\epsilon_2 g_2'^2/(4\pi)$	χ^2/dof
Single	$(17, -, 8, 40)$	3.6×10^{-9}	2.5
Double	$(17, 200, 8, 50)$	1.3×10^{-7}	2.2

Long-lived (pseudo)scalar			
Scenario	$(m_{Z'}, m_{\phi/a})$	$(g_\mu g_n \lambda)$ [MeV^{-1}]	χ^2/dof
Scalar	$(49, 1)$	2.2×10^{-8}	1.6
Pseudoscalar	$(85, 1)$	5.9×10^{-7}	1.6

TABLE I. Summary of example fits. Mass parameters are reported in MeV. In the single-mediator scenario, m_{V_2} is irrelevant, and $\epsilon_2 = \epsilon_1$ and $g_2' \to g_1'$. Due to the mass values of the mediators appearing in the scattering process, we fit the data in the limit of nucleon scattering for the double-mediator scenario, while in the limit of nucleus scattering for the others.

Consistent with meson width measurements

BR[K + → μ+ (e+)νμ(e) ν ν̄] < 2.4(60)×10−6
BR[K+ → μ+(e+)νμ(e)e−e+] < 7.1(2.5)× 10−8
BR[π+ → μ+(e+)νμ(e)νν̄] < 90(1.6) × 10−7



Model predict for MicroBooNE a coherent scattering excess ~18 events at low energy in the ($1\gamma 0p$) sample.

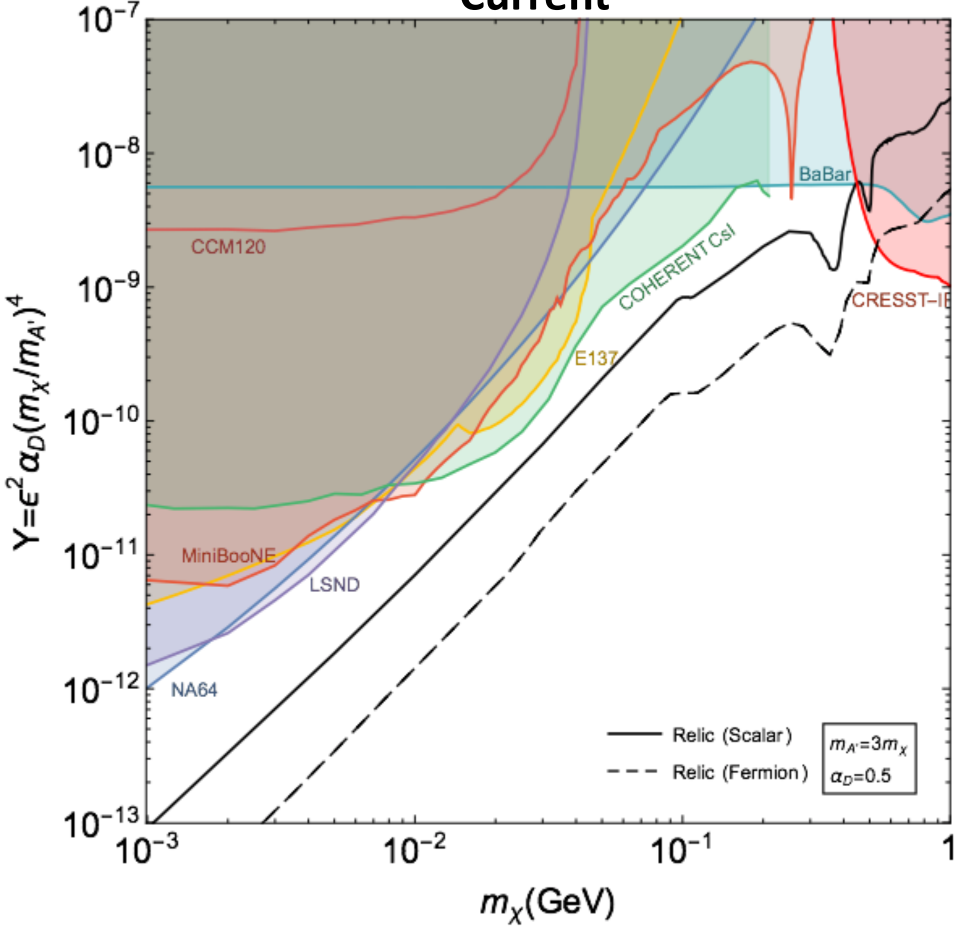
E. Dunton (Columbia)

- **CCM can cover most of the MiniBooNE solution space in 2-3 year run.**

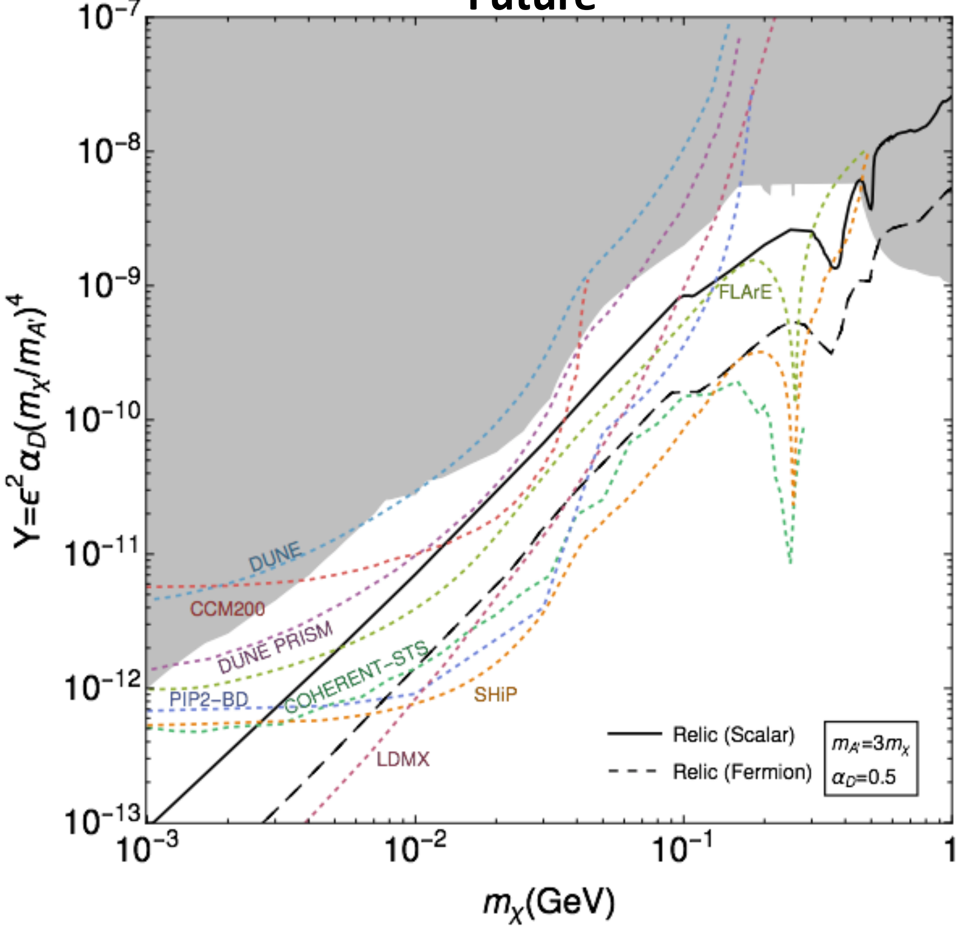
CCM at SNOWMASS 2022 (HEP Community Planning)

Vector Portal DM

Current



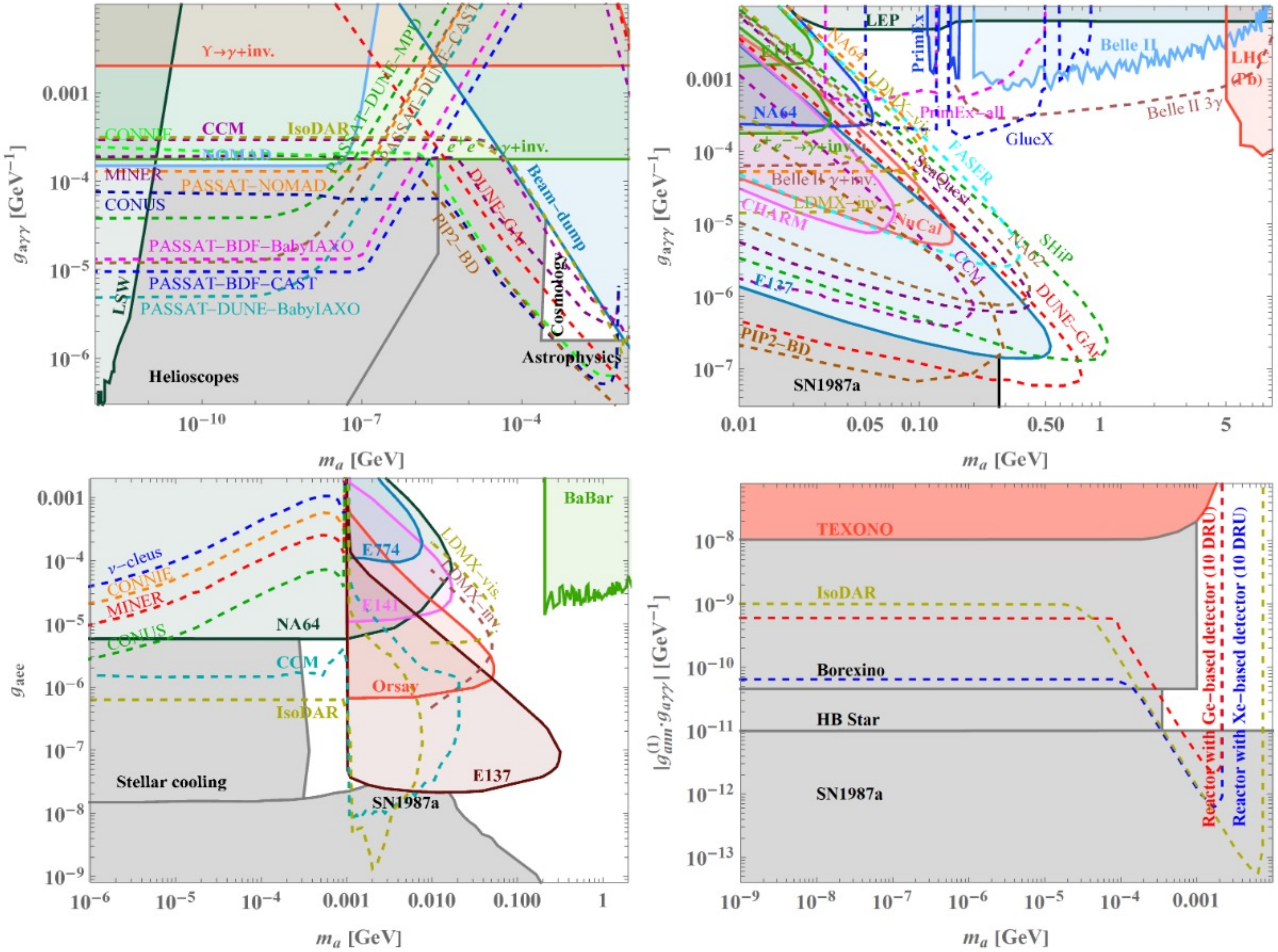
Future



- **CCM (with UGA) can cover new DM parameter space near term, other experiments further into the future.**
- **Lots of future searches!**

CCM at SNOWMASS 2022 (HEP Community Planning)

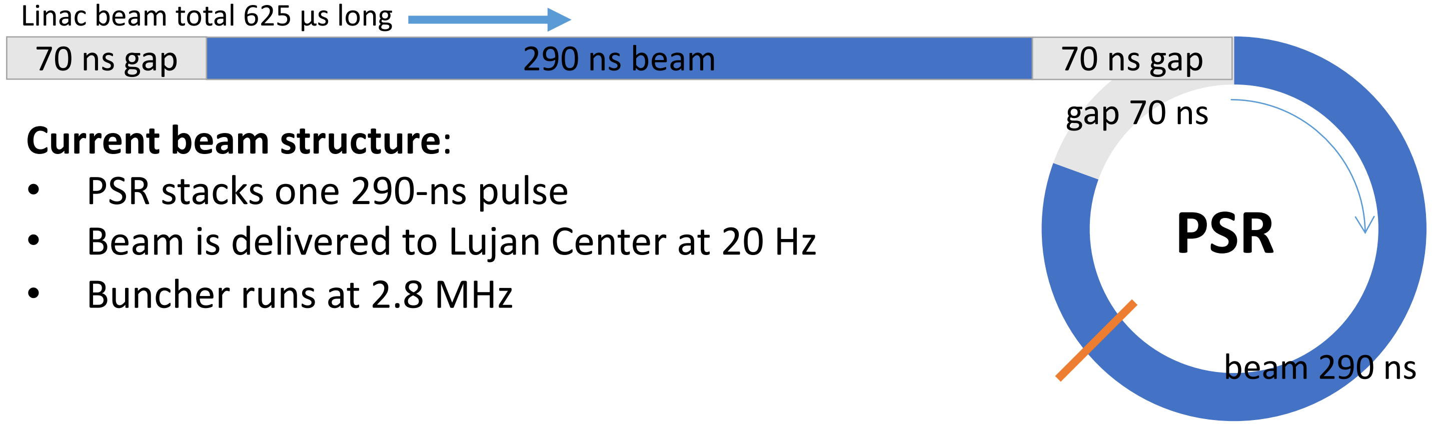
Axions



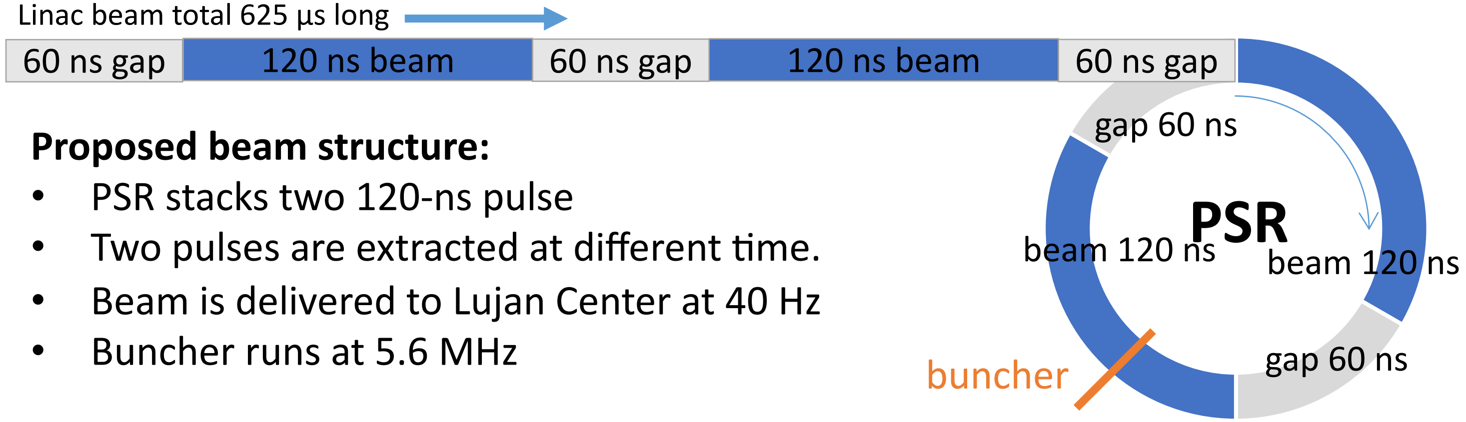
- **CCM can cover new interesting axion parameter space now.**
- **No near-term competition in cosmic rectangle region (g_{ae}).**
- **Competition from reactor experiments in cosmic triangle region ($g_{a\gamma}$).**
- **Testing astrophysical limits.**

