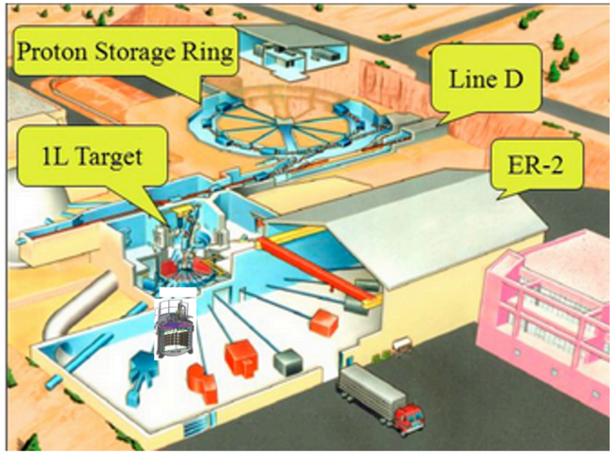
Probing the Dark Sector with Accelerators: New Opportunities!

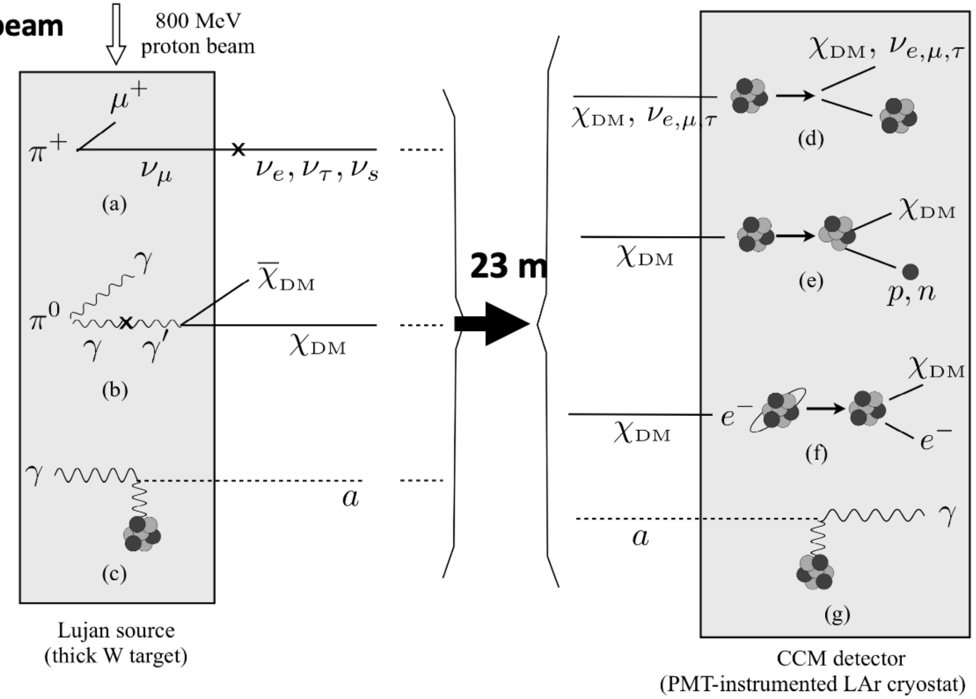
INT, April 2023

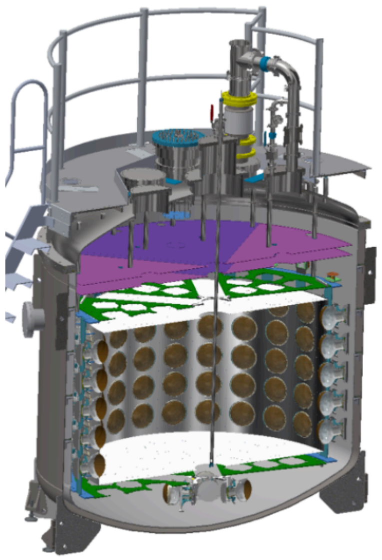
by R. G. Van de Water (LANL, P-2)

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.

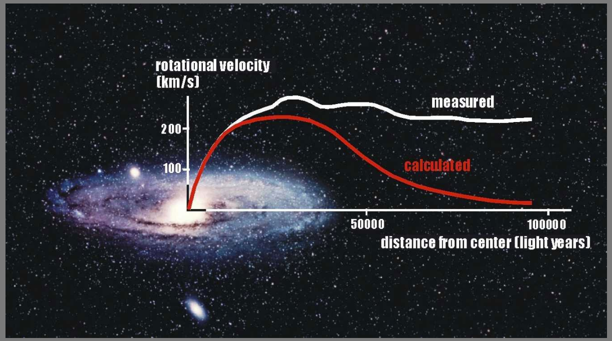
LA-UR-21-30818

Outline

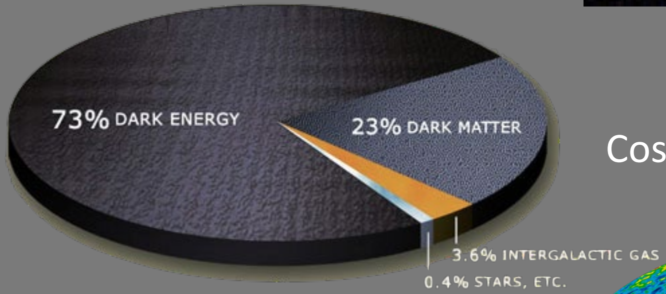
- Physics Motivation – Accelerators are ideal for probing the dark sector, high intensity stopped pion sources especially for ~MeV region.
- Example: The Coherent Captain Mills at LANSCE Experiment
  - LANSCE/Lujan beam and target
  - Production/detection of dark sector particles
  - Search strategies, CCM detector, physics reach
  - Testing dark sector interpretation of the short baseline anomalies
- Future LANSCE PSR and detector upgrades to enhance dark sector searches
- Summary

Dark Matter/Sector, One of the Biggest Known Unknowns

Galaxy Rotation Curves



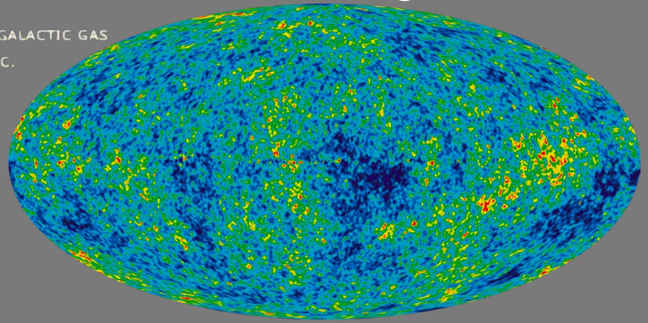
Gravitational Lensing



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

↓

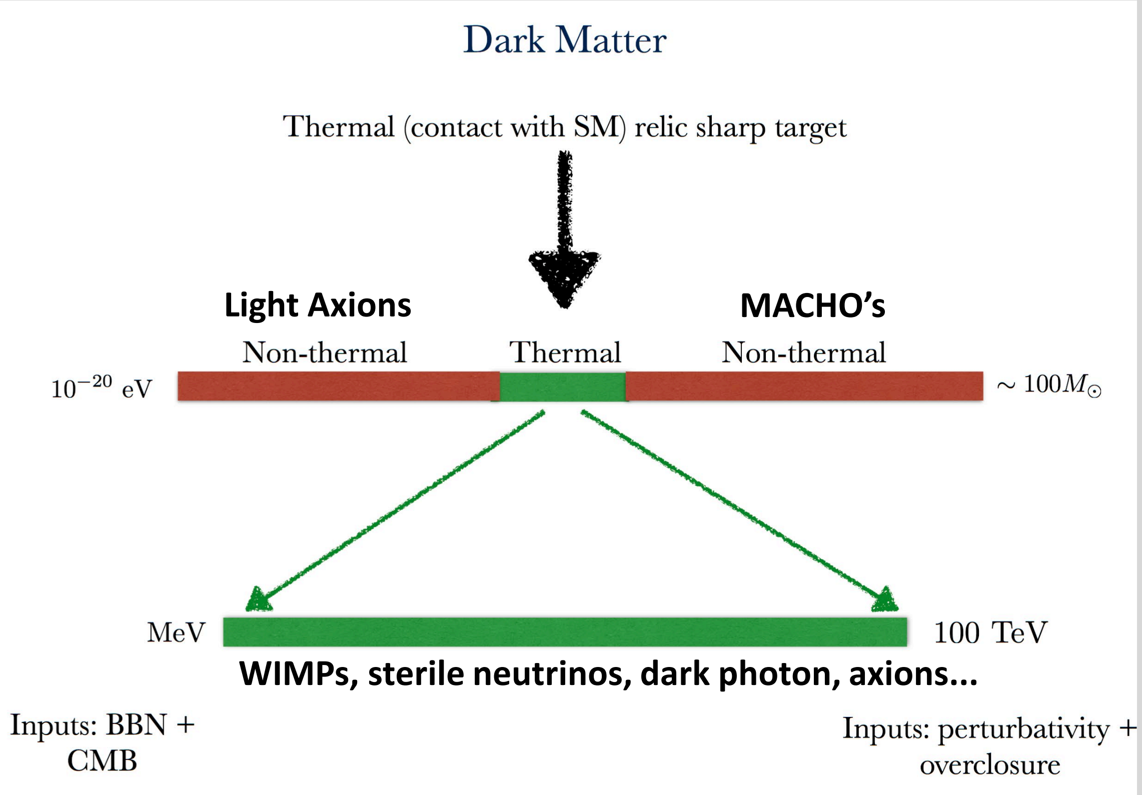
Hypothesis:
It couples to SM through 'sizable' non-gravitational interactions

↓ (consequence)

Thermal equilibrium with SM
Abundance through freeze-out

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

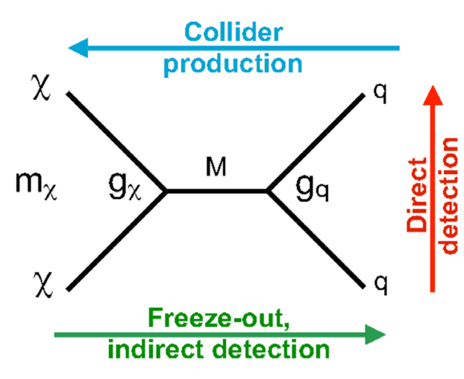
Thermal Assumption



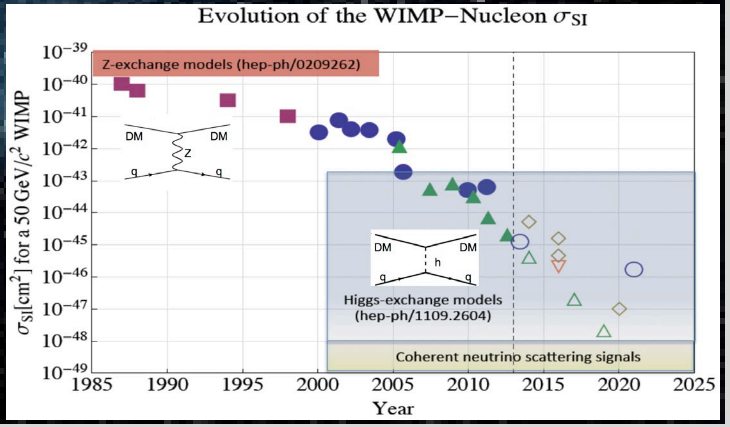
Relic DM density depends on DM mass and interaction cross section with the SM.

Traditional Search for DM: Float in space and wait for it to interact (direct detection underground experiments), DM low rate and velocity!!

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

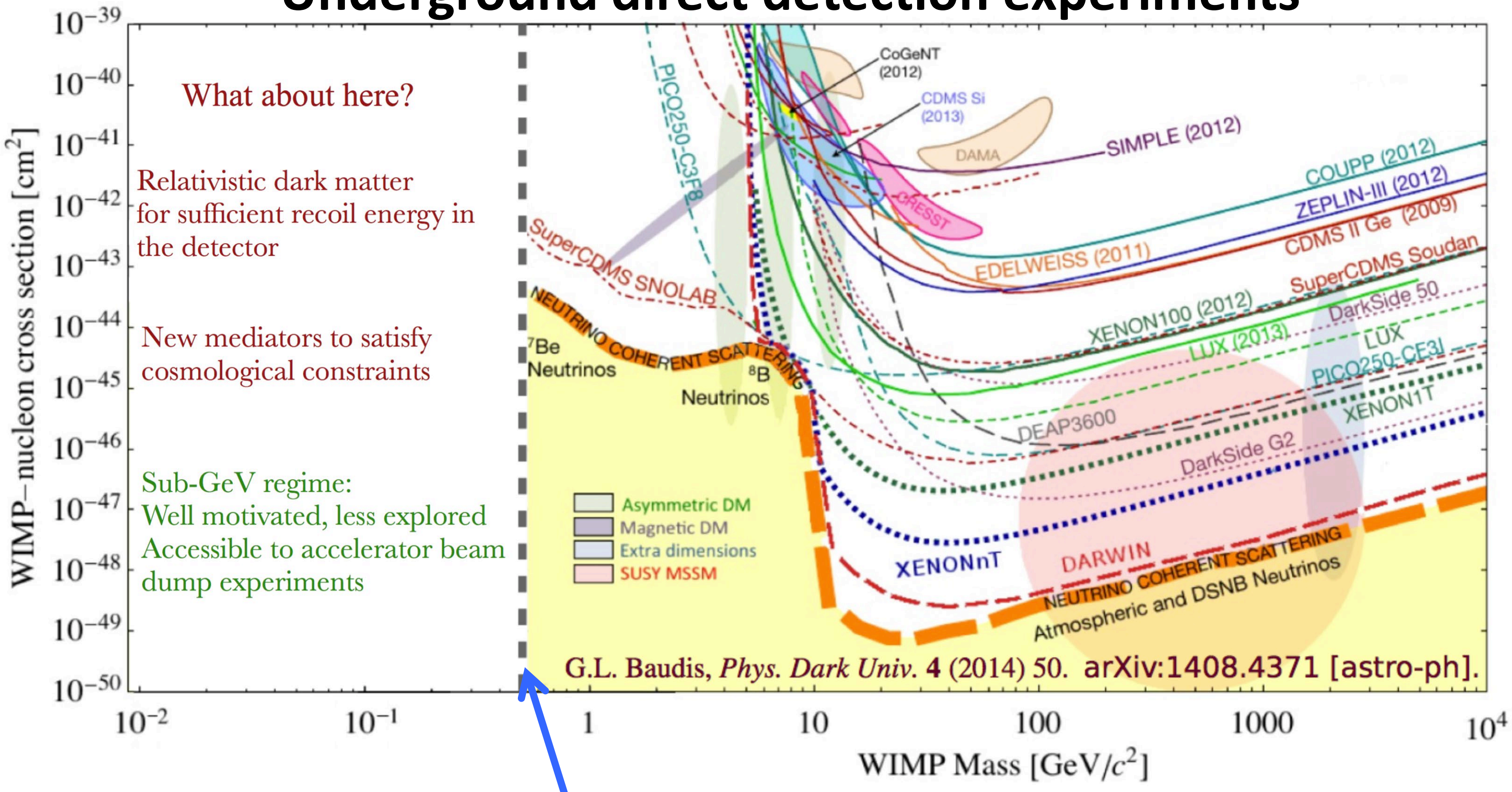


- Low recoil energies (~keV)