CCM Upgrade: Shorter Pulse Length at LANSCE Proton Storage Ring

- Shorter Pulse at PSR provides
  - greater rejection power for BSM experiments
  - reduced uncertainties in neutron TOF/energy measurement
- Funded by LANL LDRD ER, starting this September
  - Beam development starting at the second year



Current beam structure:
- PSR stacks one 290-ns pulse
- Beam is delivered to Lujan Center at 20 Hz
- Buncher runs at 2.8 MHz

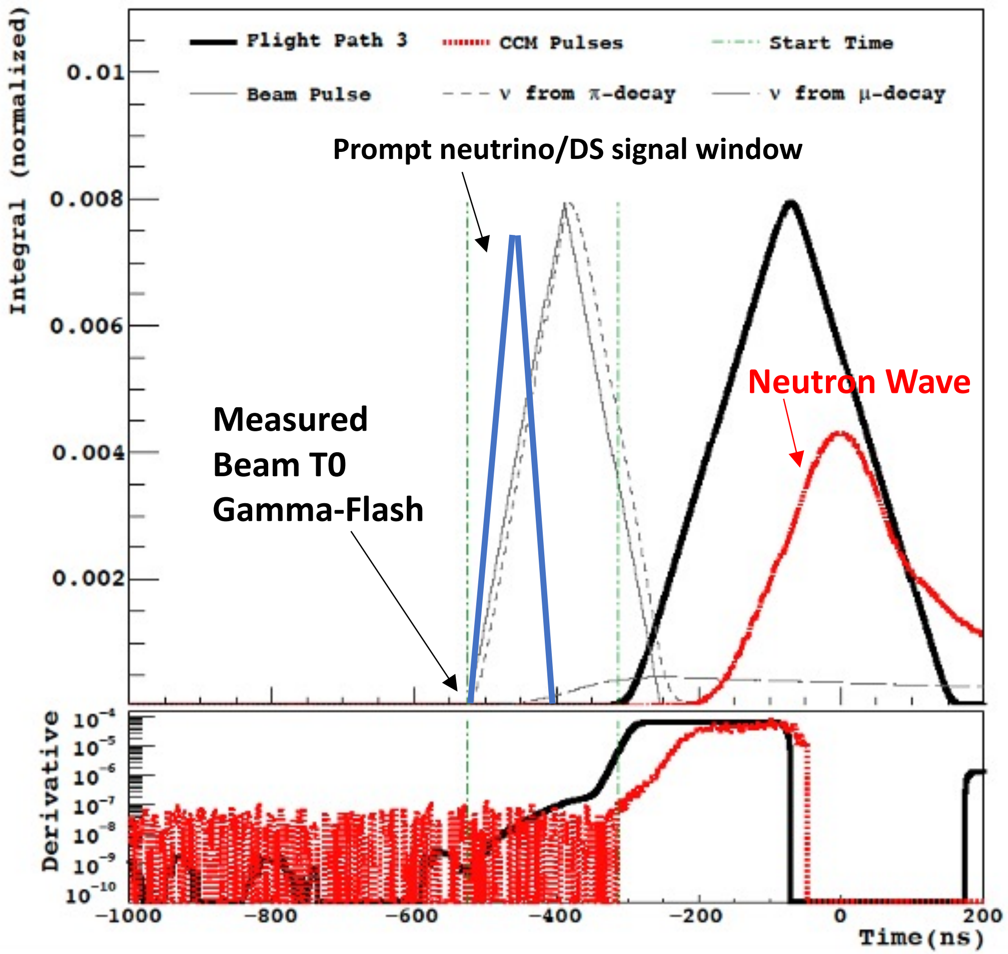


Proposed beam structure:
- PSR stacks two 120-ns pulse
- Two pulses are extracted at different time.
- Beam is delivered to Lujan Center at 40 Hz
- Buncher runs at 5.6 MHz

Shorter beam pulse will reject more beam neutrons and random backgrounds

Lujan Improved S/B with Upgrade 120 nsec Beam

TOF technique unique and powerful for isolating prompt signal and measuring backgrounds and errors from pre-beam. Key is to shorten the beam width.



Shorter beam pulse reduces random backgrounds from Ar39 decay and neutron activation

- If we shorten PSR pulse from 290 nsec to **120 nsec (Blue),** would increase signal efficiency and reduce random backgrounds, estimate increase **S/B (120 nsec) > 25**.
  - Factor ~2.5 reduction in random backgrounds from Ar39 and neutron activation
  - Factor ~10 reduction of EM events relative to nuclear scattering using Singlet/Triplet light PID.

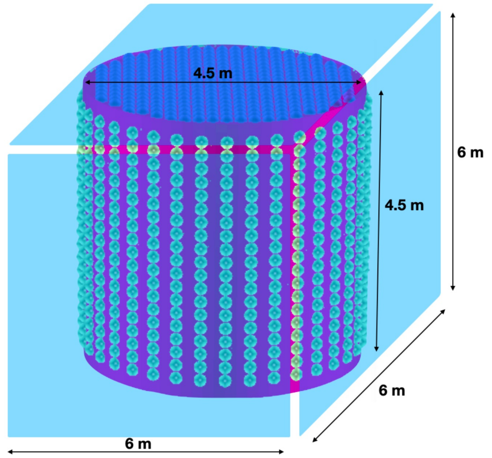
New Dedicated Facility: FNAL Proton Beam Dump @ 1 GeV: PIP2-BD

Single-phase, 100 ton scintillation-only liquid argon detector located 18 m downstream, on axis

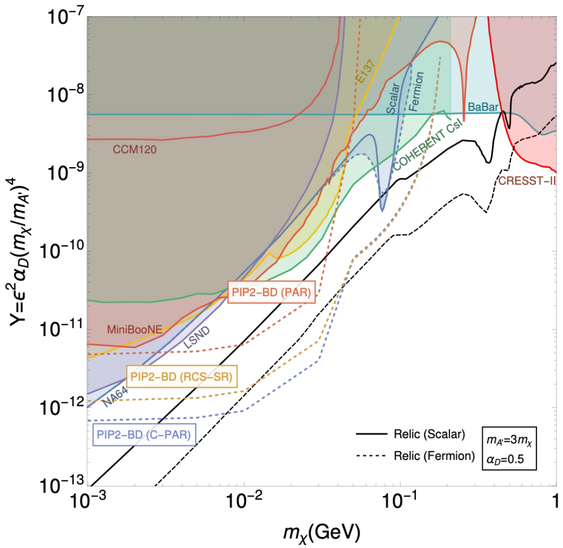
- Same technology as CCM-200

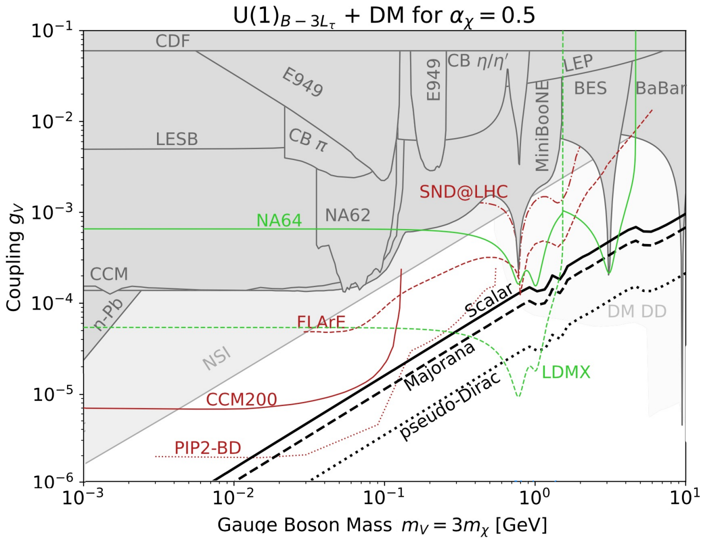
World-leading dark sector sensitivity, especially to hadrophilic dark matter, ALPs

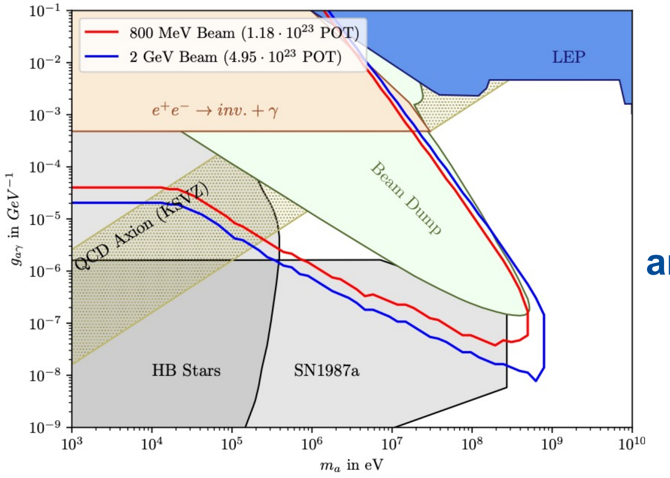
- Also supports definitive active-sterile neutrino oscillation search, neutrino cross sections measurements, etc.



1294 TPB-coated PMTs + TPB-coated reflectors on sides and end caps

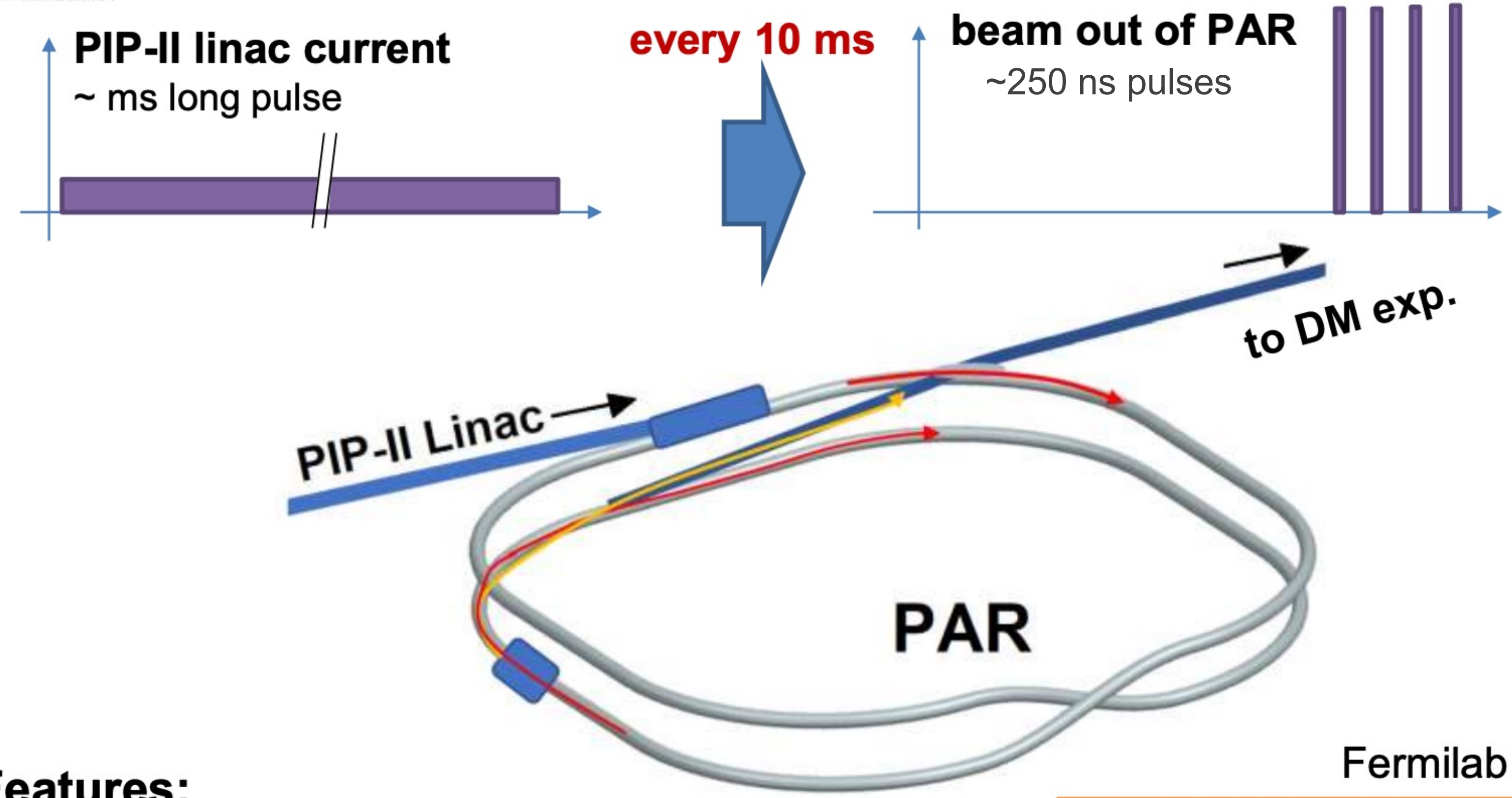






arXiv:2203.08079

Proposed PIP-II Accumulator Ring (PAR) at FNAL



Features:

- Fixed *E*=0.8-1.0 GeV proton storage ring
- *C*=480m in the form of a *folded figure 8*
- Power 100 kW for Dark Sector program, 100Hz
- There is also compact version *C*=120 m (C-PAR)

Fermilab

Summary: New Exciting Opportunities for Accelerators!

- The search for dark matter, motivated by new theoretical and experimental work, has expanded to a possible complex dark sector with new particles and forces.
- **Accelerator dark sector searches have key advantages:**
  - High intensity to probe small couplings. Boosted dark matter makes probing different relic density solutions easier.
  - Fast beam timing and high instantaneous power to reduce backgrounds.
  - Wide beam energy range to probe diverse mass parameter space (MeV to TeV).
  - Electron and proton machines compliment search strategies and probes different couplings assumption, e.g. leptophobic, hadrophillic, etc.
  - Dumps produce copious EM particle production that can couple to axions.
  - Proton machines produce copious mesons that probe sterile neutrinos, neutrino decay, and dark sector couplings to meson decay beyond present bounds.
  - Probably other things that have not even been thought yet…
- CCM can directly probe a rich list of dark sector physics (DM and ALPs) and test new parameter space. New dark sector models coupling to meson decay being investigated for sensitivity (test of the MiniBooNE excess). Results in 2-3 years!
- New dedicated efforts such as FNAL PIP-II stopped pion facility is being designed with lessons learned from CCM and would be orders of magnitude better.

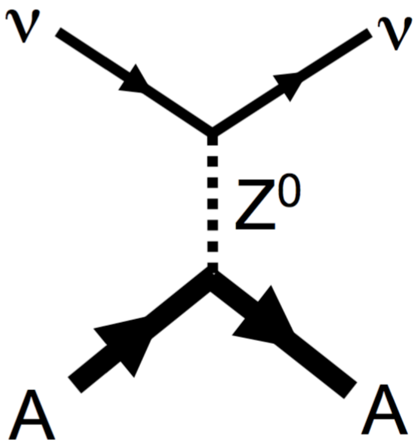
Backups: The Neutrino/DS Scatters Here!

Slide from Kate Scholberg

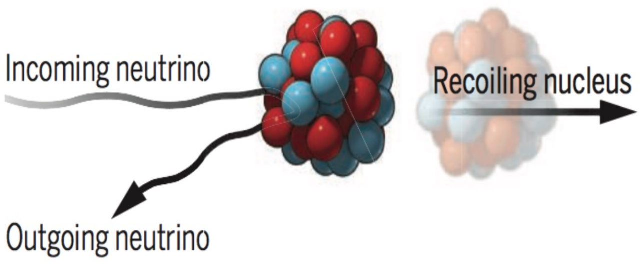
Coherent elastic neutrino-nucleus scattering (CEvNS)

ν + A $\rightarrow$ ν + A

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim$ 50 MeV



Akimov, et. al. (COHERENT), "First Measurement of Coherent Elastic Neutrino-Nucleus Scattering on Argon", PhysRevLett.126.012002, 2021

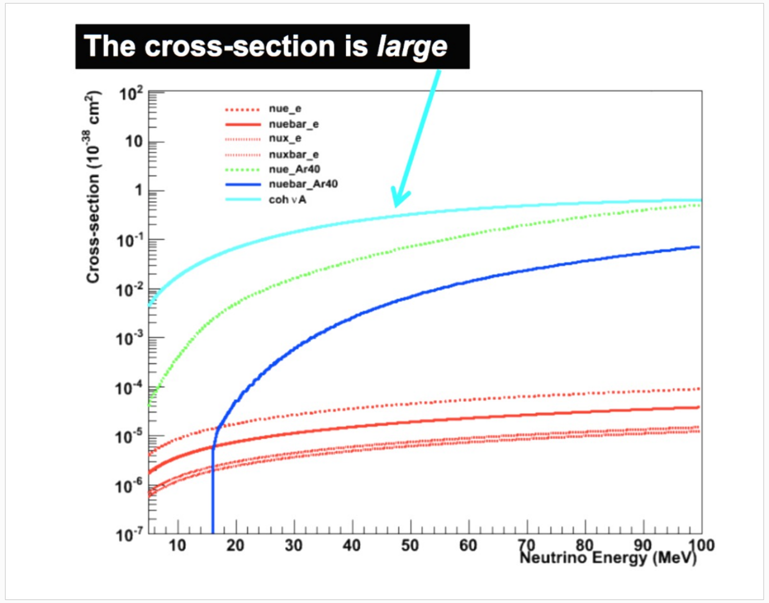


- **Low energy nucleus recoil E ~ 10's keV**
- Well-calculable cross-section in SM: SM test, probe of neutrino NSI
- Dark matter direct detection background
- Possible applications (reactor monitoring)

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

$$\propto N^2$$

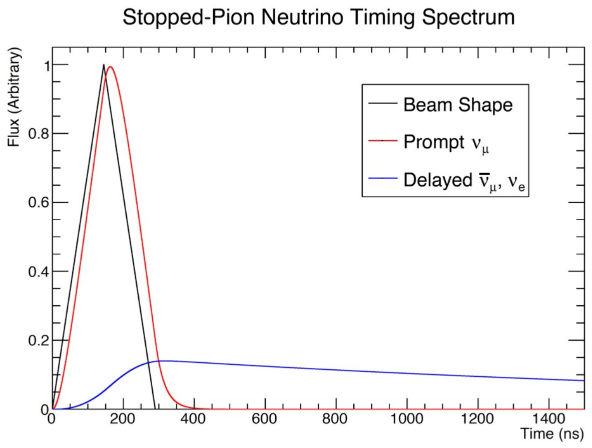
Expected CAPTAIN-Mills LAr Event Rates for Three Years

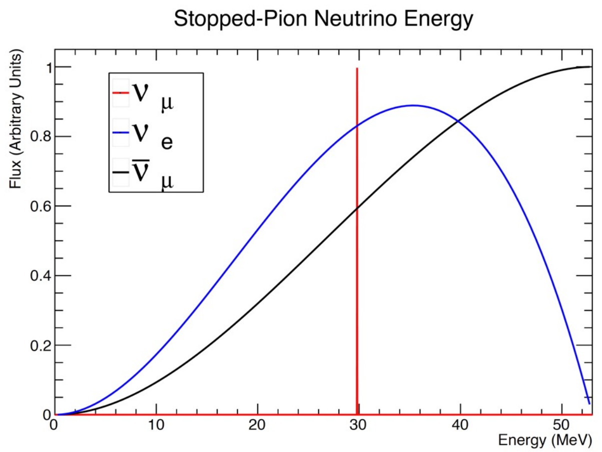


Large LAr **coherent eleastic neutrino-nucleus scattering**

Reaction	L = 20 m (events/yr)	L = 40 m (events/yr)
Coherent ν_μ (E = 30 MeV)	2709	677
Coherent $\nu_e + \bar{\nu}_\mu$	9482	2370
Charged Current ν_e	257	64
Neutral Current ν_μ	36	18
Neutral Current $\bar{\nu}_\mu$	79	20

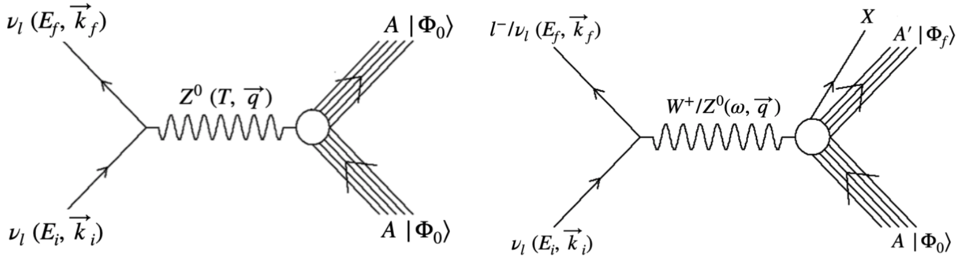
- Two oscillation analysis samples with different strategy/backgrounds:
  - **PROMPT** with beam (mono-energetic $\boldsymbol{\nu_\mu}$) – scattering end point energy 50 keV
  - **DELAYED** 4 usec after the beam ($\boldsymbol{\nu_e} + \boldsymbol{\overline{\nu_\mu}}$) - scattering end point energy 148 keV



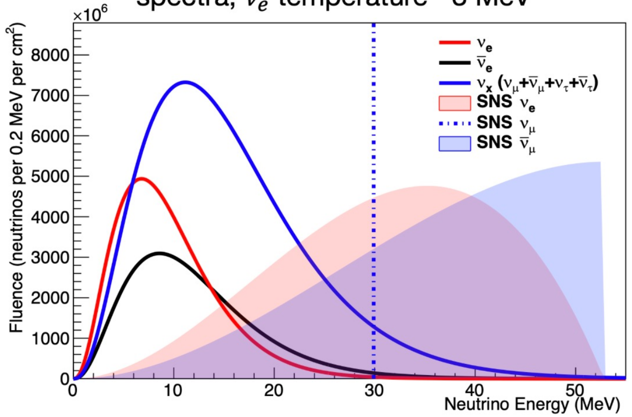


CEvNS, Sterile Neutrinos, and Cross Sections on Argon

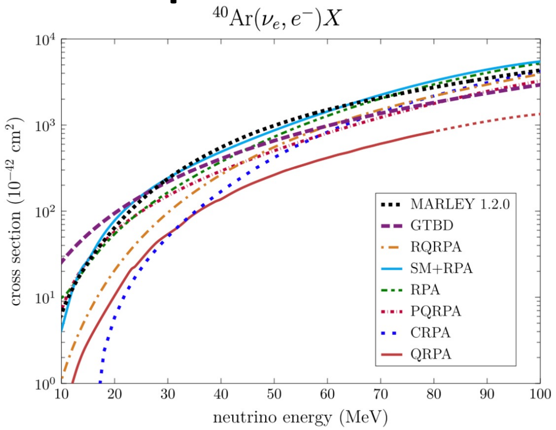
Limited data on Argon CEvNS and CC/NC cross sections



Supernova flux (10 kpc): pinched spectra; ν_e temperature ~3 MeV

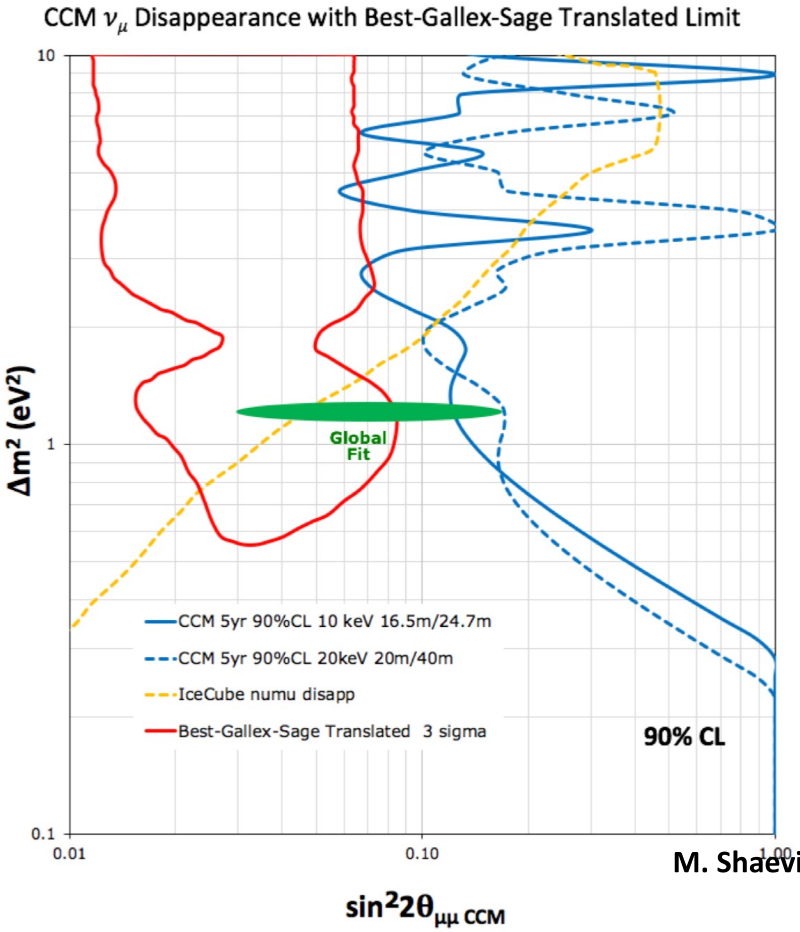


~25% spread on CC models



DUNE SN Physics requires CC and NC on Argon measurements

Need to first observe CEvNS before embarking on sterile neutrino search (two detectors ideal)

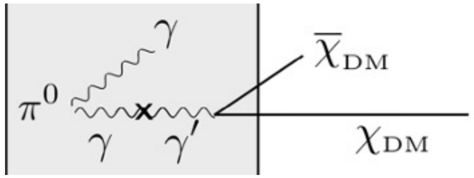


M. Shaevitz (Columbia)

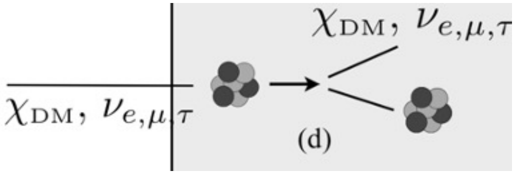
- Need to first establish 10 keV threshold and observe CEvNS.
- CCM can make smoking gun measurement. However, sterile neutrino sensitivity is marginal, but global situation can change.
- Can make ~16% cross section measurement on LAr at Supernova energies for DUNE => theory currently at ~30%.