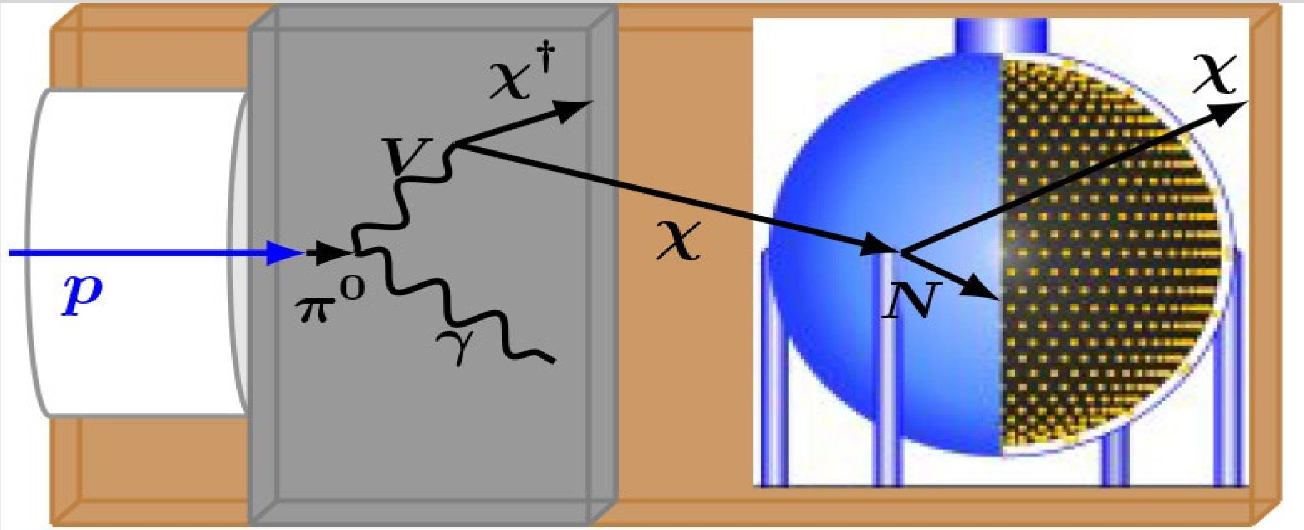
Experimental Motivation for Accelerator sub-GeV Dark Matter Searches

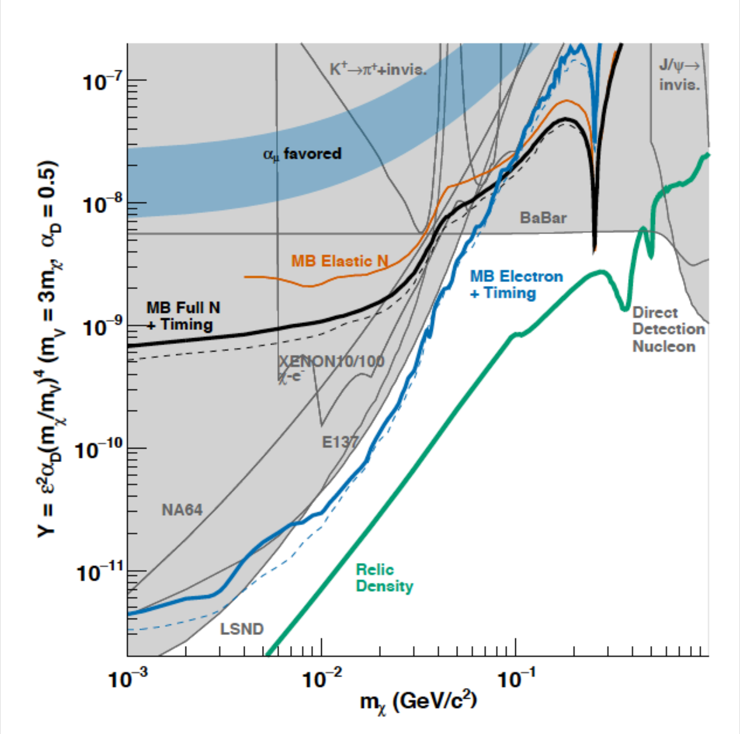
Underground direct detection experiments



- 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.

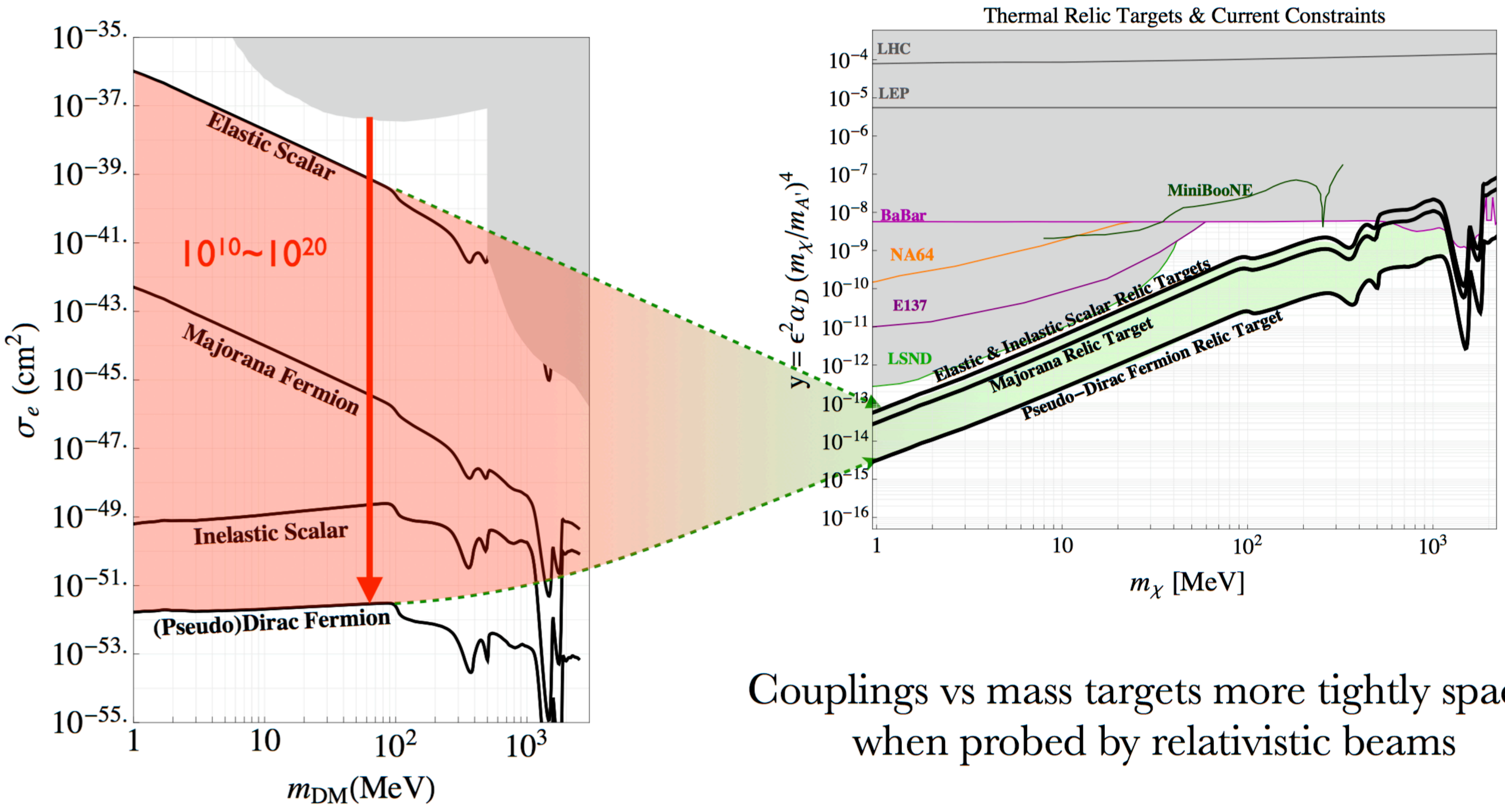
- Large and sensitive detector required for high rates and good background rejection.
- **Final state particle energies ~MeV**

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

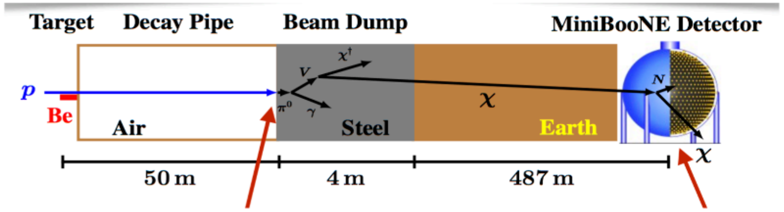
Sensitive to **any** thermal relic

Closing in on well defined goal post!

Many Techniques to Search for Accelerator Produced Dark Sector Particles (World Wide Effort)

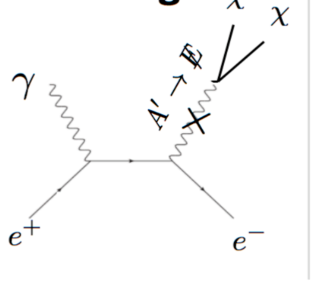
Experiments and Facilities for Accelerator-Based Dark Sector Searches.
In 2022 Snowmass Summer Study, arXiv:2206.04220, 2022

Proton / electron beam dump



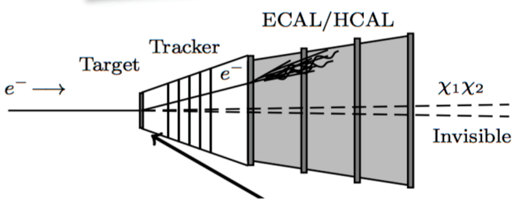
Probes DM interaction twice

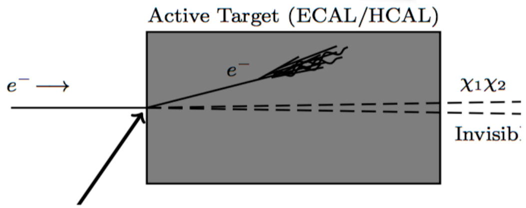
Missing mass



Resonance signal, rate gives coupling information

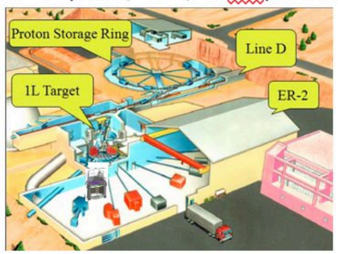
Missing energy / missing momentum



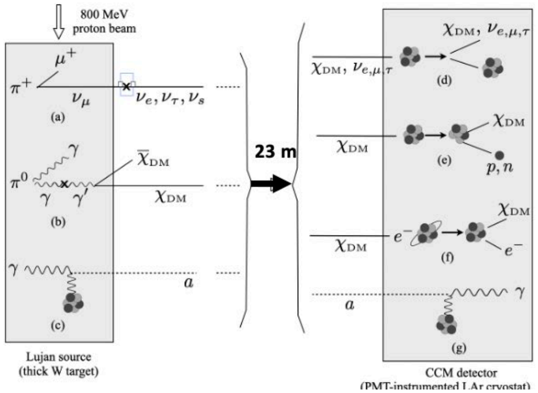


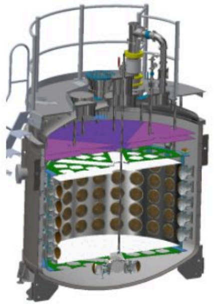
Best yield scaling with luminosity

800 MeV protons, 100kW, 290 nsec pulsed beam



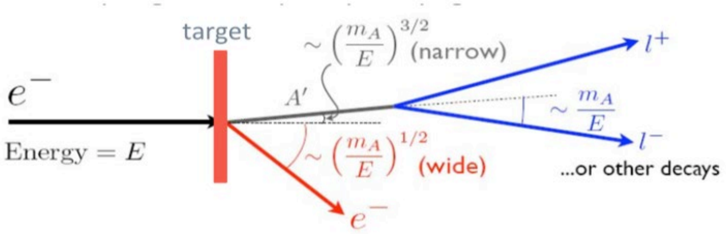
LANSCE-PSR-Lujan Target: Prolific source of charged/neutral pion's and photons that produce neutrinos and potential dark sector particles.





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

Searches for the mediator

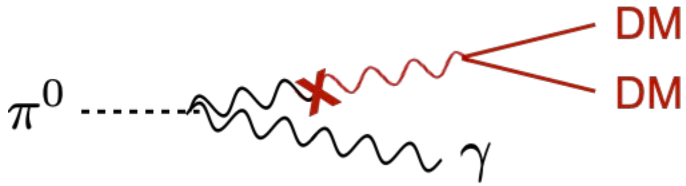


Complementary to DM searches

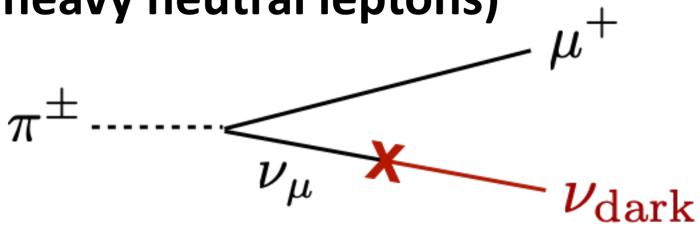
Intense/recent theoretical efforts developing a rich and evolving set of Dark Sector models: DS is maybe not so simple as a single WIMP particle!