CCM Strategy: Dark Matter Production and Detection

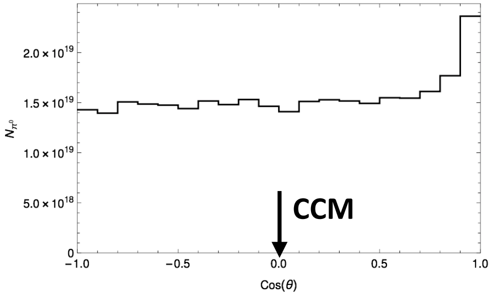
Production: DM couples to π^0 $decay$
Lifetime – 8.5 x 10^{-8} nsec

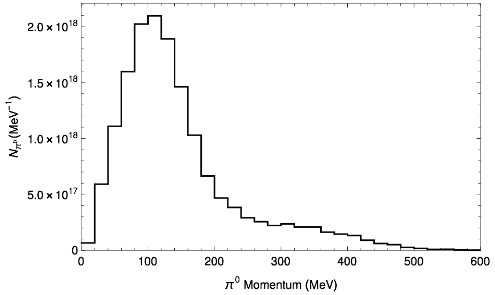


Detection: DM coherently scatters off Argon – 10 to 100s keV recoil

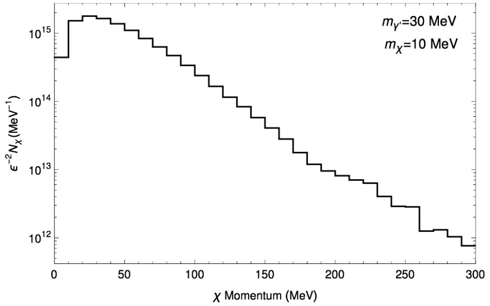


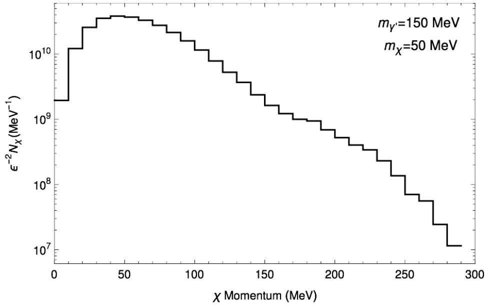
MCNP modeling of π^0 in Lujan Tungsten Target



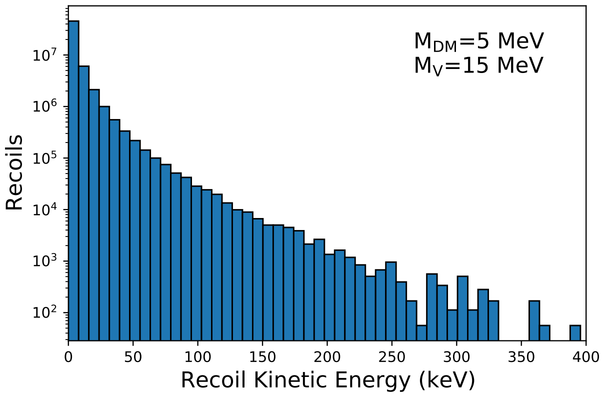


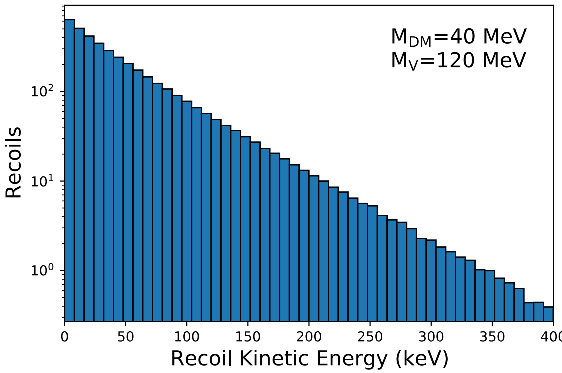
Generated π^0 kinematics





Generated dark matter momentum



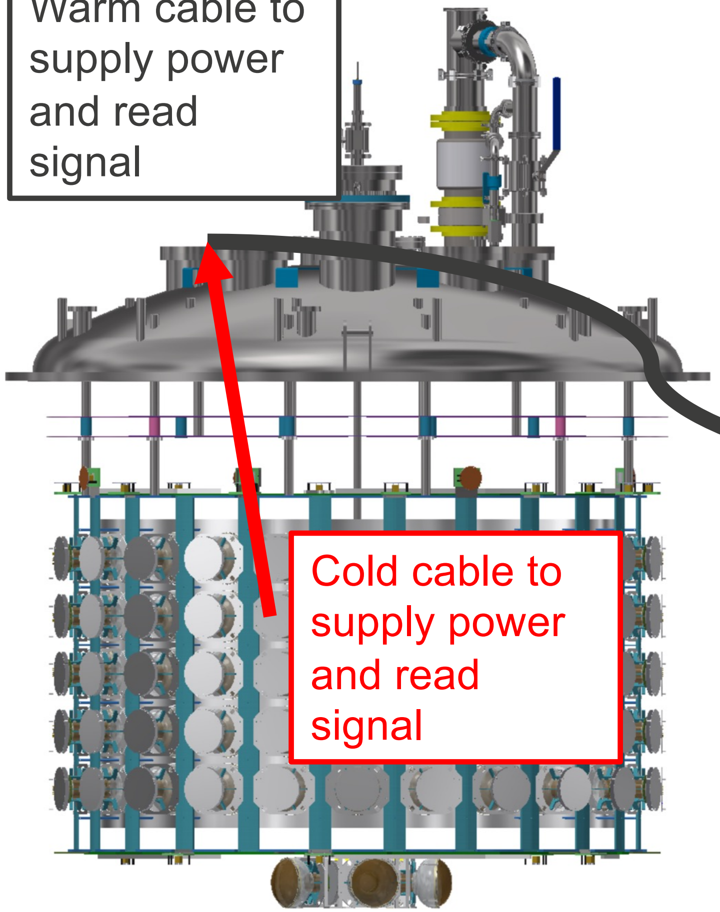


DM recoil spectrum off Argon

Prompt neutrino endpoint 50 keV

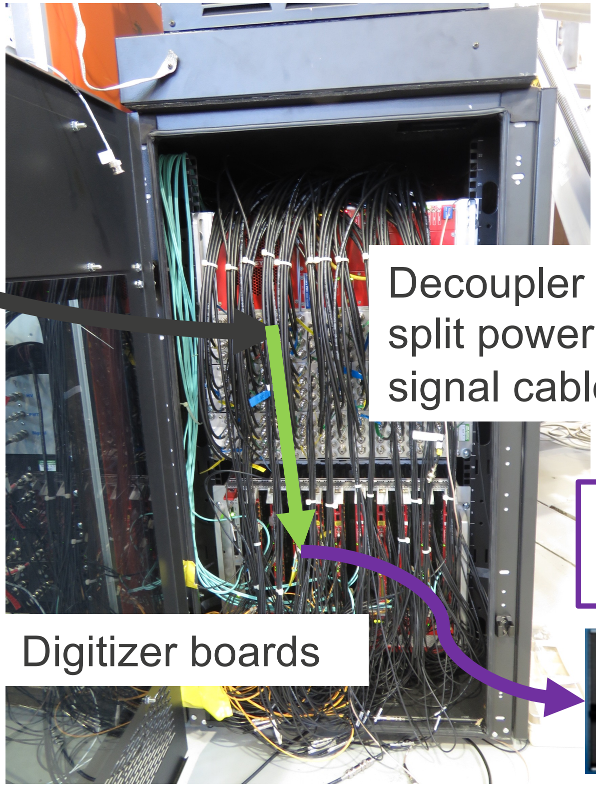
BdNMC code, deNiverville, et. al. arXiv:1609.01770

CCM120 Flow of Data



Warm cable to supply power and read signal

Cold cable to supply power and read signal



Decoupler box to split power and signal cables

Digitizer boards

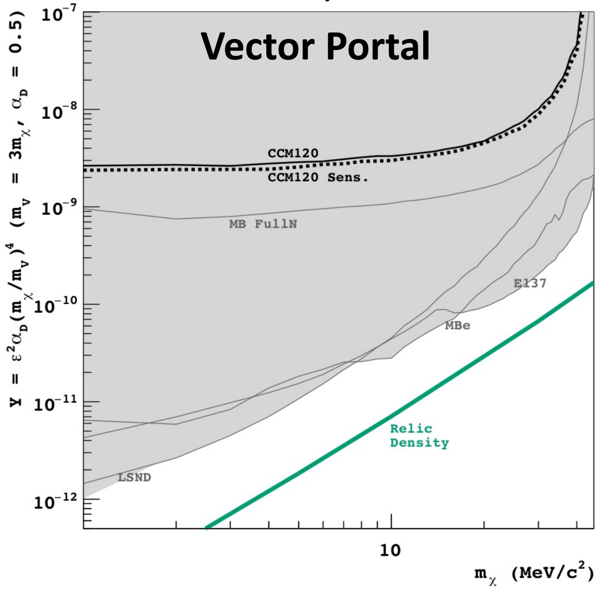
- CAEN V1730
- 500 MHz clock
- 16 Channels
- 2^{14} Bit ADC Chip per channel
- 2 V range
- 17 boards

Fiber Optic connection to DAQ computer

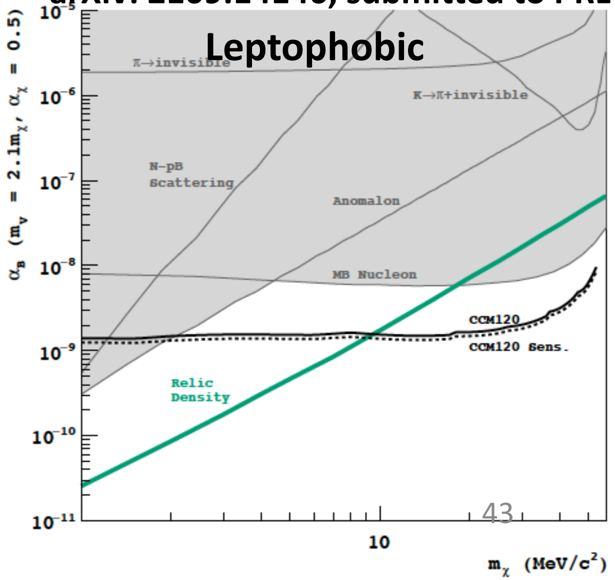
CCM@LANL Overview and Status: 2019 to 2022

- With LDRD funding, built and successfully ran the CCM120 (120 PMT's) prototype detector in 2019.
- CCM120 two month beam run was thoroughly analyzed and dark matter limits submitted for publication.
  - O_2/H_2O in LAr severely reduced scintillation attenuation length preventing threshold below 100 keV and detection of neutrino coherent scattering (CEvNS) events.
- LDRD funding built upgraded CCM200 detector (200 PMTs), shielding, and filtration system to improve low energy threshold for CEvNS, begun running Oct 2021.
  - Reserve LDRD funding FY22 to commission filtration system, beam run 2022, measure CEvNS.
- Goal to secure HEP funding to operate for three years to achieve excellent sensitivity to dark sector physics.