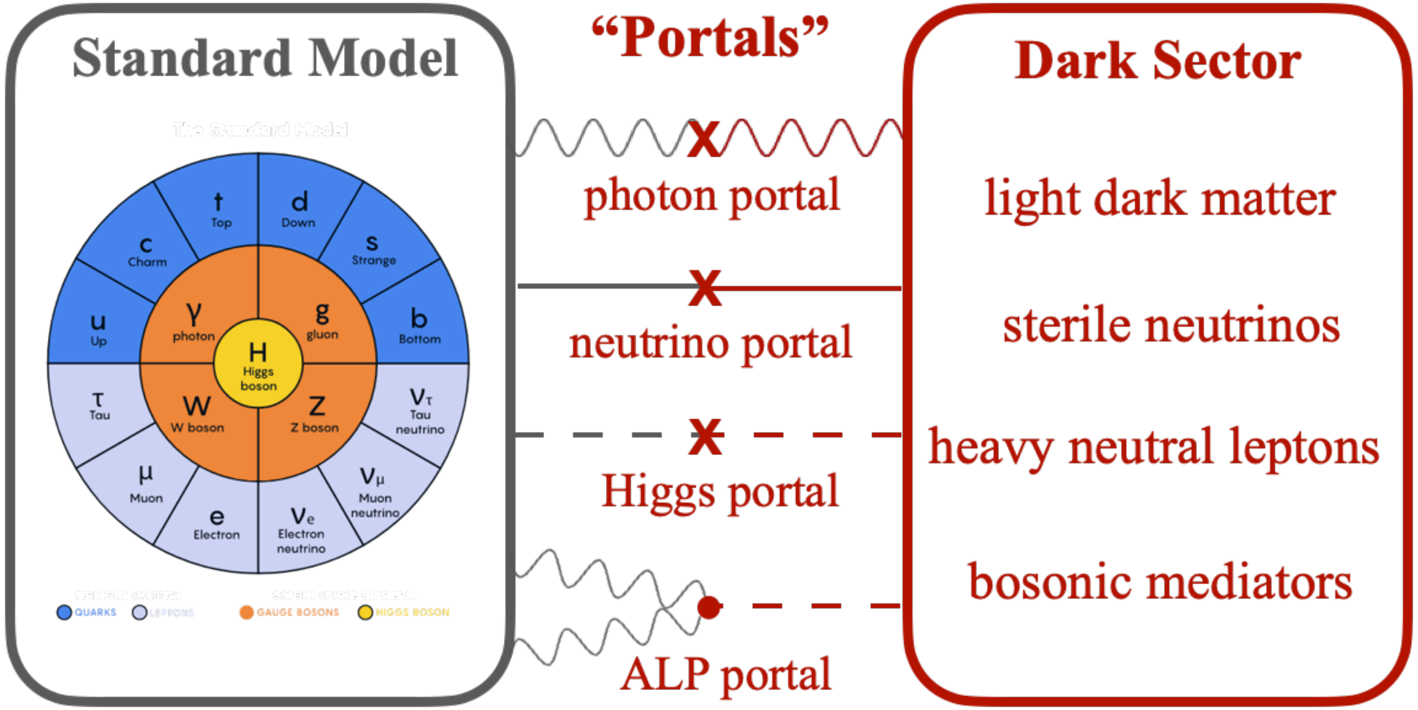
Brian Batell et al. Dark Sector Studies with Neutrino Beams. In 2022 Snowmass Summer Study, arXiv:2207.06898, 2022

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



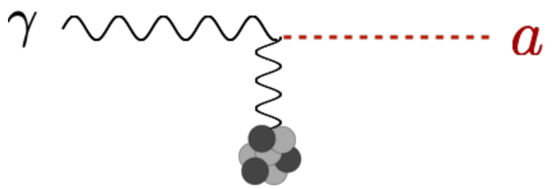
- **Neutrino Portals (sterile neutrinos, heavy neutral leptons)**

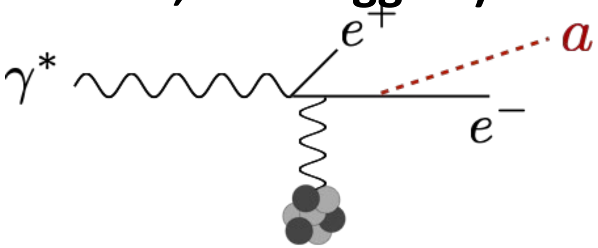




Intense proton/electron colliders and beam dumps can probe all these portals

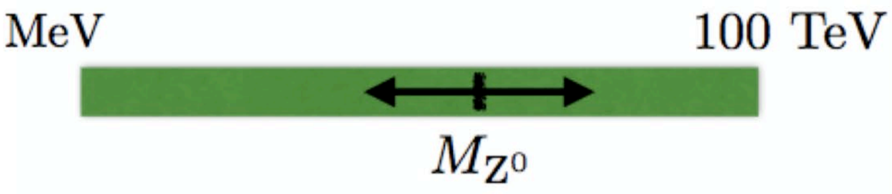
- **Dark Sector Mediators (ALPs, dark vectors, dark higgses)**



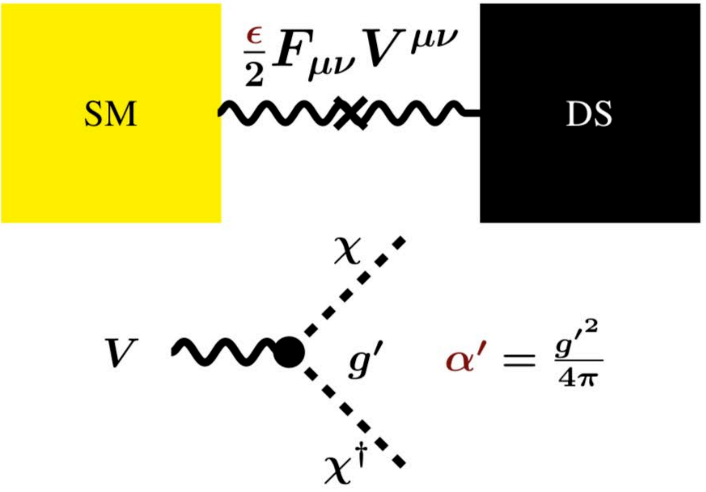


Example Benchmark Dark Sector Model: Vector Portal Dark Photon

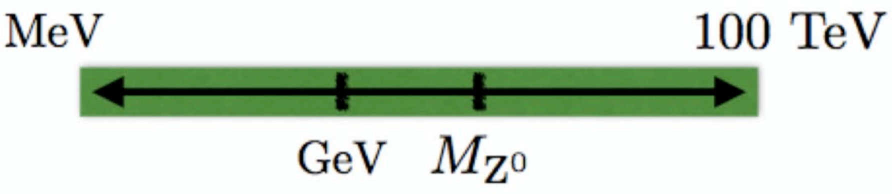
Standard WIMP



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



New Light Mediator

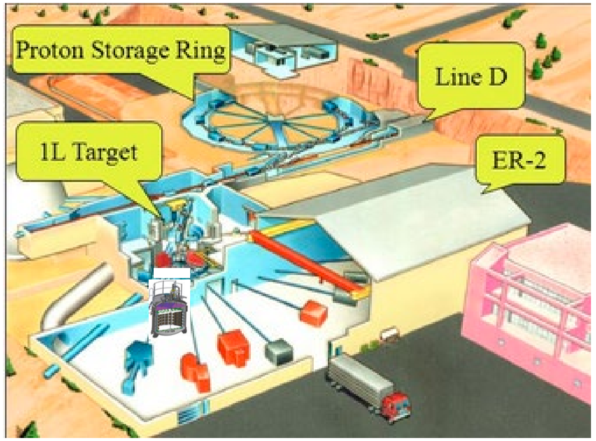


- Does not assume mediator is the Z boson
- Simplest model assumes mediator is a vector (dark photon)
  - 4 free parameters
    - Mass of the dark photon m_V
    - Mass of the dark matter m_χ
    - Mixing angle between SM and dark sector ε
    - Coupling between dark photon and dark matter α_D

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

Probing the Dark Sector with Accelerators: New Opportunities at LANL with CCM!

800 MeV protons, 100kW, 290 nsec pulsed beam



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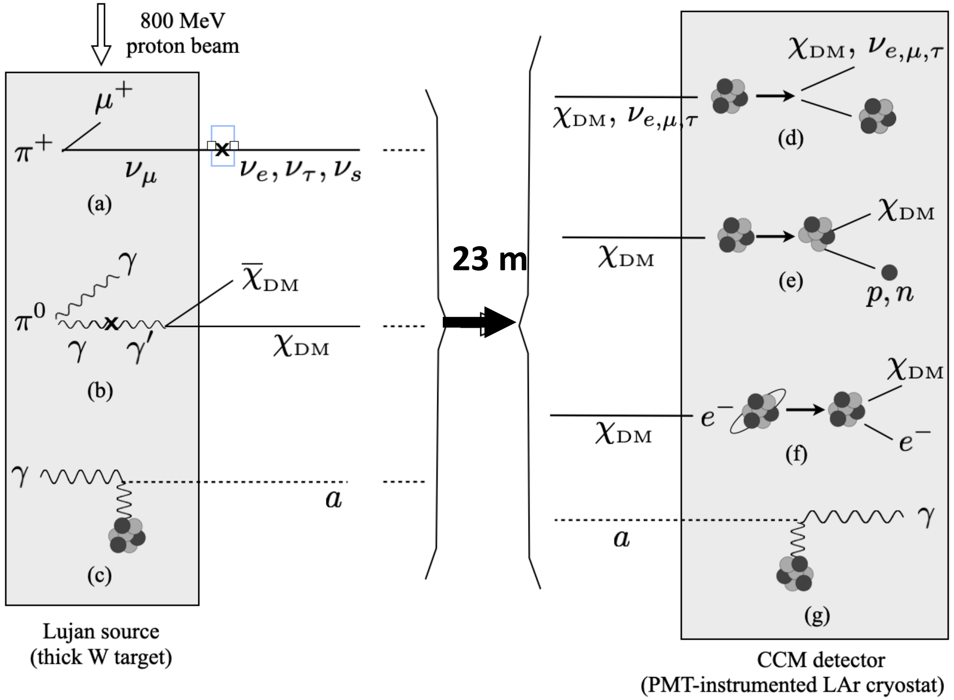
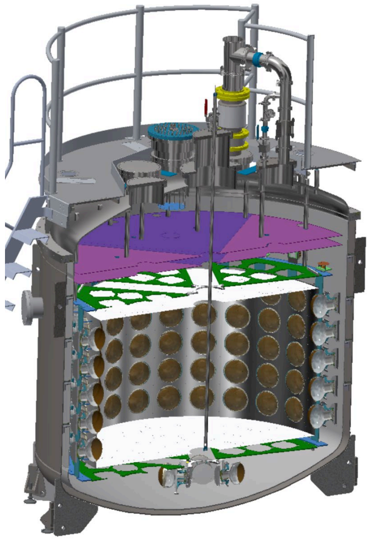




CCM: 10-ton Liquid Argon (LAr) detector instrumented with 200 8" Photo-multiplier tubes, veto region, shielding, fast electronics.

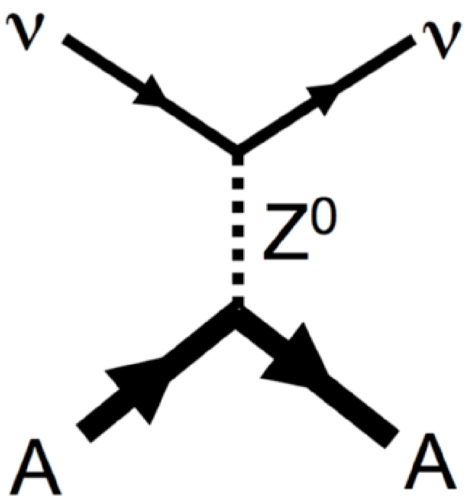
Planned Scope (LANL LDRD 2019-2021, 2022 Reserve):

- 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 (DOE HEP Dark Matter New Initiative – DMNI – funded to run 2023-2025):

- 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

Universidad Nacional Autónoma de México

Fermilab

University of Florida

Los Alamos National Laboratory EST. 1943

CCM Collaboration – Hands on experiment with rich list of physics topics leading to many potential theses and publications. Pipeline for students/PD's

Axion-Like Particles at Coherent CAPTAIN-Mills

A.A. Aguilar-Arevalo,[8] D. S. M. Alves,[6] S. Biedron,[9] J. Boissevain,[1] M. Borrego,[6] L. Bugel,[7] M. Chavez–Estrada,[8] J.M. Conrad,[7] R.L. Cooper,[6,10] A. Diaz,[7] J.R. Distel,[6] J.C. D'Olivo,[8] E. Dunton,[2] B. Dutta,[11] D. Fields,[9] J.R. Gochanour,[6] M. Gold,[9] E. Guardincerri,[6] E.C. Huang,[6] N. Kamp,[7] D. Kim,[11] K. Knickerbocker,[6] W.C. Louis,[6] J.T.M. Lyles,[6] R. Mahapatra,[11] S. Maludze,[11] J. Mirabal,[6] D. Newmark,[7] N. Mishra,[11] P. deNiverville,[6] V. Pandey,[5] D. Poulson,[6] H. Ray,[5] E. Renner,[6] T.J. Schaub,[9] A. Schneider,[7] M.H. Shaevitz,[2] D. Smith,[4] W. Sondheim,[6] A.M. Szelc,[3] C. Taylor,[6] A. Thompson,[11] W.H. Thompson,[6] M. Tripathi,[5] R.T. Thornton,[6] R. Van Berg,[1] R.G. Van de Water,[6] and S. Verma[11]
(The CCM Collaboration)