arXiv: 2105.14020, submitted to PRD

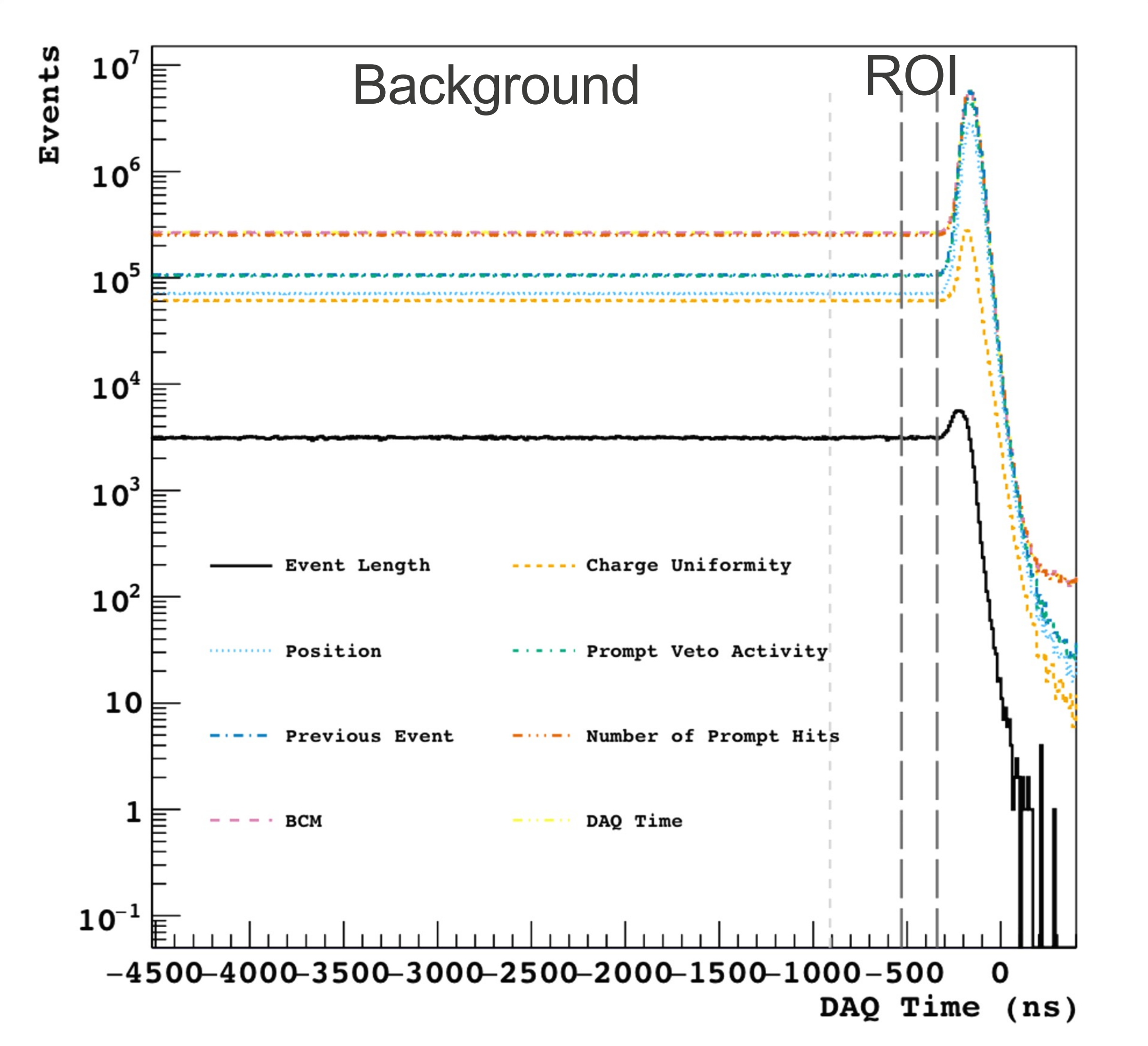


arXiv: 2109.14146, submitted to PRL



CCM120 Analysis: Measuring Steady State Backgrounds

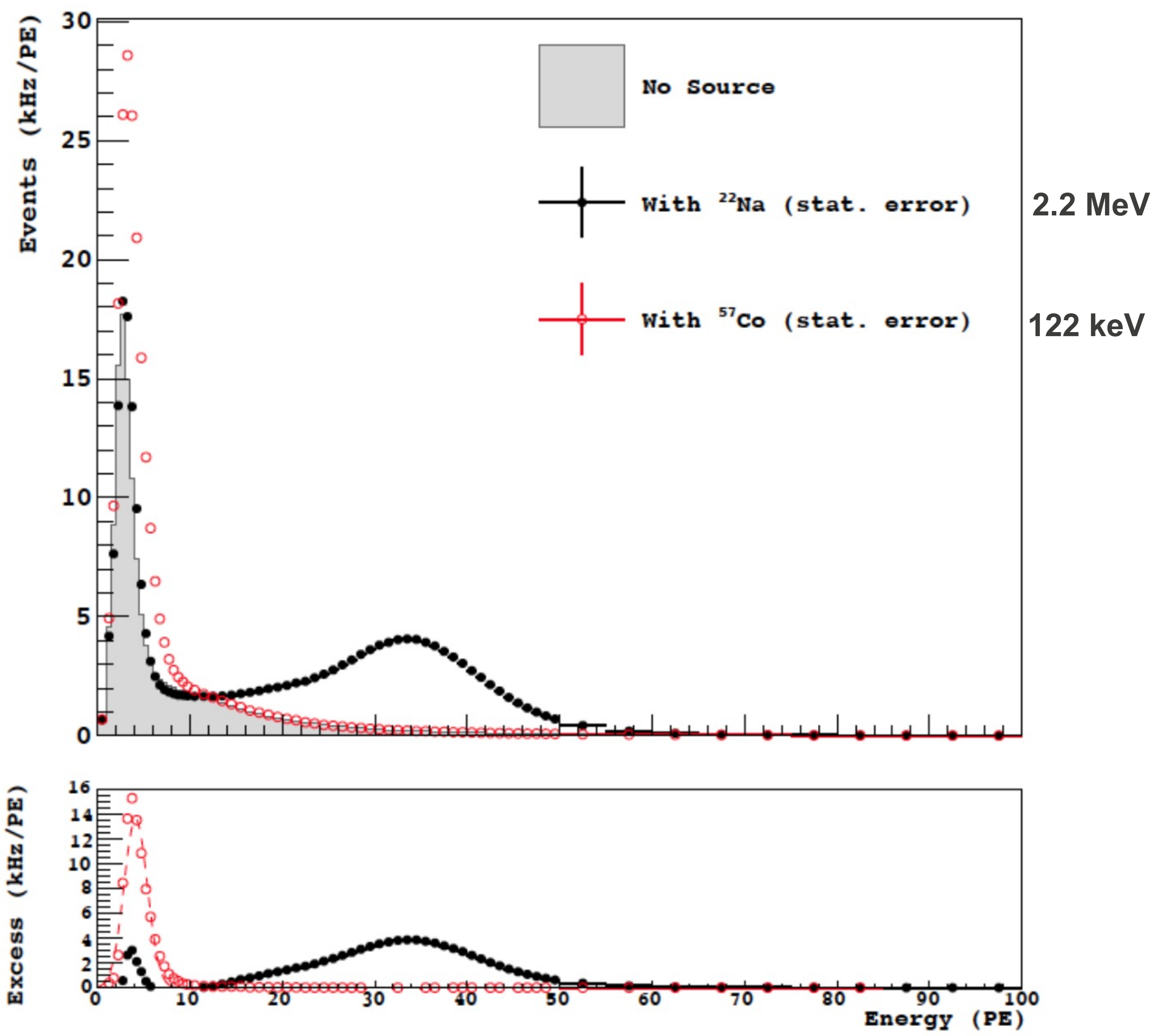
- Prompt light only analysis
- Dynamic event lengths allow a poor-persons PID
  - Maximize dark matter over Ar39 puts the length cut at 44 ns
- Pre-beam is flat in time (no bias) allowing a good prediction of what to expect in the prompt speed of light window (ROI)
- ROI is a beam-related background free region, so the prediction on the number of events is statistical only (systematics will be on DM signal)
- Ideal for Machine Learning techniques



Tyler Thornton (LANL)

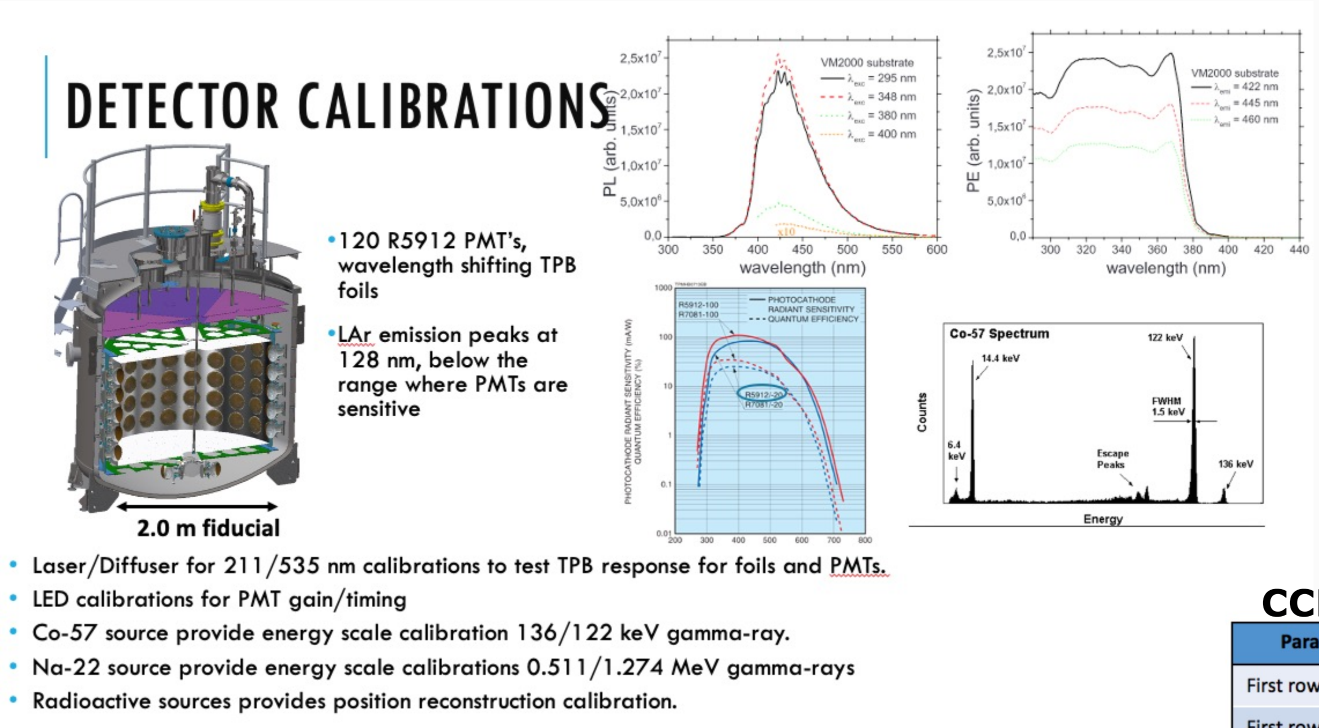
CCM120 Results from Calibration

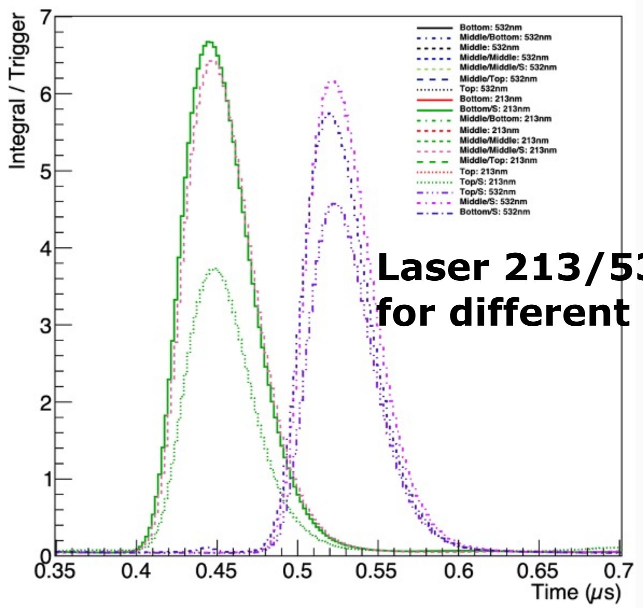
- Impurities from not recirculating or filtering the argon led to low light levels O(ppm) O_2 reduced the 128 nm light attenuation length from O(10 m) to ~50 cm
- According to simulations the 4.7 PE peak for Co57 is an artifact of the event cuts, the real peak is ~2 PE
- Na22 33.2 ± 8.9 PE for 2.2 MeV
- Both Co57 and Na22 rates are within 25% of simulation prediction
- Pre-Beam Beam Off background consistent in shape with Ar39 prediction from simulations



Tyler Thornton (LANL)

CCM120 Optical Model: Key Analysis Results and Lessons Learned from Calibrations and Optical Model Development





Laser 213/532 nm response for different path lengths

Measured low light output due to O_2 and H_2O at ~ppm levels absorbing 128nm scintillation light

Lesson learned: Require recirculation and filtration

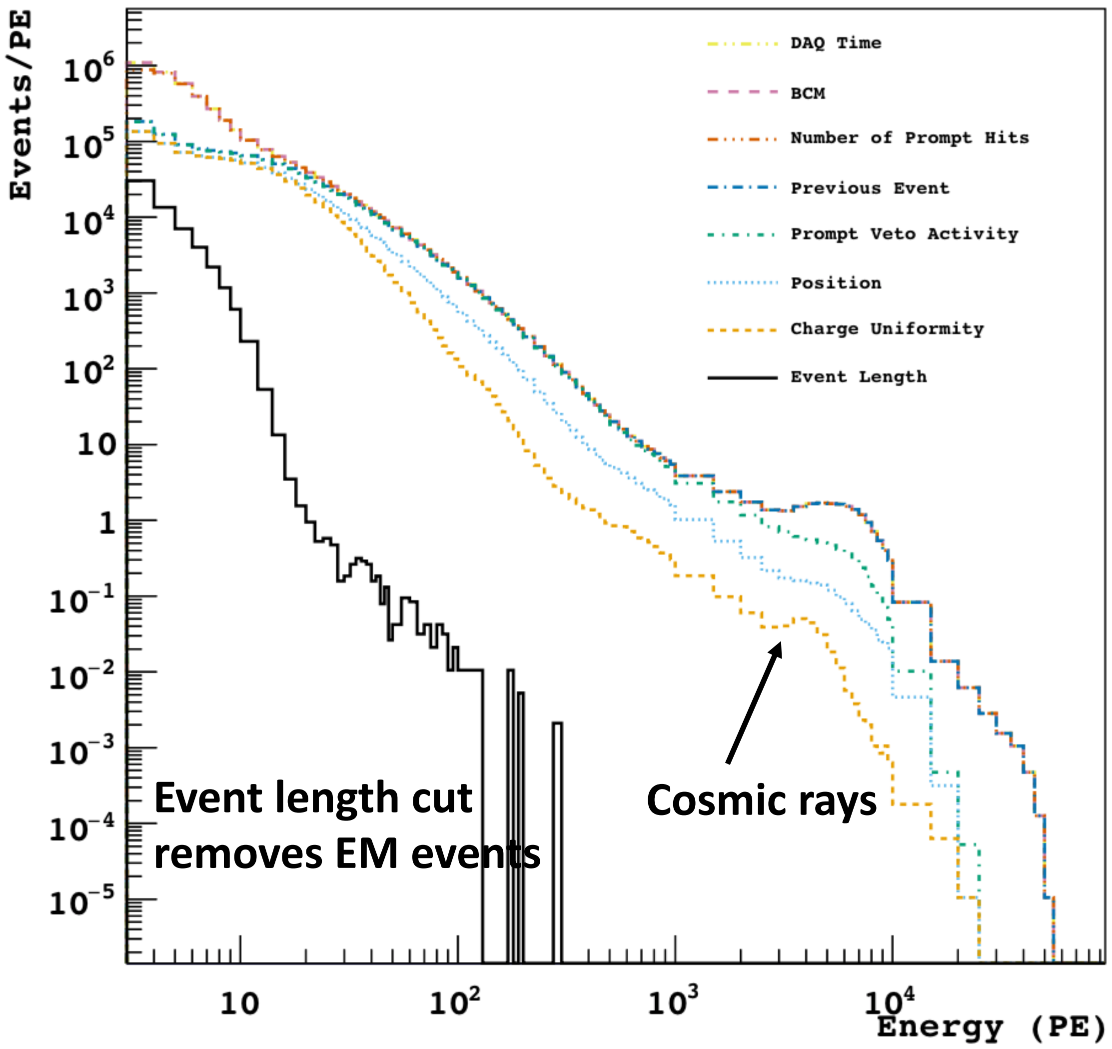
CCM120 Measured Optical Model

Parameter	Value	Error
First row clouding	12.23%	5.92%
First row radius (unclouded portion)	64.05 cm	11.08 cm
Foil Efficiency	45.55%	7.97%
128 nm Absorption length	55.95 cm	6.92 cm
LED Cone Width	7.555 cm	1.488 cm
LED Cone Height	4.457 cm	1.444 cm
213 nm Absorption Length	37.55 cm	18.17 cm
300 nm Absorption Length	1310 cm	172 cm
Top foil thickness divider	26.12	14.17
Bottom foil 'un-smoothness'	2.922	0.480
Oxygen Quenching Factor	0.55	0.0

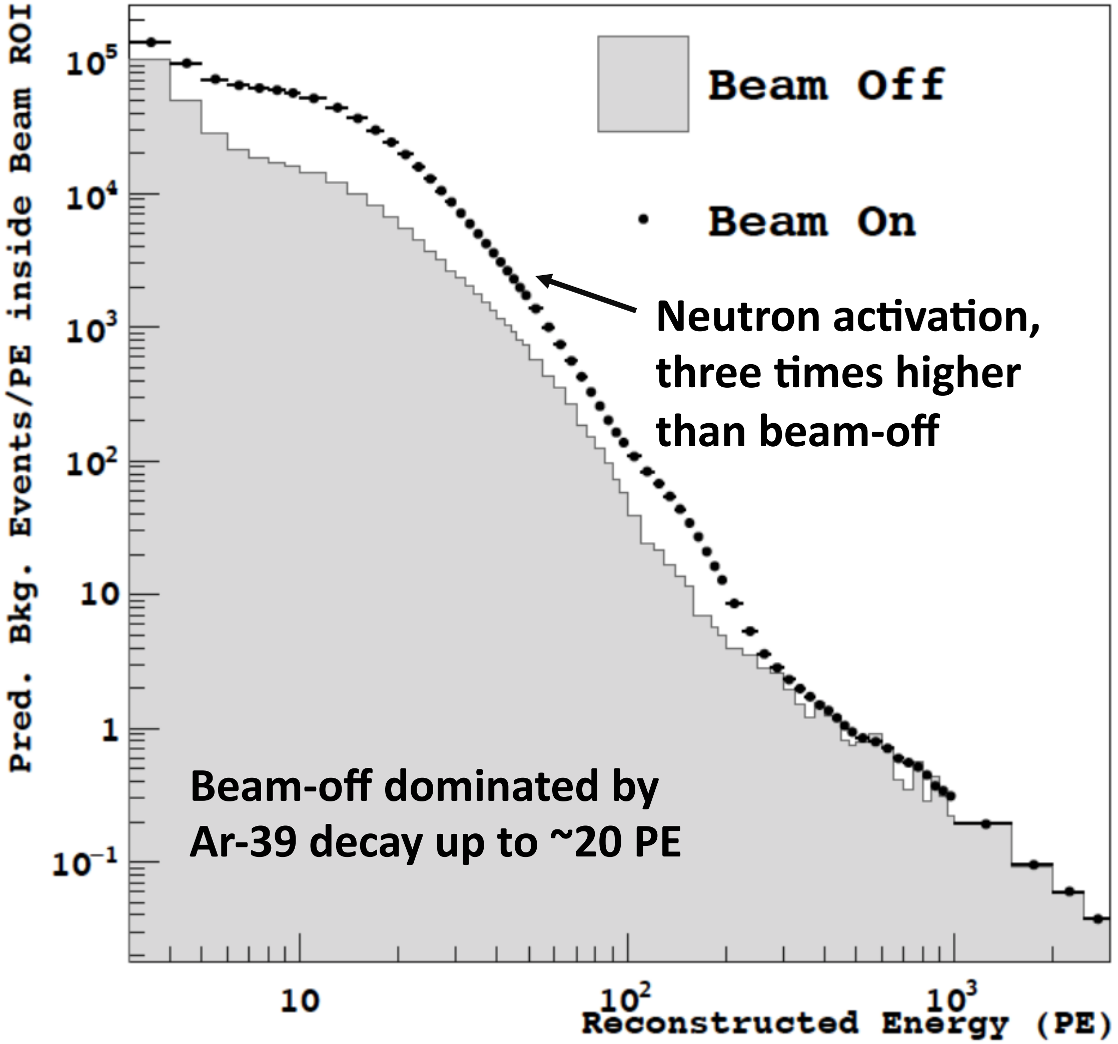
128 nm attenuation should be 2000 cm for clean LAr.