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[2] *Columbia University, New York, NY 10027, USA*
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[6] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
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[10] *New Mexico State University, Las Cruces, NM 88003, USA*
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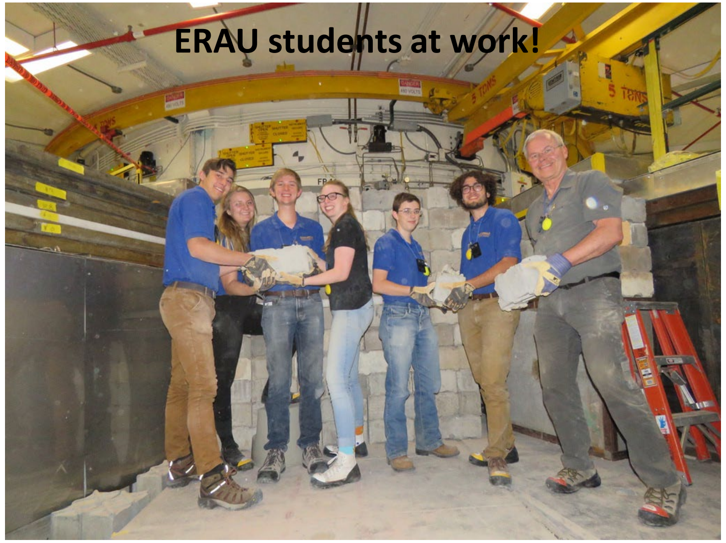
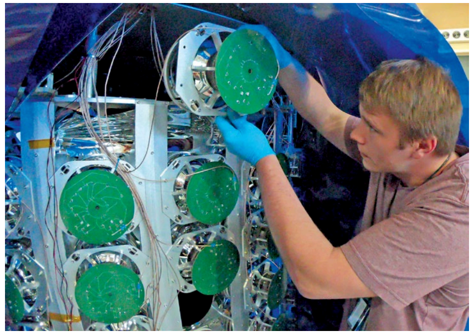


TJ Schaub - UNM



William Thompson, LANL-SULI

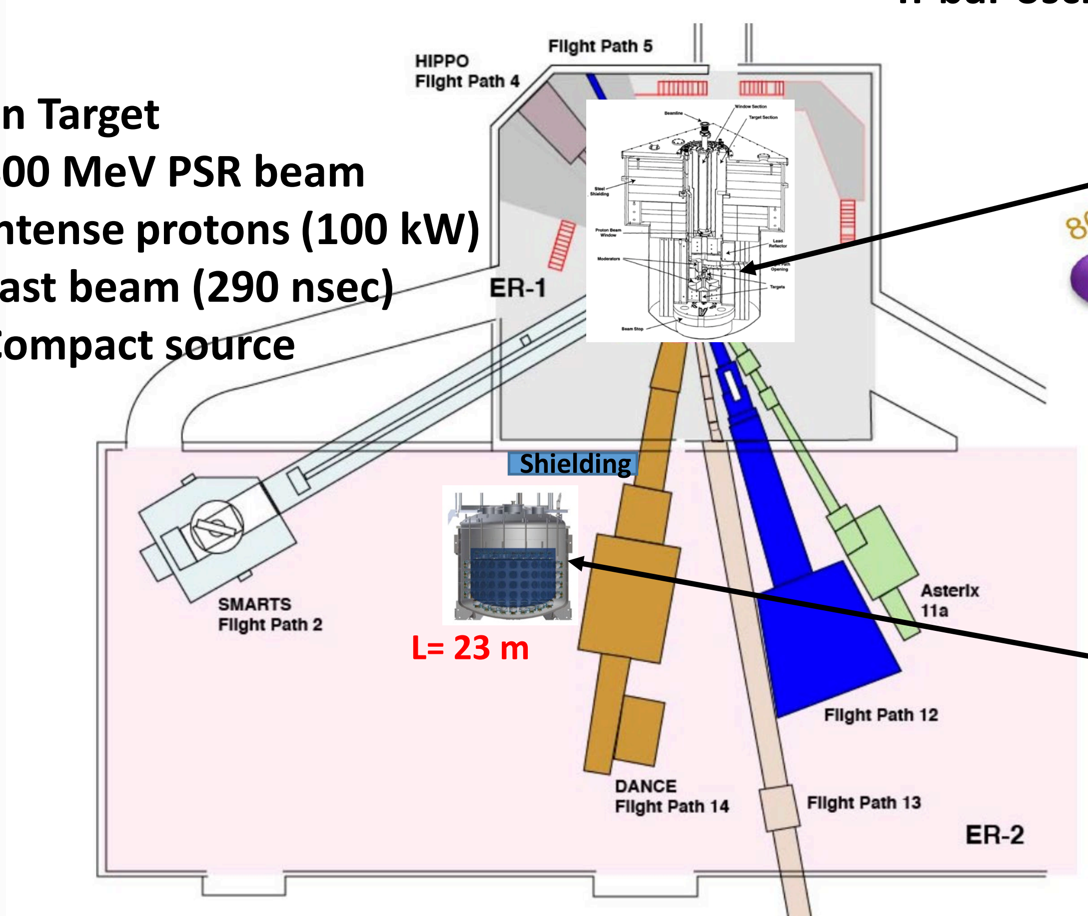
- **CCM PostDoc conversions to AOT staff: En-Chuan Huang and Tyler Thornton.**
- **Directors funded PD Austin Schneider (MIT), new PD hire Ed Dunton (Columbia).**
- **Excellent crop of Phd students: E. Dunton (Columbia), TJ Schaub (UNM), M. Tripathi (U. Florida), M. Chavez (UNAM-Mexico), D. Newmark (MIT), Sharada Sahoo (TAMU).**
- **Attract local summer/post-bac students: W. Thompson, Aayush Thapa (St. Johns College).**

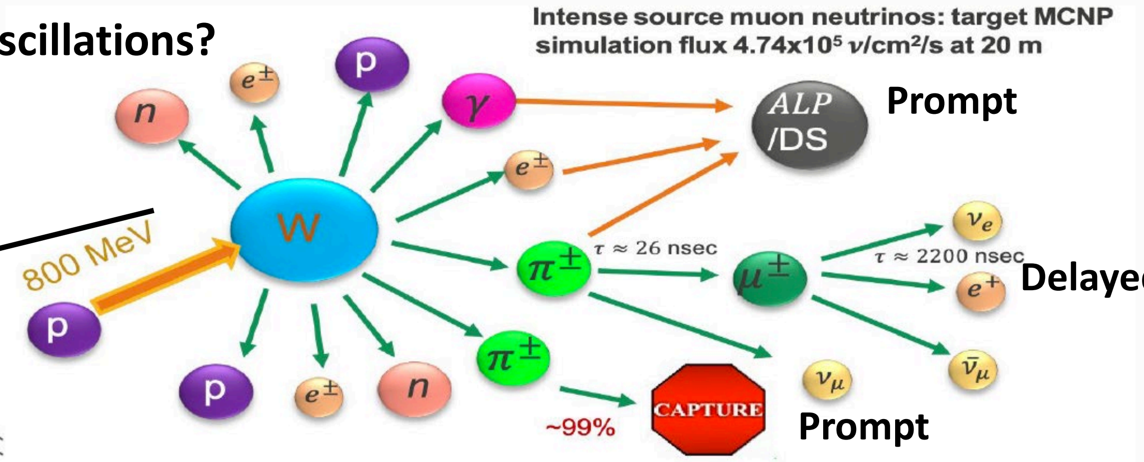
LANL Institutional Support

LANSCE-Lujan Facility a unique place to perform significant and timely search for Dark Sector particles and forces

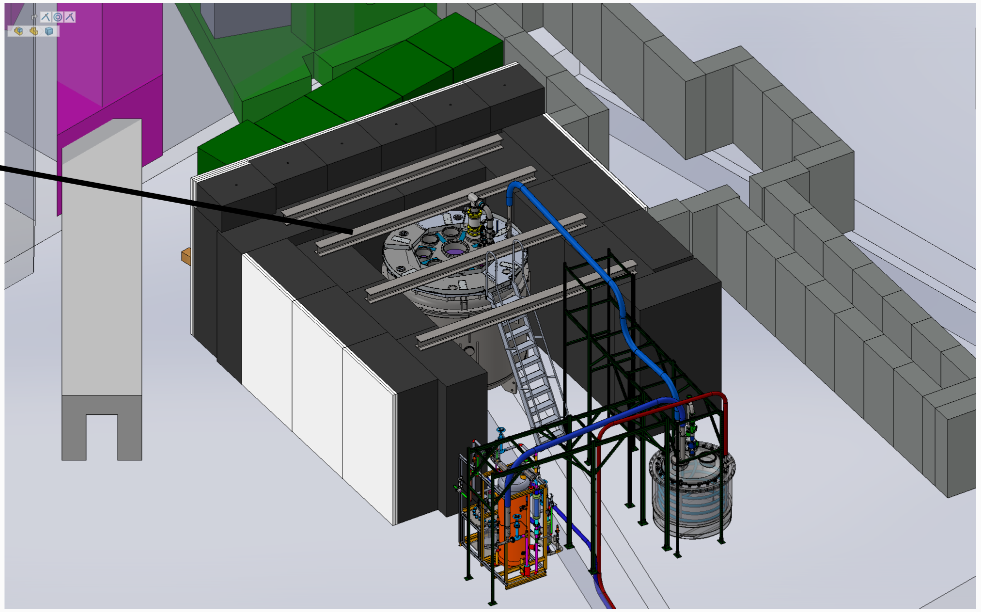
n-bar oscillations?

Lujan Target
- 800 MeV PSR beam
- Intense protons (100 kW)
- Fast beam (290 nsec)
- Compact source





CCM200 is 23m from target behind extensive shielding



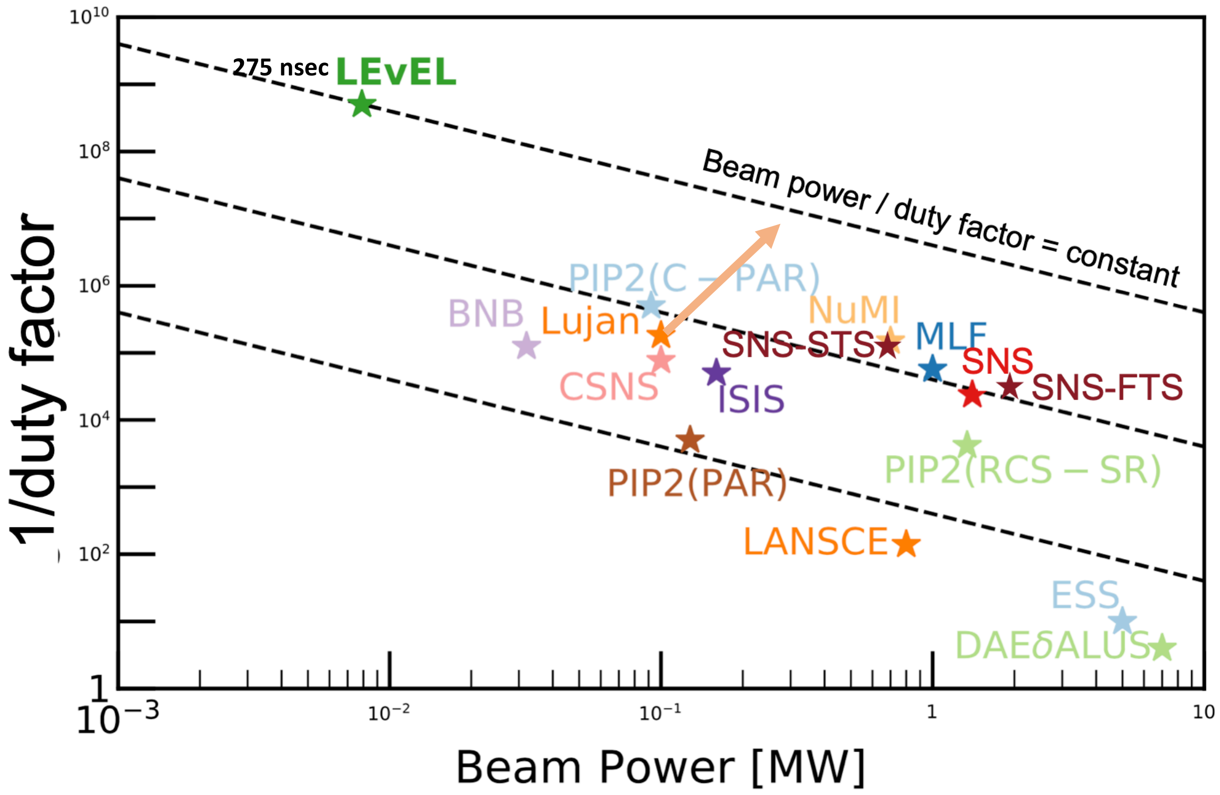
Lujan Experimental Area
- Space for large 10-ton liquid Argon neutrino detector.
- Can run detector in multiple locations – background studies
- Room to deploy shielding, large overhead crane, power, etc

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

Proton Beam Dump Accelerator Facilities

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!