E. Dunton (Columbia)

CCM120 Steady State Backgrounds – Pre-beam Region



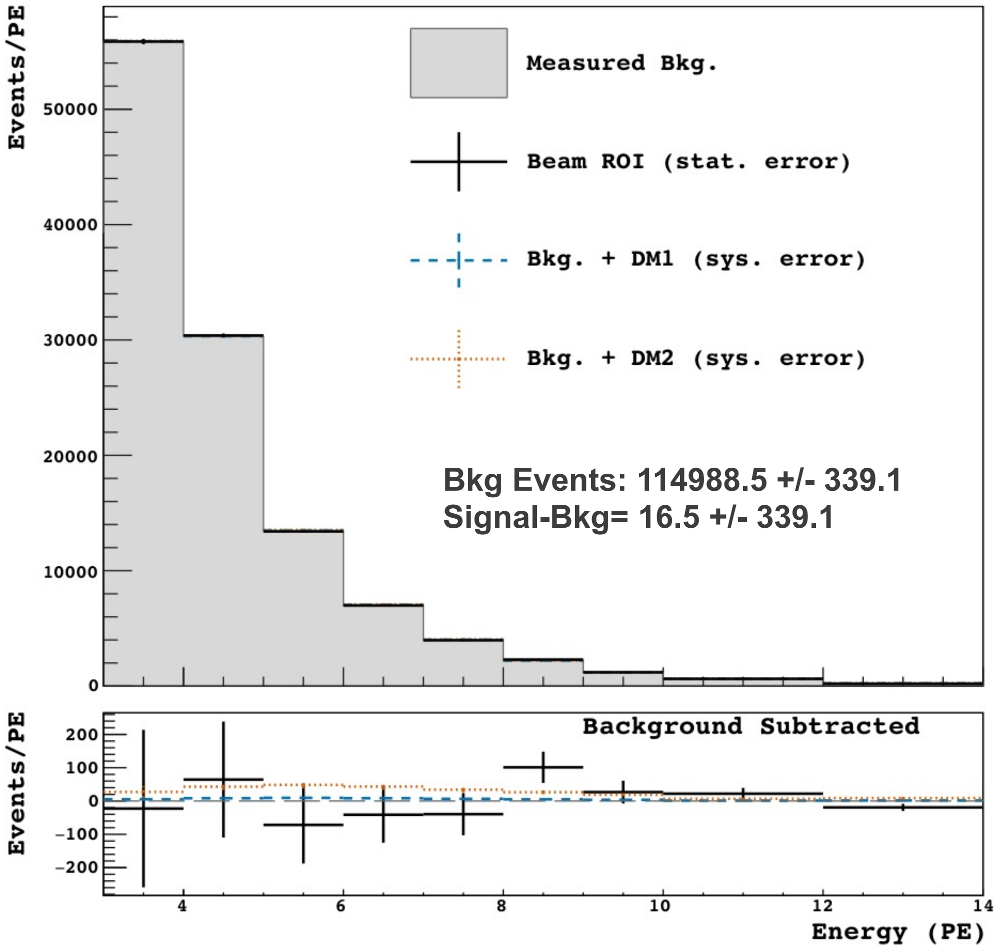
No Length Cut

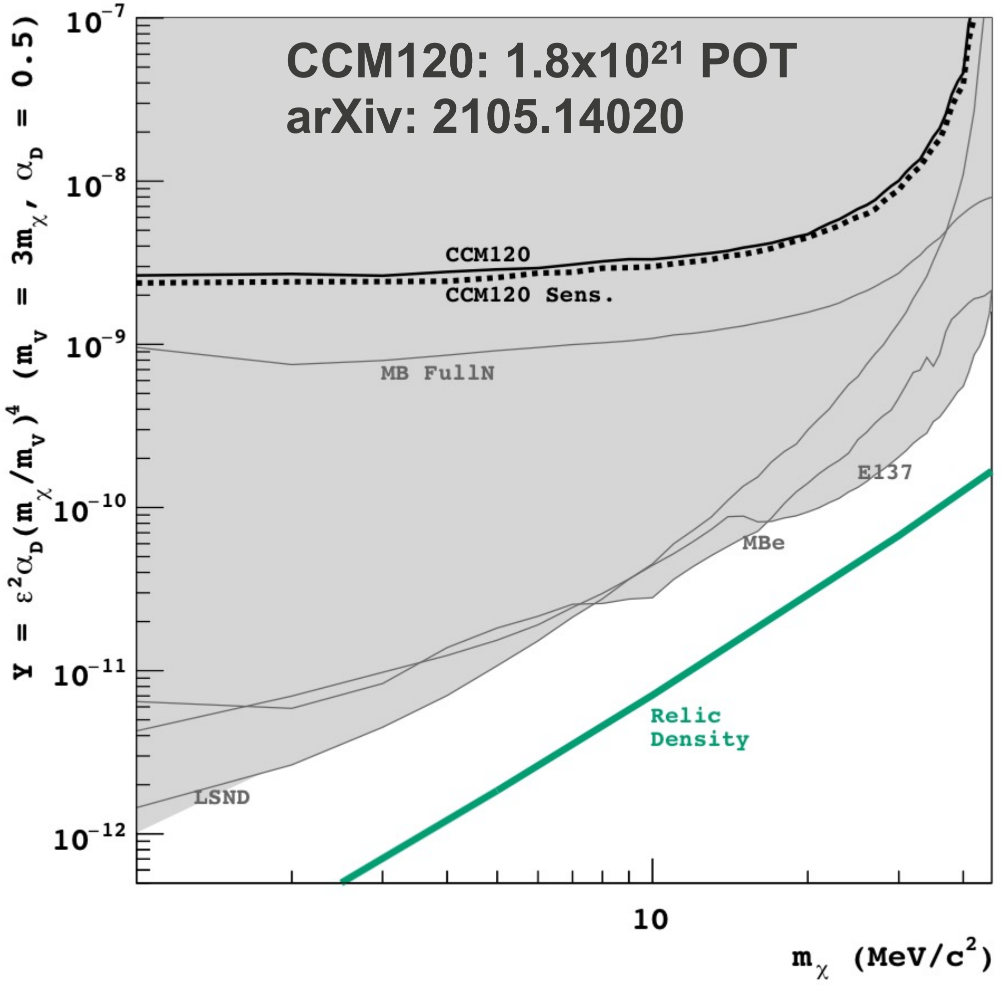


Tyler Thornton (LANL)

See backup slides 64 and 65 for supporting Ge detector measurements

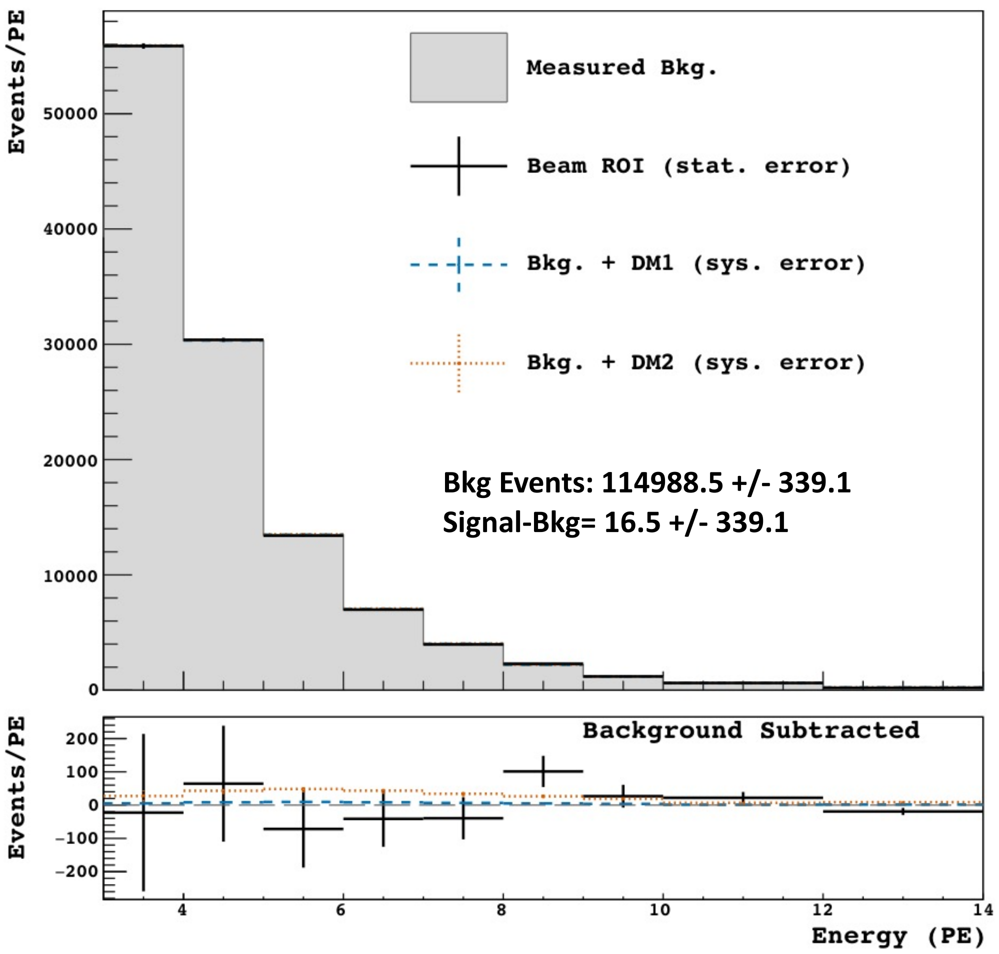
CCM120 Signal Region Analysis and DM Fits/Limits

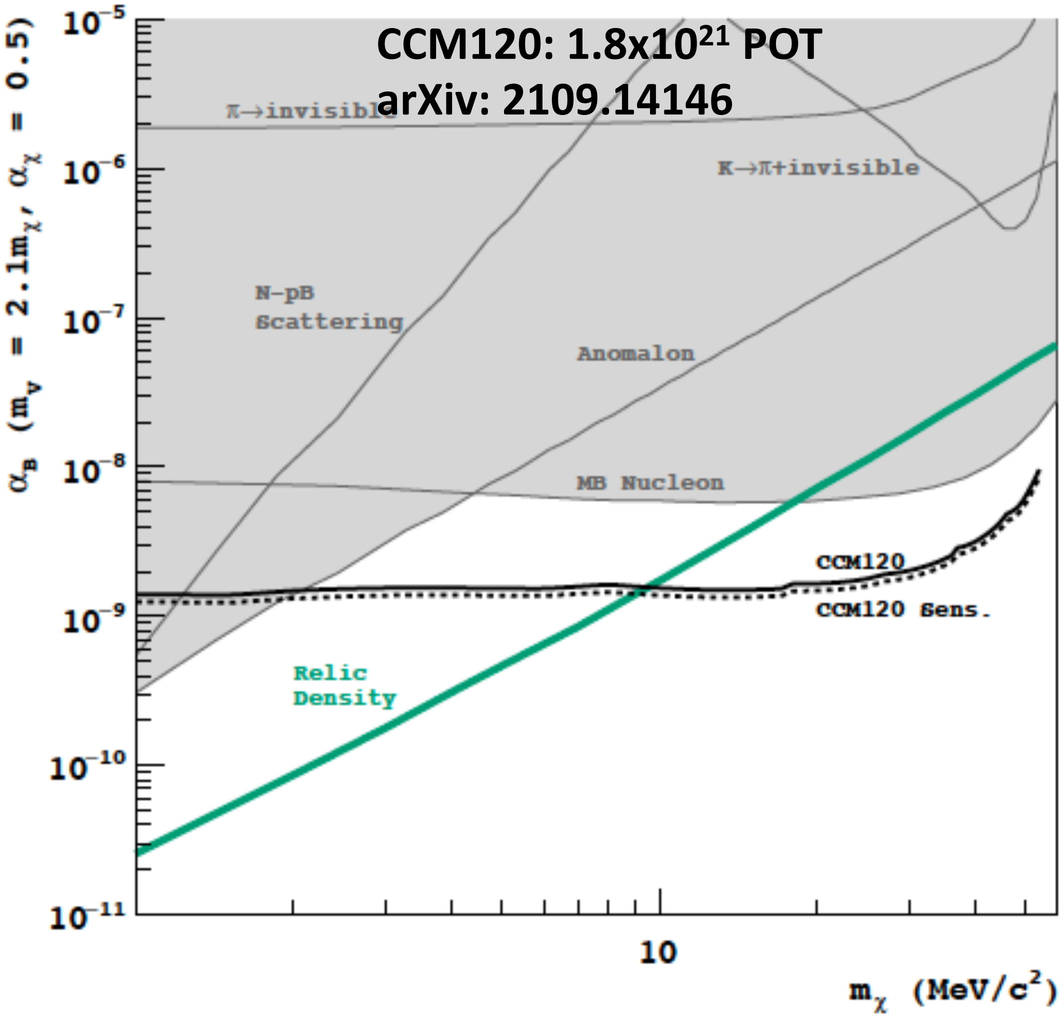




- DM spectrum fits to left plot yields limits. Signal systematics 22.6%
- Impressive with ~1 month data, but goal to get down to relic line to sample new interesting space.