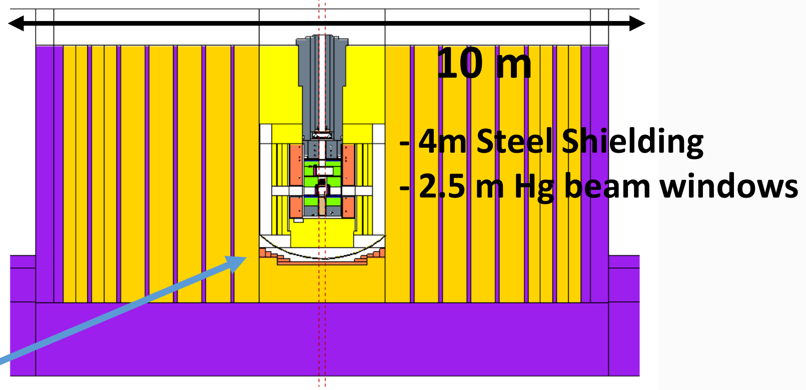
Fermilab

15 1/31/23 Matt Toups, Fermilab I New Proton Beam Dump Experiments at Fermilab

- **Neutrino/DM experiments require high Instantaneous Power (IP) – measure of Signal/Background (S/B):**
- 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

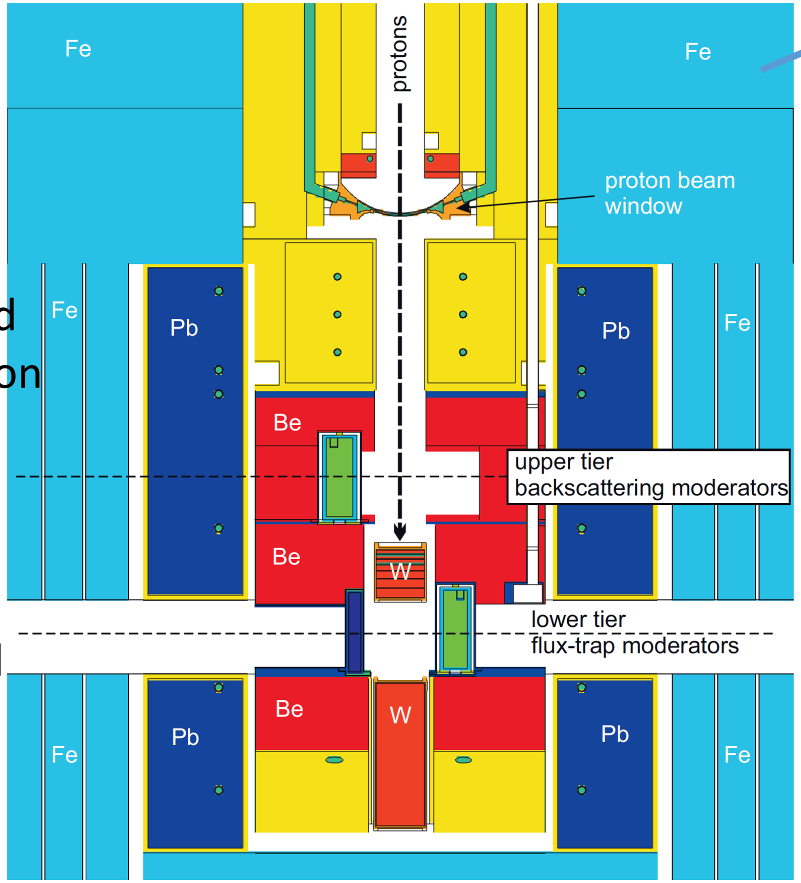
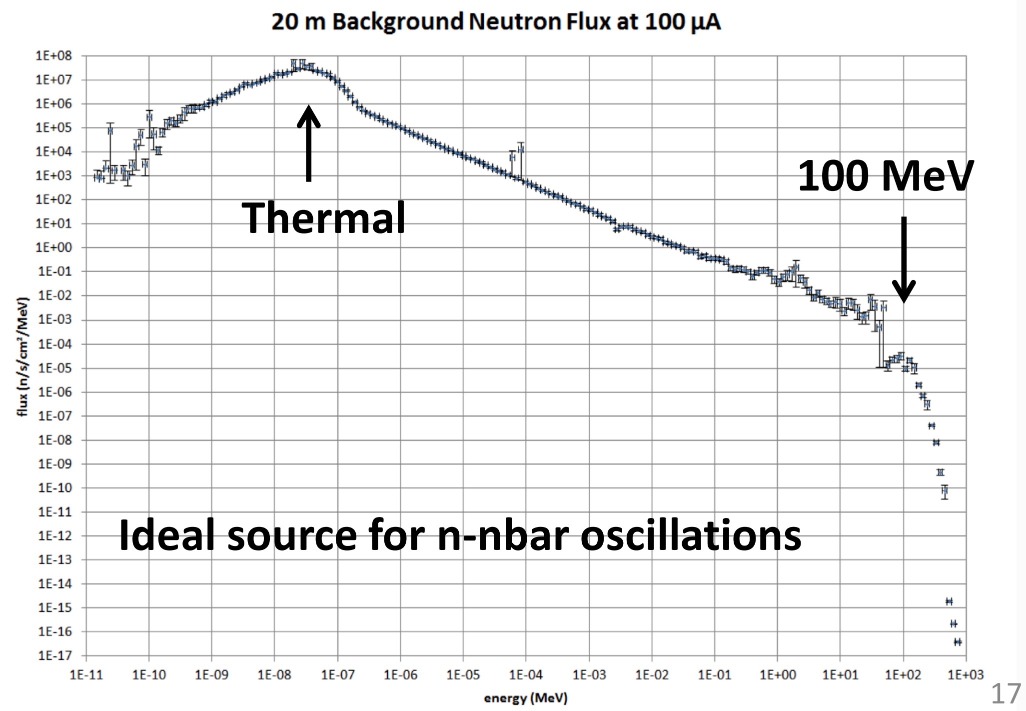


Fig. 1. Elevation view of the Lujan Center's TMRS geometry used in our calculations. The main components are labeled: split tungsten target (W), beryllium reflector (Be), lead reflector–shield (Pb), and the steel reflector–shield (Fe).

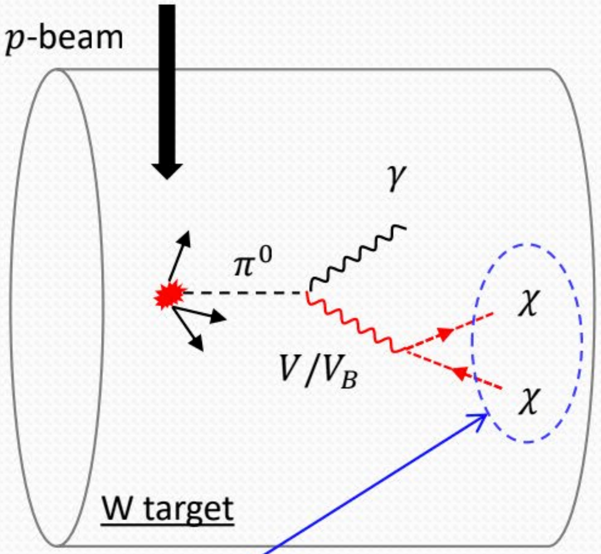
Complex target tuned for neutron production
Copious amounts of π^0, γ, e, n, p also produced.

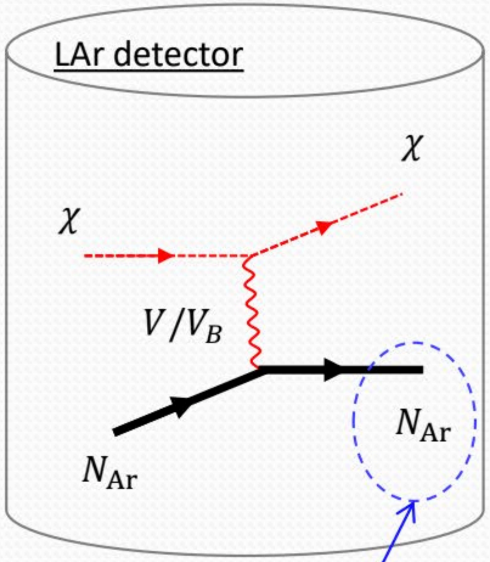
Beamlines controlled by Hg window

- 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

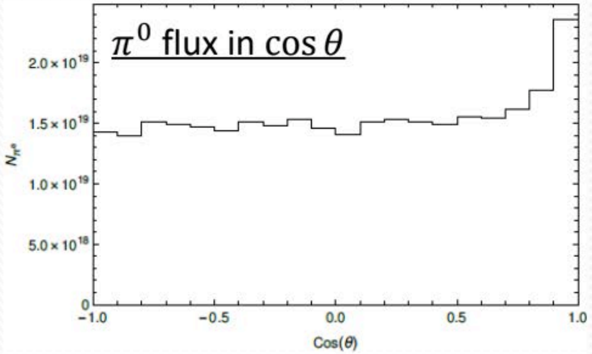




DM coherent scatter final state E ~100's keV

π^0-induced DM flux widespread in angle

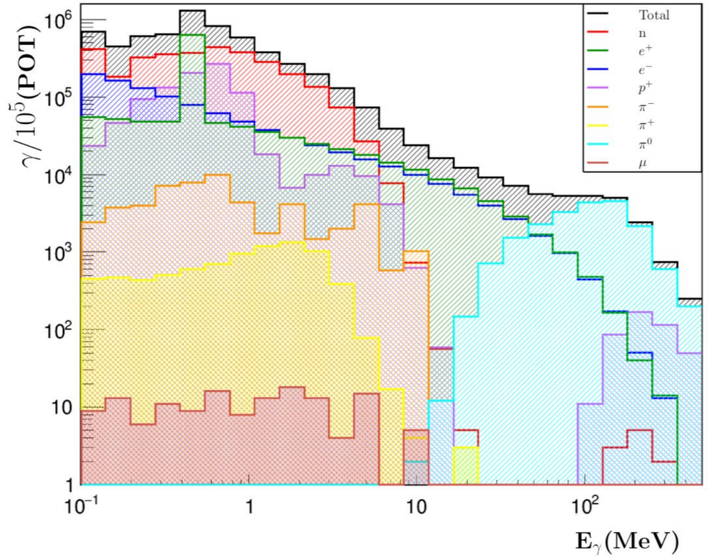
$N_{\pi^0} = 0.115$/POT



Observing a coherent scattering off an Ar nucleus

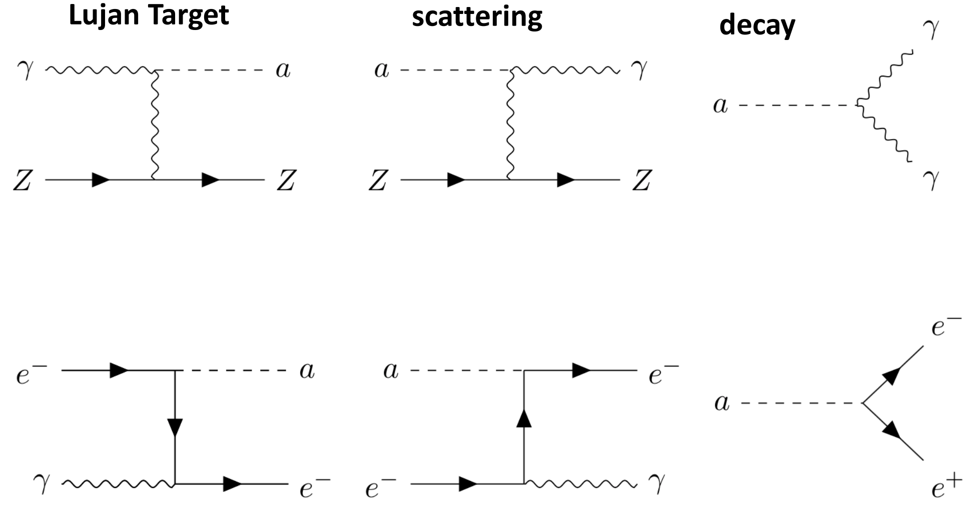
Axion Like Particles (ALPs) from Photon and Electron Production

Prolific Photon/electron Production in Lujan Target

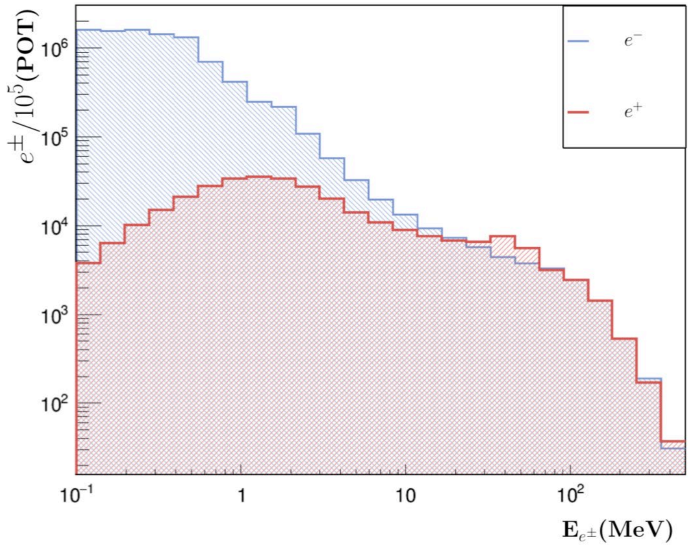


ALP (a) Primakov production and inverse-Primakov scattering

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

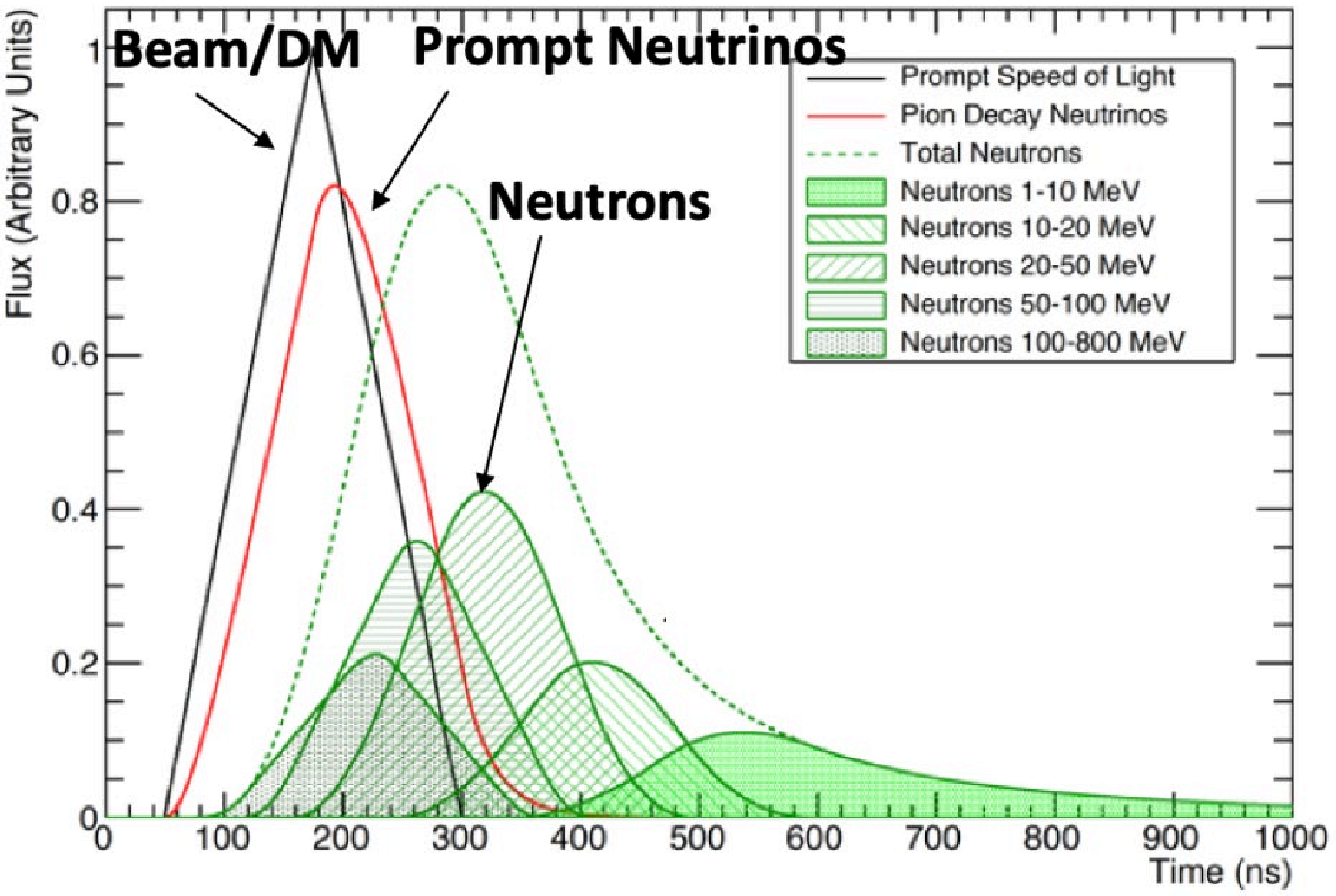


Final state scatter 0.1 – 10's MeV



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

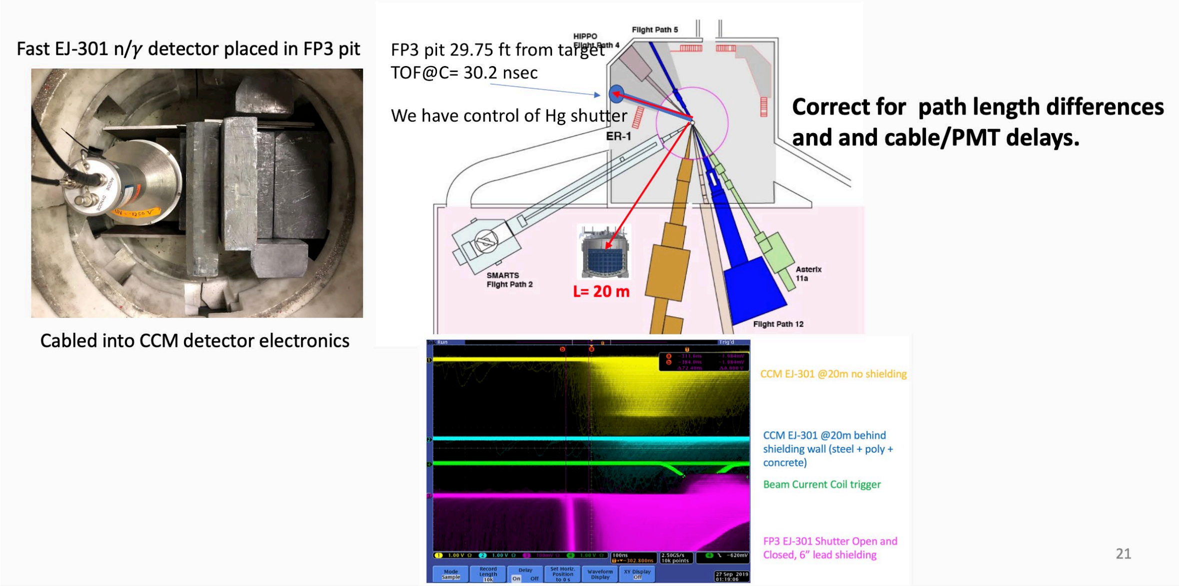
Key Requirement: Fast (~nsec) Beam and Detector Timing to Remove Beam Neutrons



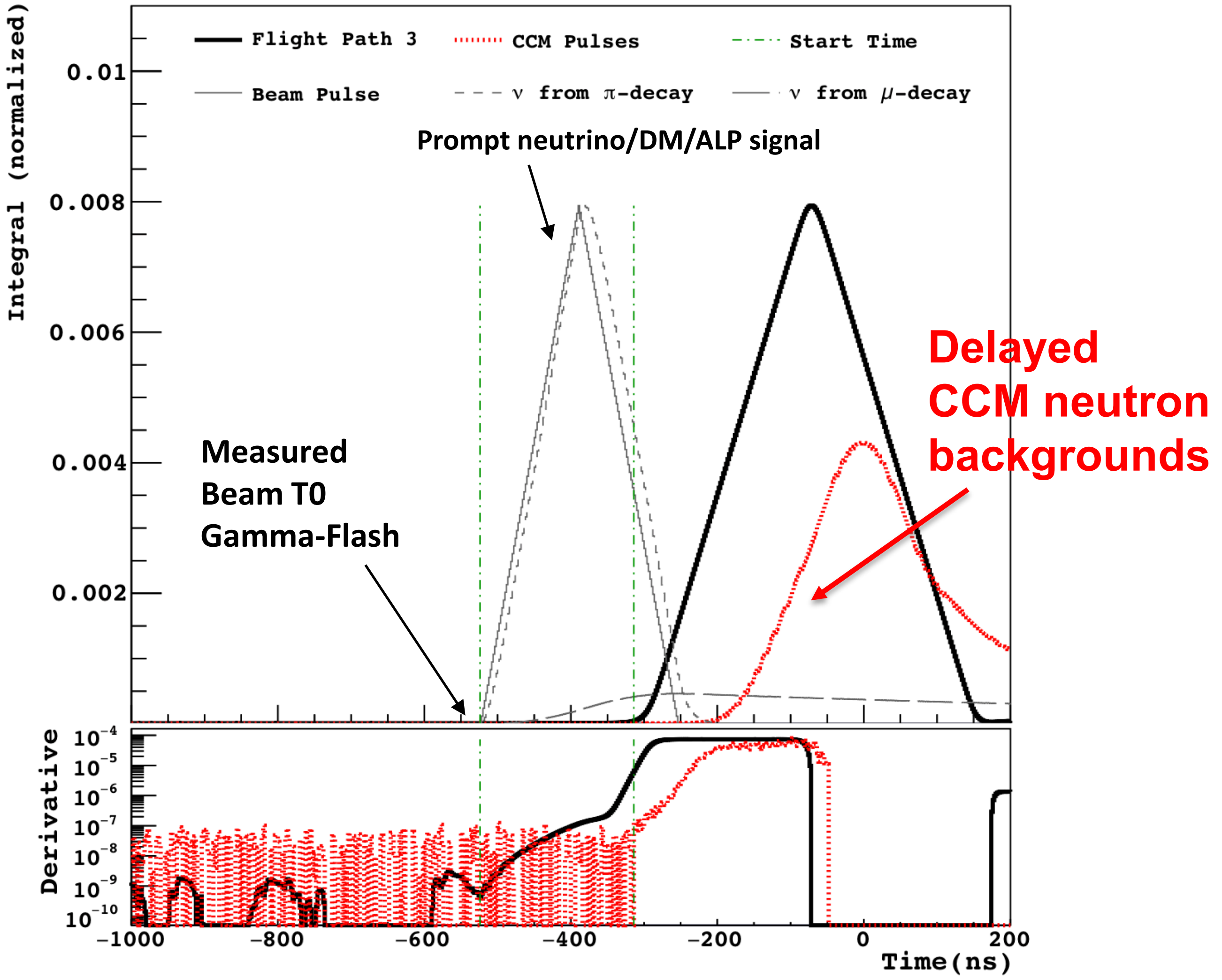
- Extensive 5m of steel and 3m concrete slows down neutrons
- Speed of light neutrinos and dark sector particles show up ~200 nsec earlier.

Timing is key to separating slow beam related neutrons from speed of light neutrinos and BSM particles

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



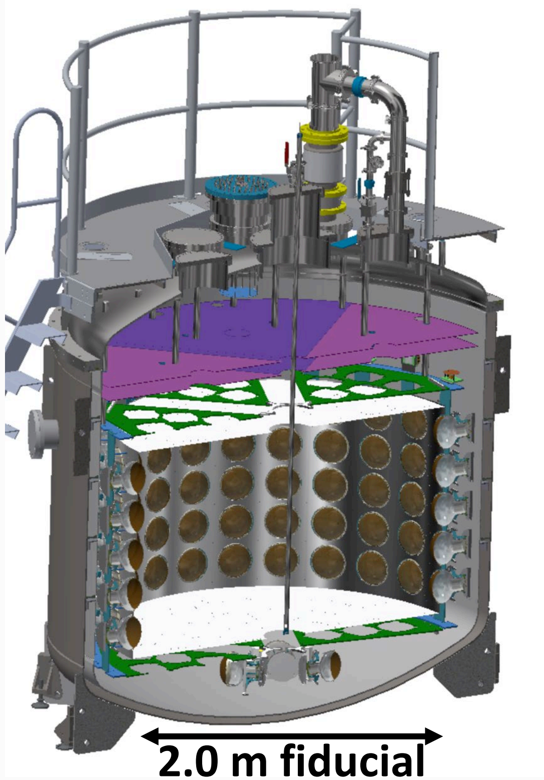
- **~200 nsec prompt time window maximally sensitive to dark sector physics**
- **The shorter the beam spill the larger the separation of signal and backgrounds**



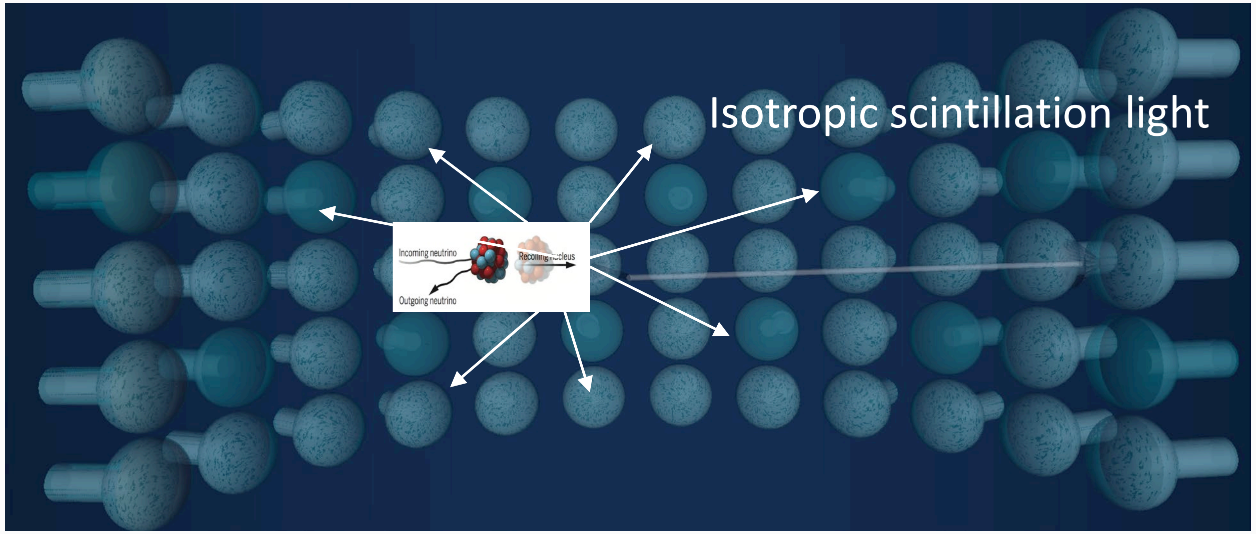
Tyler Thornton (LANL)

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

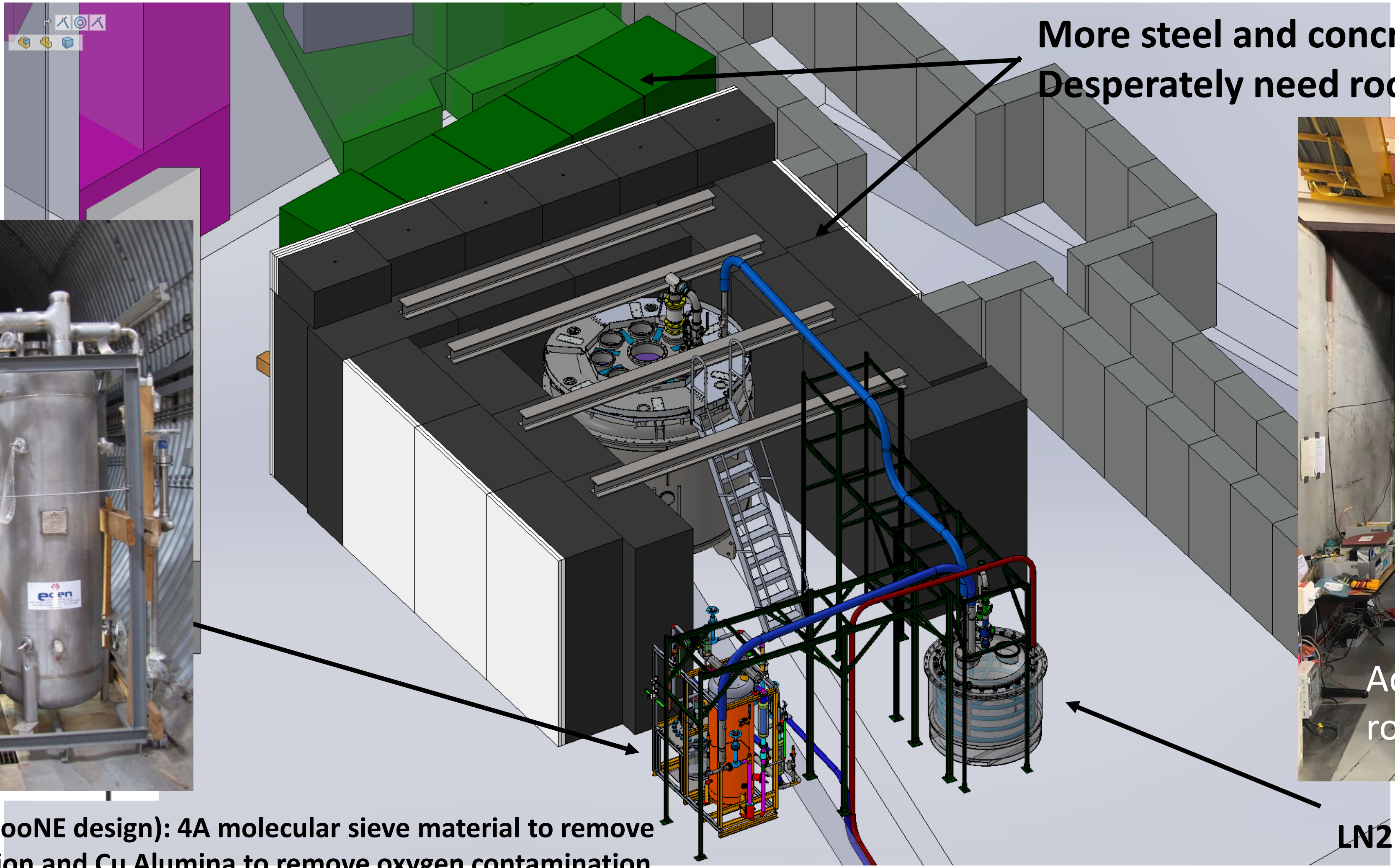


Simulations predict ~1 PhotoElectron/keVnr – singlet light

- **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's 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)