CCM120 Signal Region Analysis DM Fits/Limits: Leptophobic Models

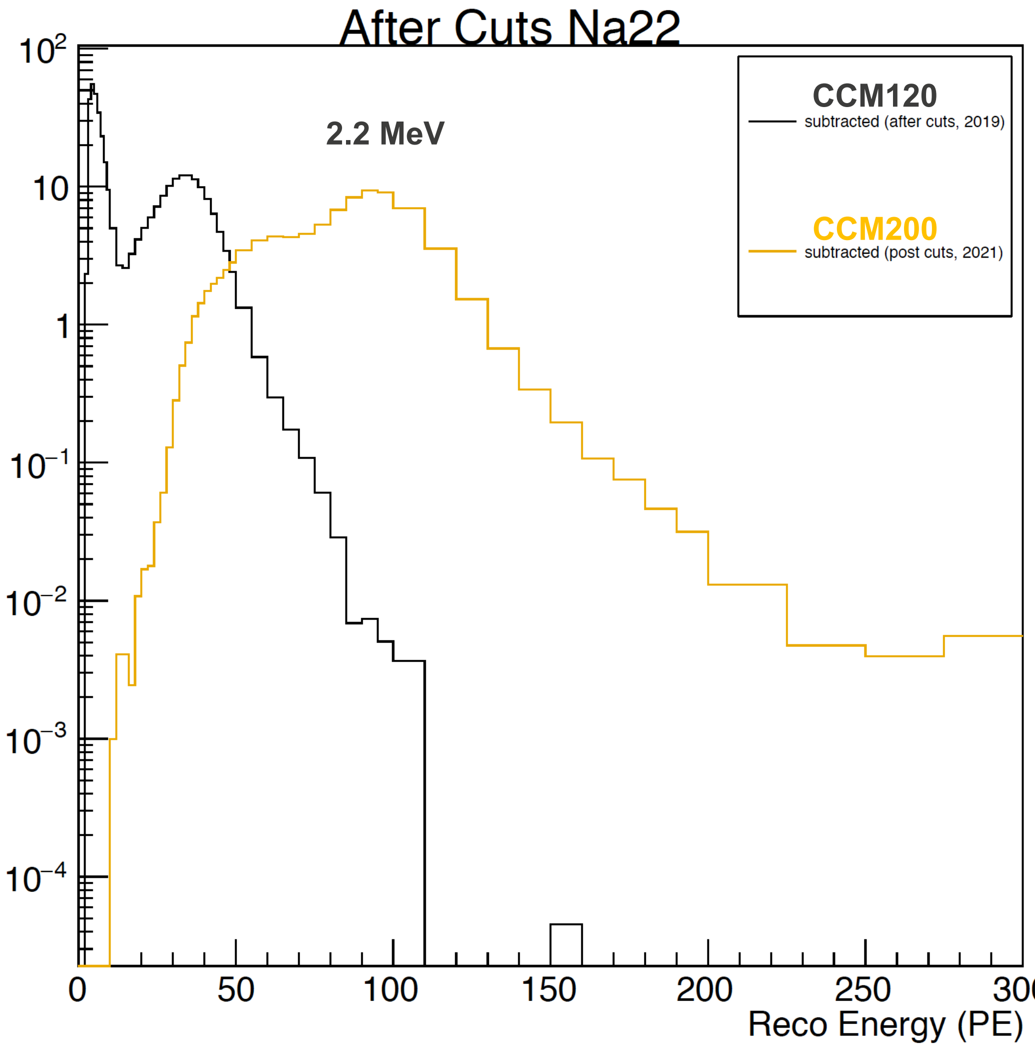




- DM spectrum fits to left plot yields limits. Signal systematics 22.6%
- Better coverage due to higher DM coherent cross sections for leptophobic models.

CCM120/CCM200 Results from Energy Calibration

- Impurities from not recirculating or filtering the argon led to low light levels O(ppm) O_2 reduced the 128 nm light attenuation length from O(10 m) to ~50 cm
- CCM120: Na22 33.2 ± 8.9 PE for 2.2 MeV
- CCM200: 106 PE for 2.2 MeV
- CCM200 over three times more light detection efficiency.
- **Filtration of LAr will increase this by another factor of ~5 necessary for 10 keV thresholds.**



Ed Dunton (Columbia)

Underground Argon: DMNI Phase II

- There is a global need for low activity Argon (Ar-39 removed) such as Darkside, DEAP, CEvNS, LEGEND, FNAL, etc. (see https://arxiv.org/pdf/1901.10108.pdf)
- SNOMASS White paper written.
- For CCM200 to reach relic density limits will require further suppression of random backgrounds by two orders magnitude, from ~10000+/-100 to levels of 100 +/- 10 events over three years.
- Darkside-50 (kg) acquired Argon from underground (UGA) source in southern CO with Ar-39 reduced by a factor of 1000.
- We are investigating ways with the community to acquire larger volumes of UGA for CCM200. Need to first demonstrate re-circulation and heat exchanger system reduces LAr losses to minimal levels.

Denver Post

NEWS

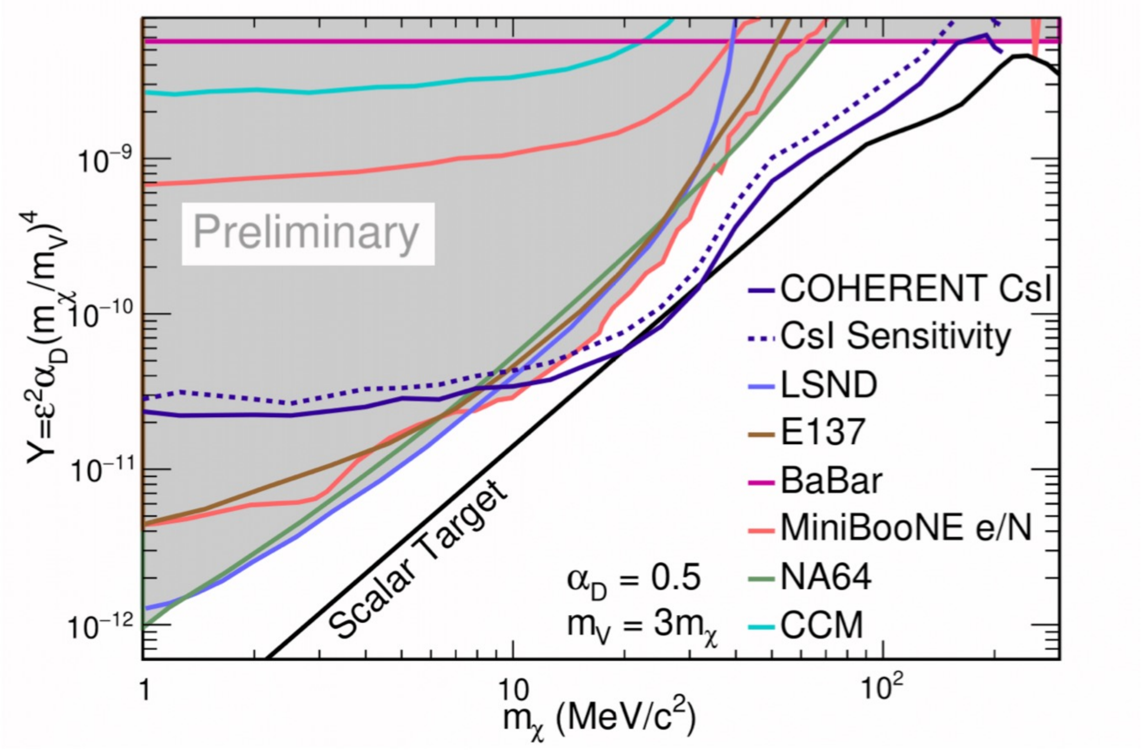
Colorado argon will be at the heart of dark matter experi

1 of 2

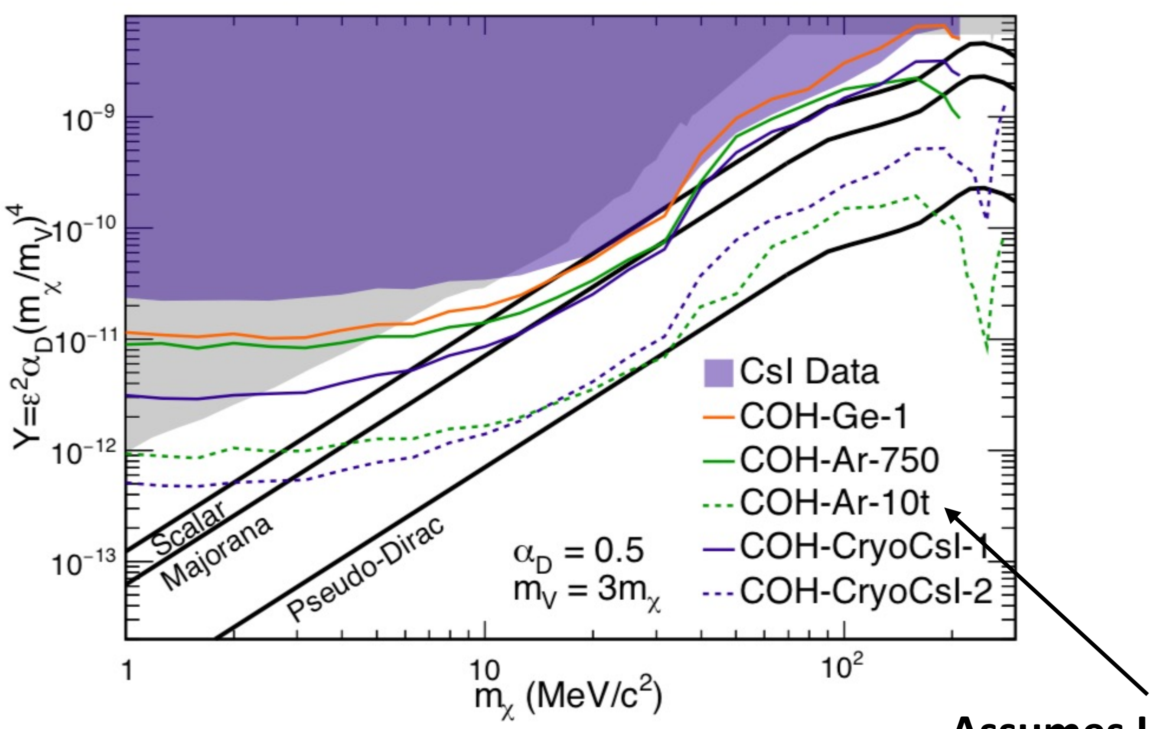
Kinder Morgan plant operator Joe Buffington, left, and operations supervisor Stan Mannis look over Fermilab's argon-extraction unit that they call "a little plant within our plant" north of Cortez.

Global Picture: Direct Competition to DM Search
COHERENT@SNS DM Search: Current and Future (arXiv: 2110.11453)

Current



Future



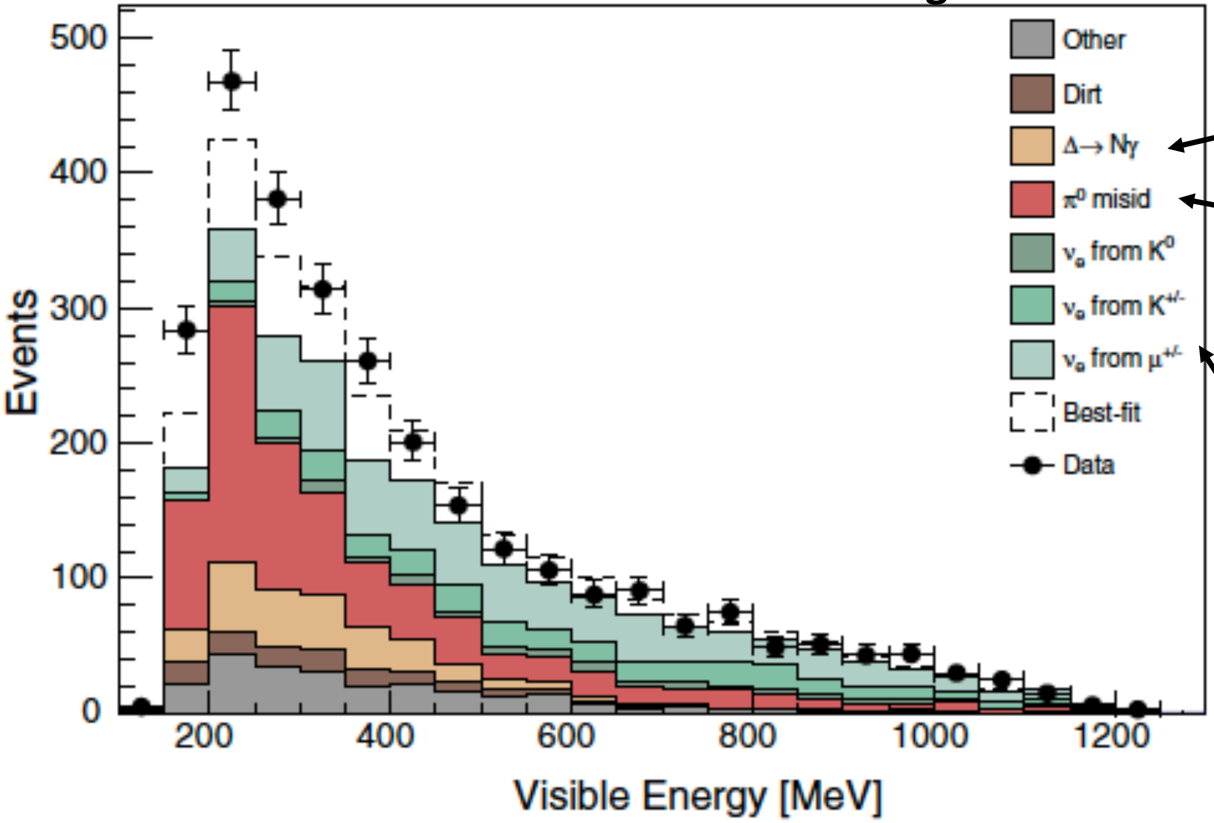
Assumes UGA.