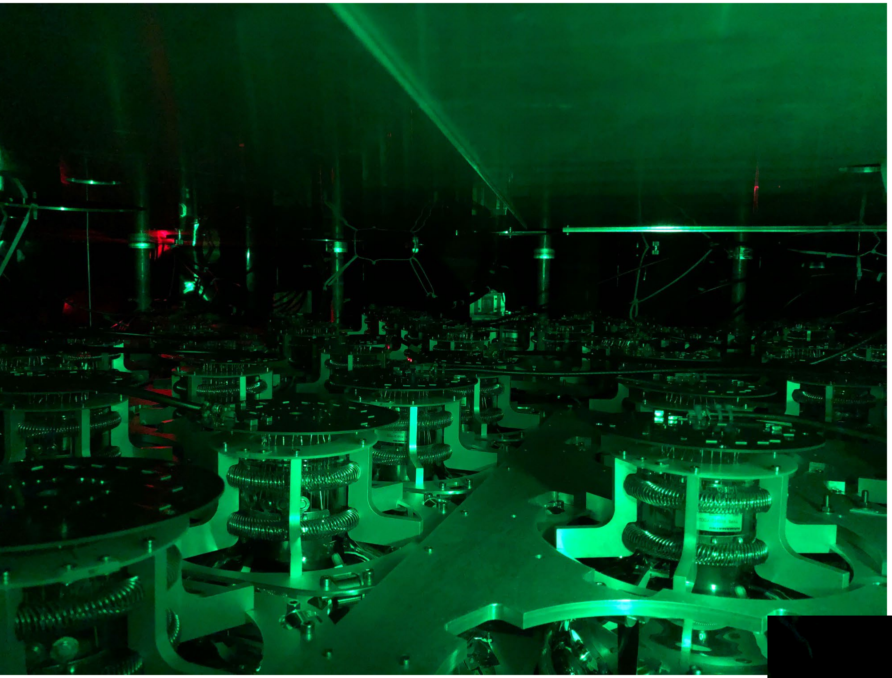
LN2 heat exchanger to reduce LAr losses (especially important if we use isotopically pure U/G LAr in the future).

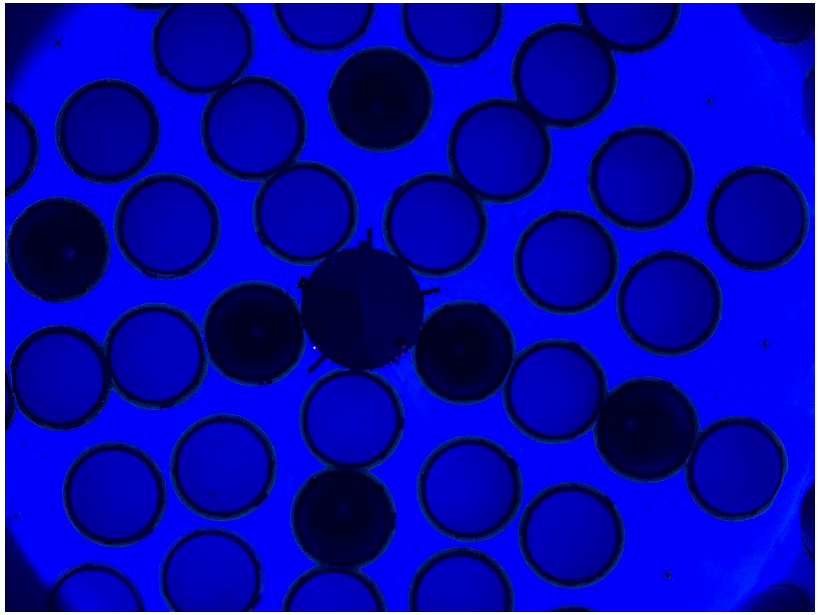
CCM200 successfully constructed during COVID, begun running early Oct 2021

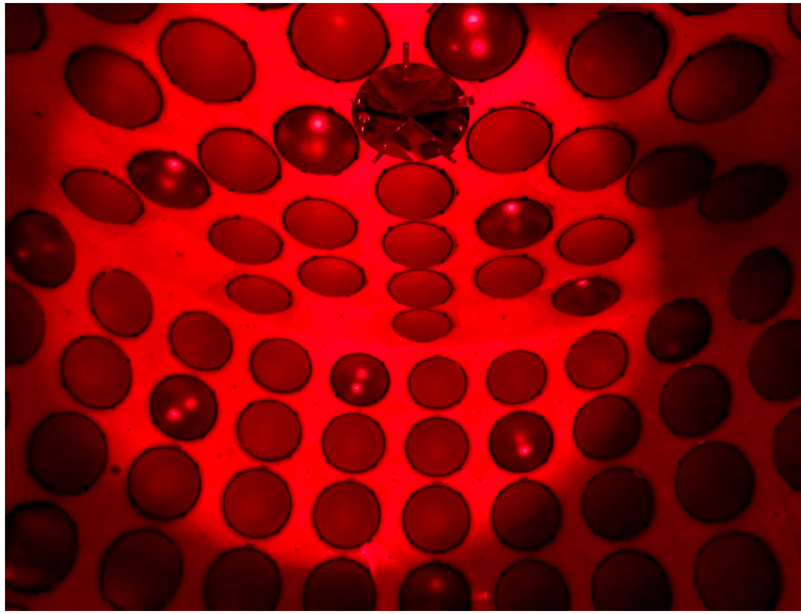
Huge effort by installation team (left to right):
TJ Schaub (UNM)
Mayank Tripathi (UFlorida)
Will Thompson (P-2 PostBac)
Ed Dunton (ColumbiaU)

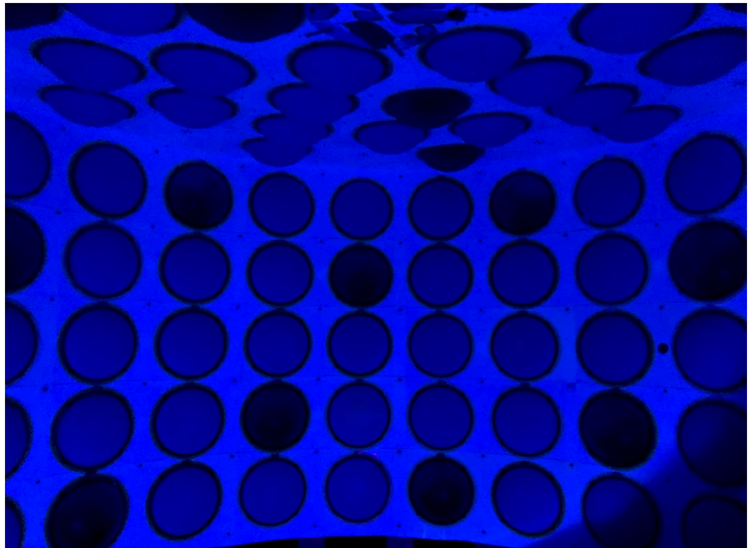
Los Alamos NATIONAL LABORATORY EST. 1943

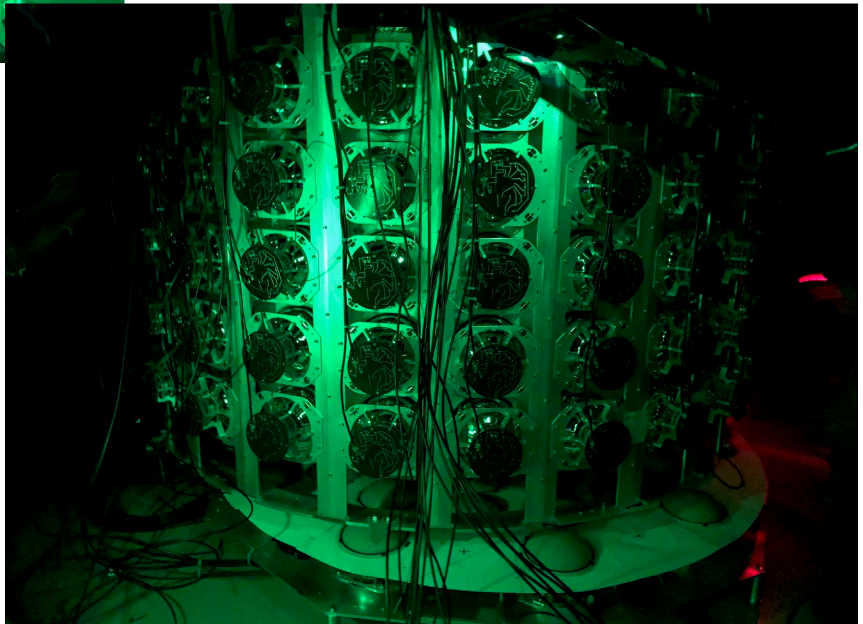
More Cool Pics of CCM200….

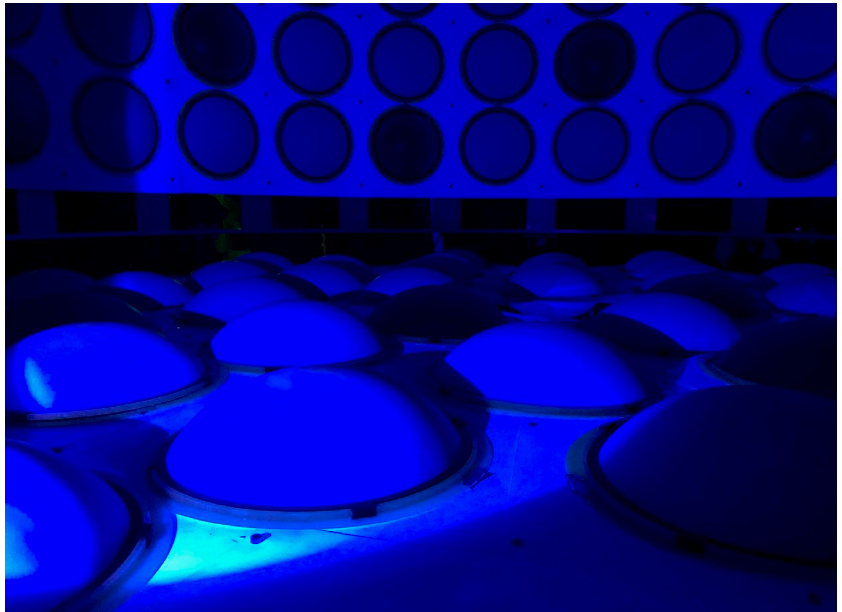








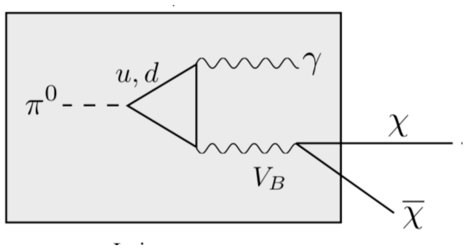




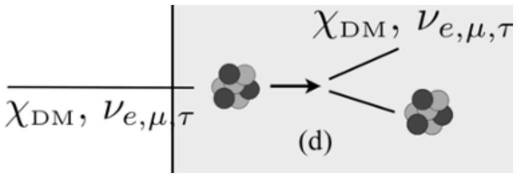
LeptophobicElastic Dark Matter: CCM120 Results and Expected CCM200 Sensitivity

Physical Review Letters **Vol. 129, No. 2 (2022), "First Leptophobic Dark Matter Search from Coherent CAPTAIN-Mills"**
Physical Review D **106, 1, (2022), "First dark matter search results from Coherent CAPTAIN-Mills"**