- COHERENT finished running, CCM200 could improved DM limits with underground argon.
- New COHERENT limits on Leptophobic (see backup slides).
- **Limited/no sensitivity for EM searches > 1 MeV. Unique to CCM200.**

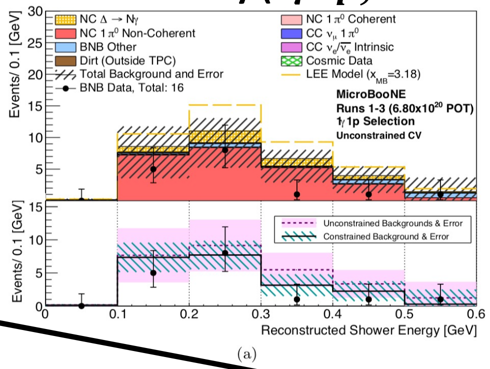
NEW! Explaining the MiniBooNE Excess – Recent MicroBooNE Results (arXiv 2110.00409 + 2110.14054 + other uB papers)

- New MicroBooNE results demonstrates MB excess is robust – confirmed Delta radiative, π^0, and intrinsic υ_e backgrounds estimates.

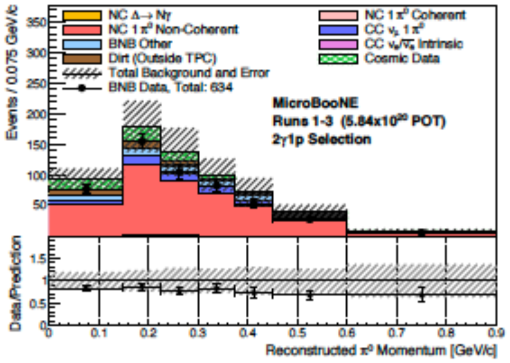
uB confirms MB standard model backgrounds



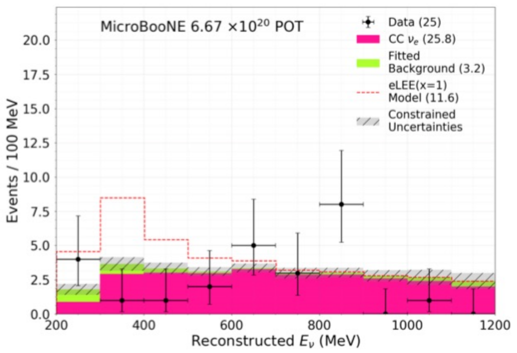
Delta Decay ($1\gamma 1p$)



π^0 ($2\gamma 1p$)



Intrinsic υ_e (1e1p)



NEW Model! Coupling of DM and axions to charged meson decays can explain MiniBooNE excesses (MDSC)

MI-HET-766
LA-UR-21-30532

Solutions to the MiniBooNE Anomaly from New Physics in Charged Meson Decays

Bhaskar Dutta,[1] Doojin Kim,[1] Adrian Thompson,[1] Remington T. Thornton,[2] and Richard G. Van de Water[2]
[1] *Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77845, USA*
[2] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

arXiv 2110.11944, submitted to PRL

Two possible sources via three body meson decays (leptonic currents)

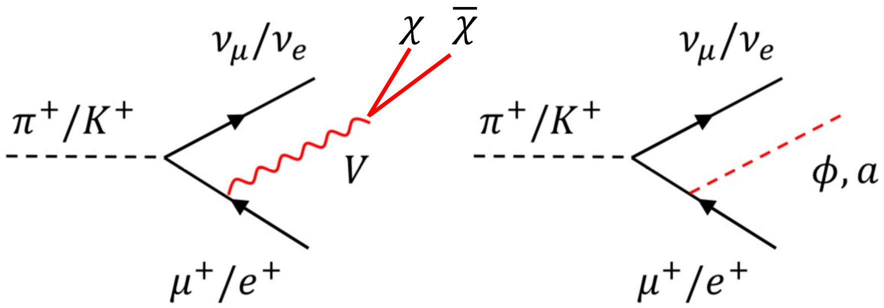


FIG. 1. Three-body charged meson decay into a scalar, pseudoscalar, or vector.

Detection involves gamma-like only final states

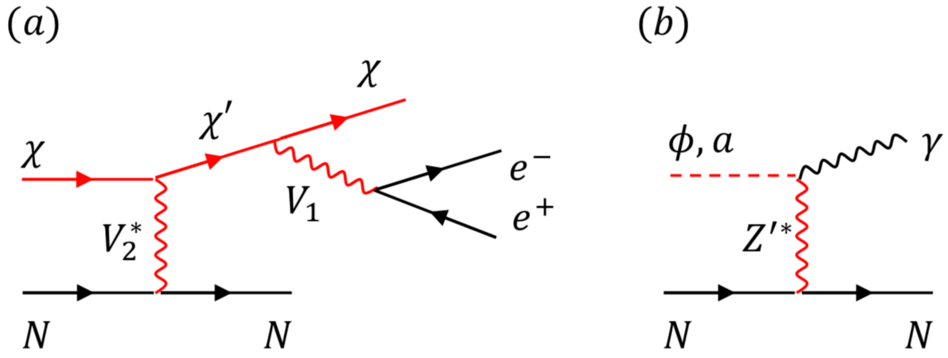


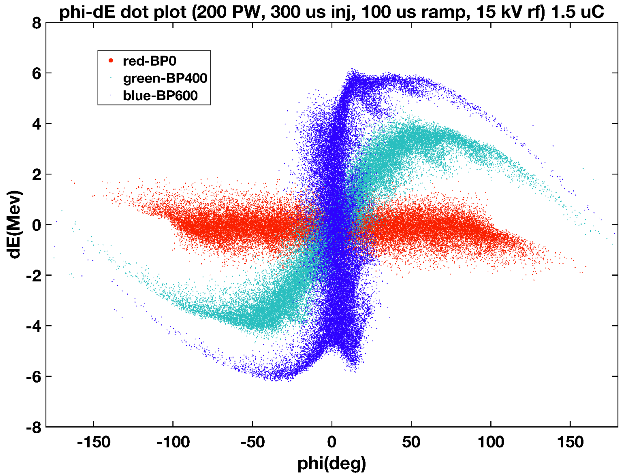
FIG. 2. (a): Dark-matter upscattering via a vector mediator. In the single-mediator scenario, $V_2 = V_1$. (b): "Dark Primakoff" scattering of a scalar ϕ or pseudoscalar a via a light Z'.

Coupling of dark sector particles to charged mesons (instead of π^0) decays focused by horn ensure correct event rates for neutrino, antineutrino, and beam dump modes.

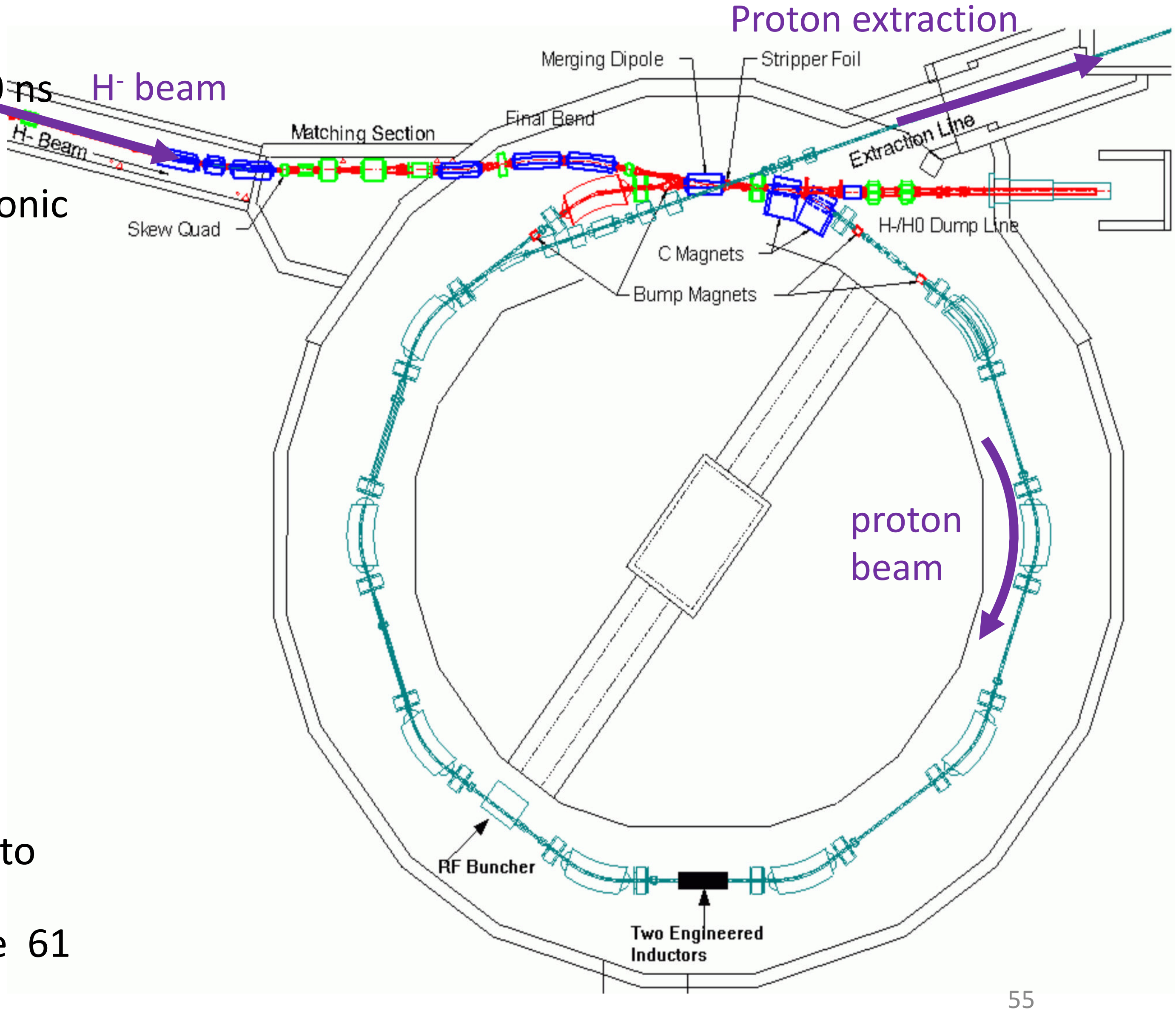
γ-like only final states and NO final state hadronic activity i.e. MiniBooNE excess is e/γ inclusive, expect excess in MircoBooNE ($1\gamma 0p$) sample.

The LANSCE Proton Storage Ring (PSR) – Short Pulse Plan - LANL-AOT and UNM

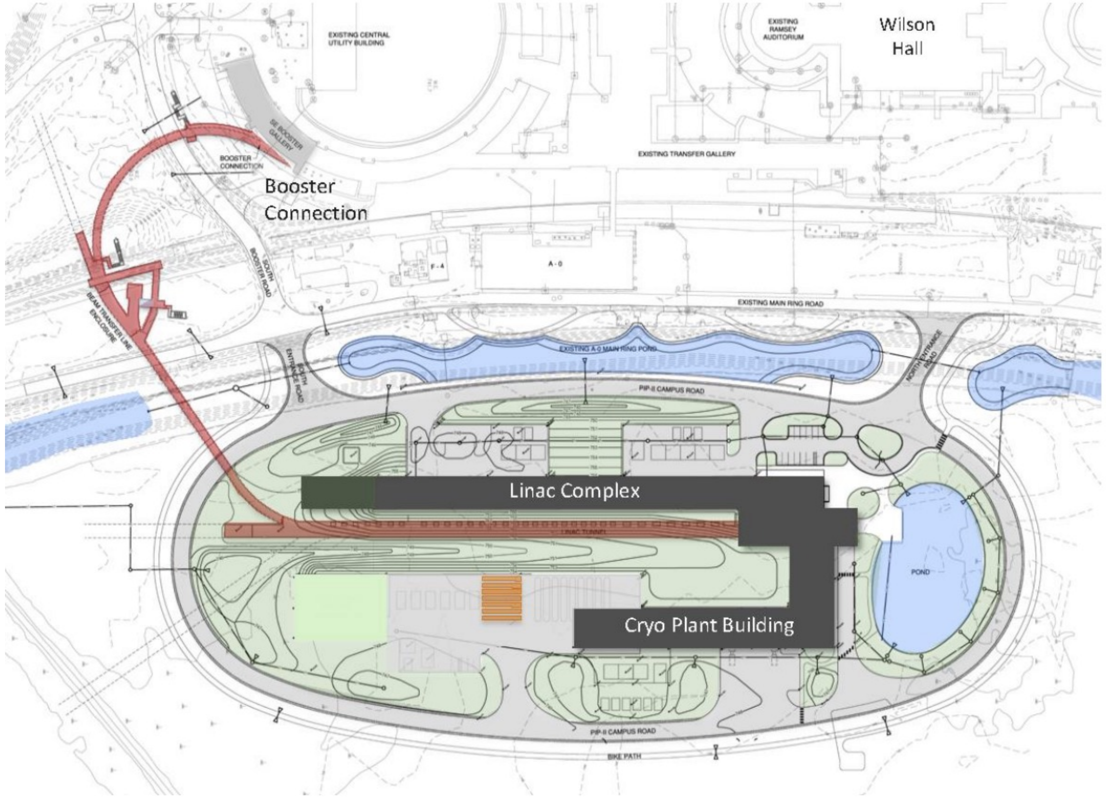
- The LANSCE Proton Strage Ring (PSR) accumulates protons from a 625 us pulse into a more intense 300 ns beam pulse (3.1x10^{13} protons per pulse at 20 Hz)
- As the beam is circulated, it is bunched by the harmonic buncher, trading increase dE for less time spread.



- **Improved beam tuning and orbit simulation could achieve ~100 nsec and 120 uA current by 2022 run.**
- Longer term looking into improved ferrite materials to reduce microwave instability, and active feed back systems, to achieve 30 nsec beam – see backup slide 61



PIP-II Linac & Upgrade



800 MeV H− linac
- Warm Front End
- SRF section

Linac-to-Booster transfer line
- 3-way beam split

Upgraded Booster
- 20 Hz, 800 MeV injection
- New injection area

Upgraded Recycler & Main Injector
- RF in both rings

Conventional facilities
- Site preparation
- Cryoplant Building
- Linac Complex
- Booster Connection

E. Pozdeyev, SpaceCharge19

Project construction started in 2022 (CD3)
First beam in Booster: 2028 (plan)
MI 1.2 MW beam on target: 2032 (projection)