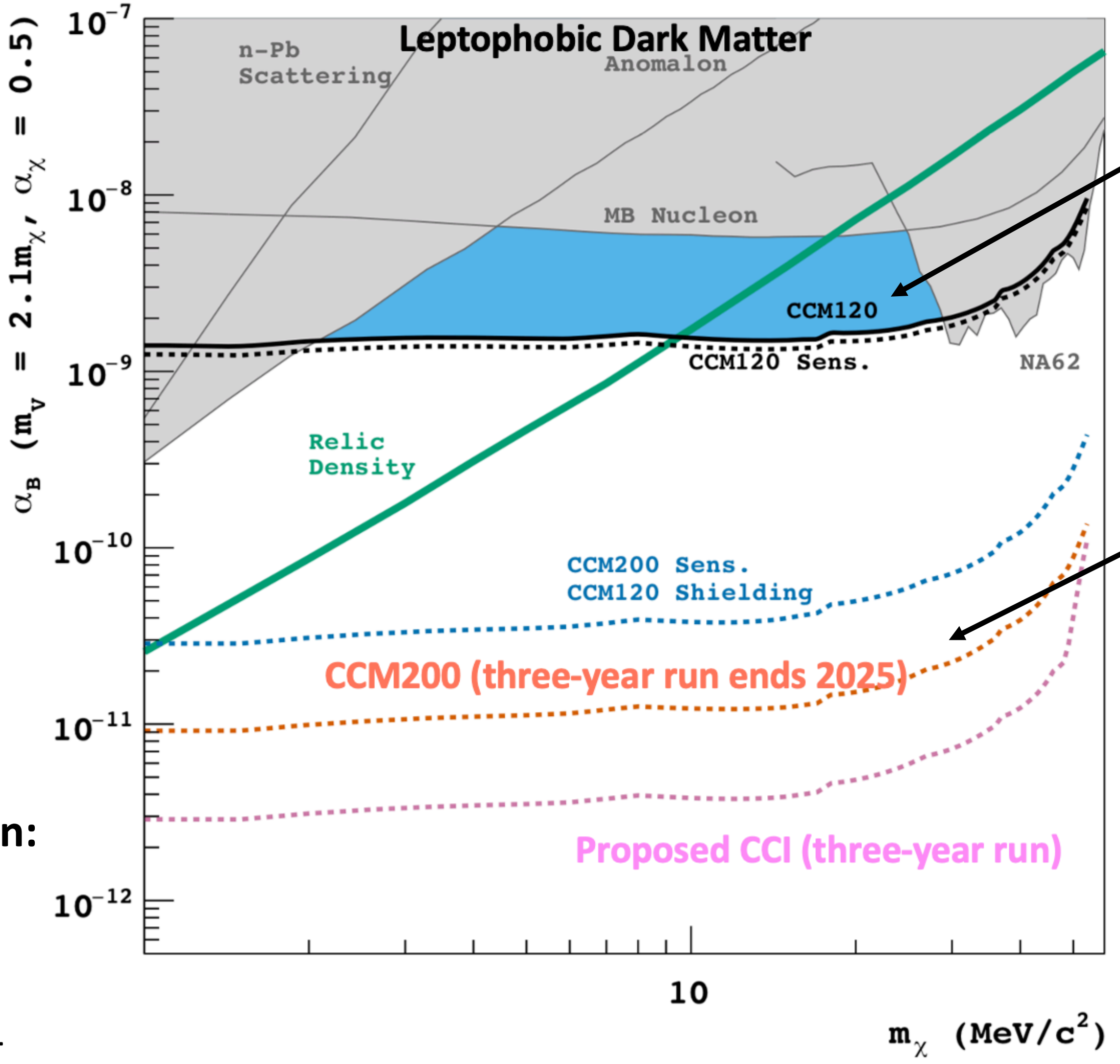
DM Source



DM Coherent Detection



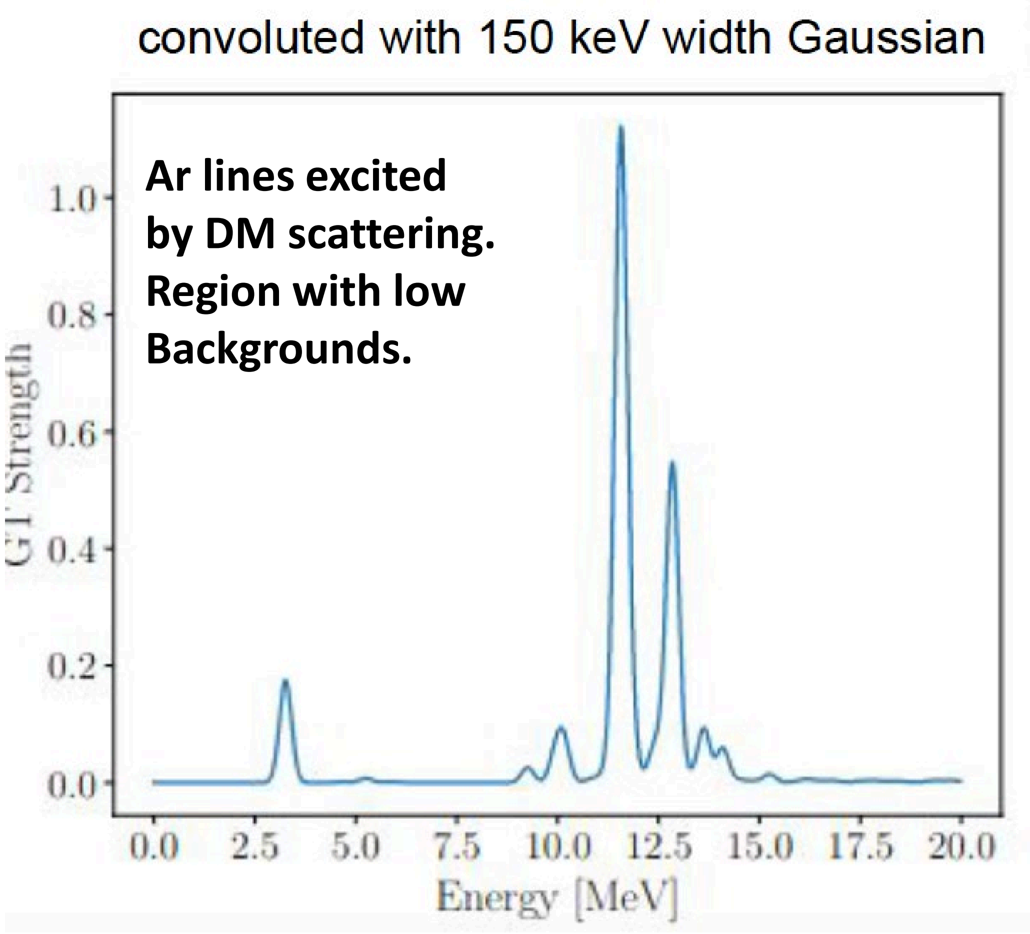
Beam Delivered:
CCM120 run
2019: 1.8E21 POT
CCM200 run with no LAr filtration:
2021: 2.4E21 POT
2022: 2.4E21 POT
CCM200 with filtration
Planned 2023-2025: 2.25E22 POT

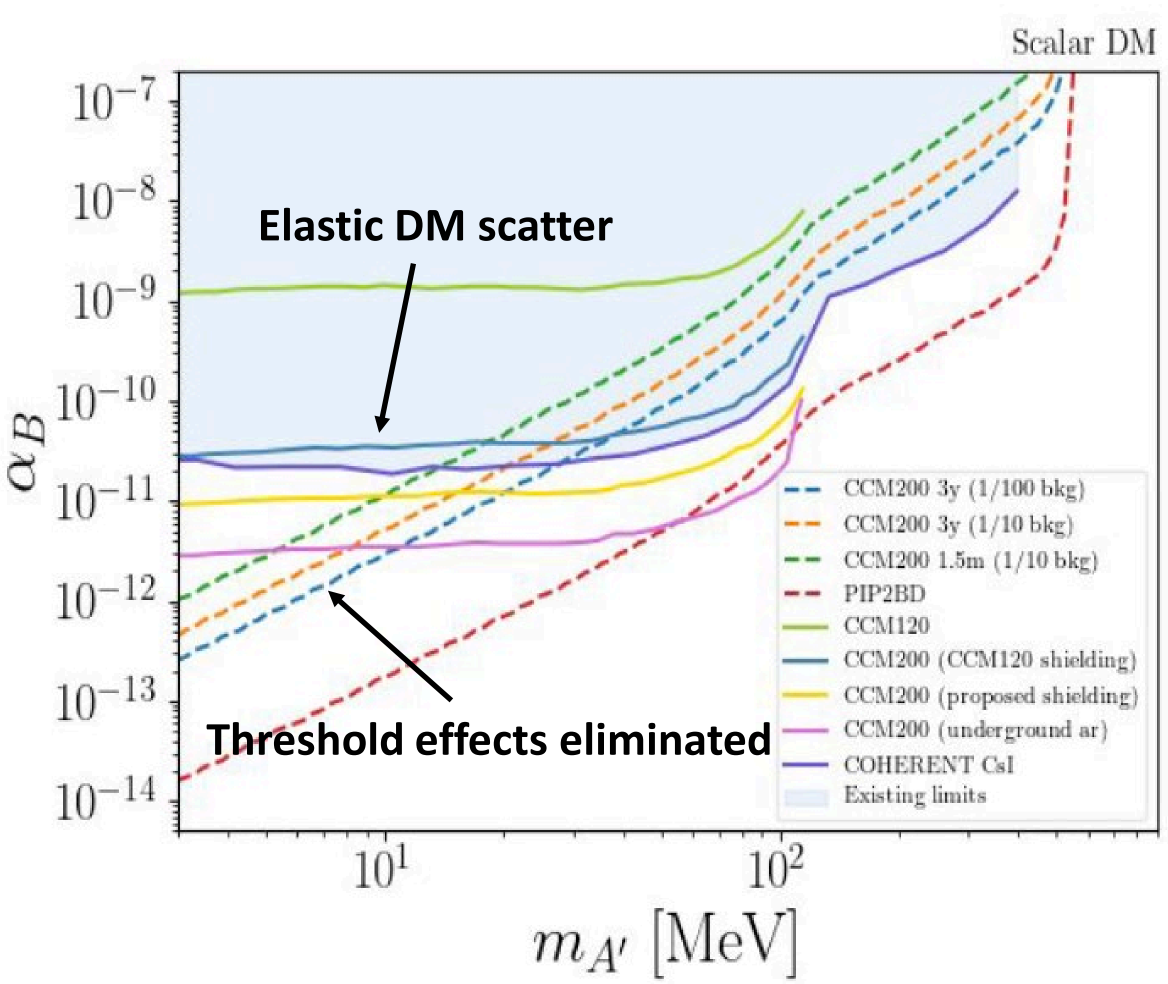


Proves CCM concept with 6-week run in 2019, covers new DM parameter space

CCM200 three-year run 2.25×10^{22} POT with two orders magnitude improvement

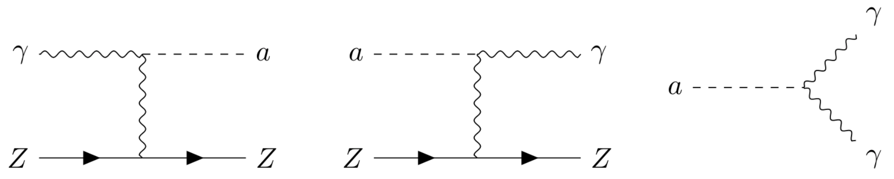
Inelastic DM: Large LAr detectors ideal to detect ~MeV gamma-rays
Reduced threshold effects improves sensitivity at DM low mass

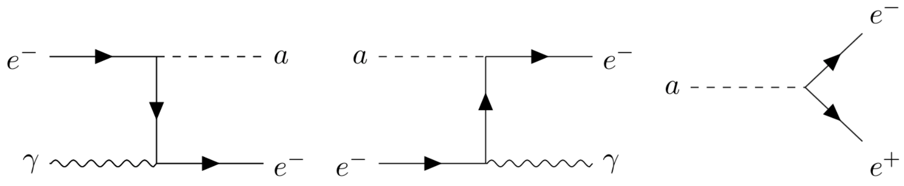


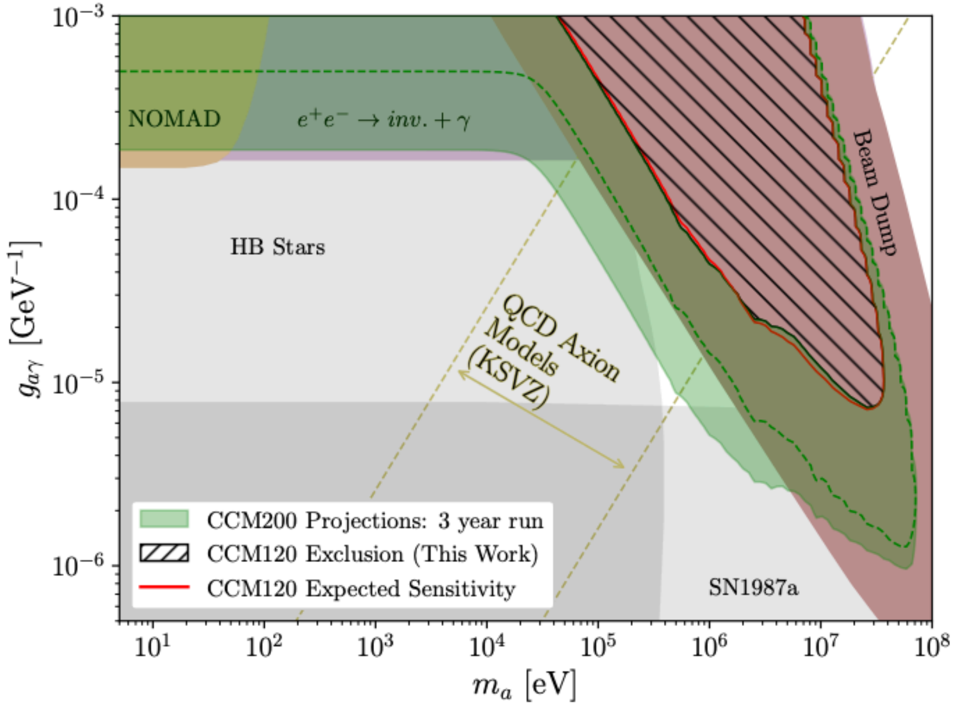


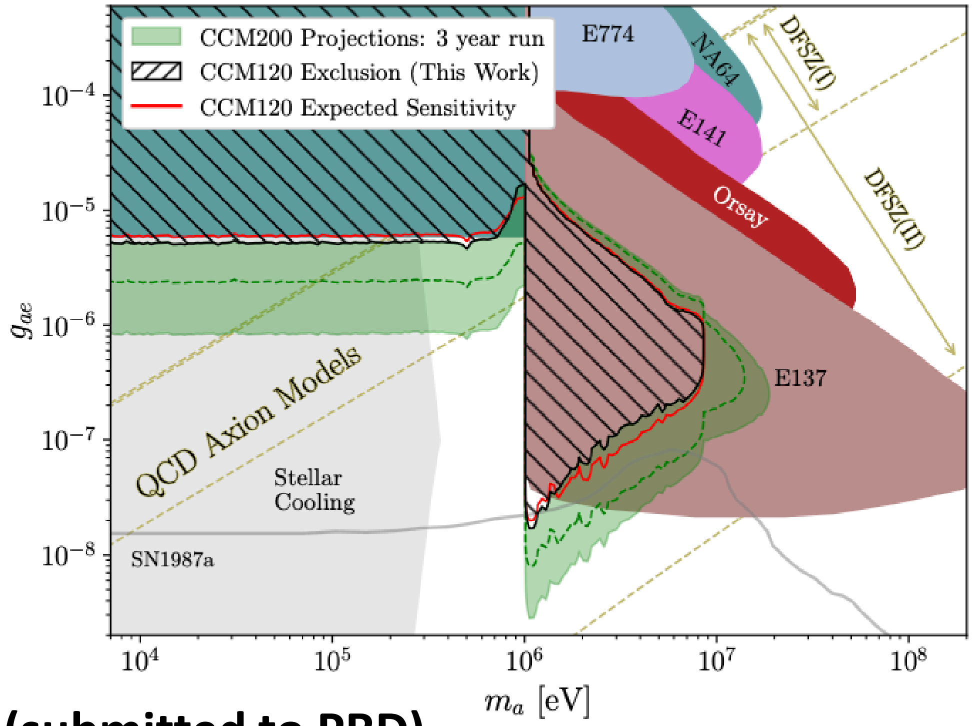
B. Dutta, W.C. Huang, J. L. Newstead and V. Pandey, PRD 106 (2022)

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







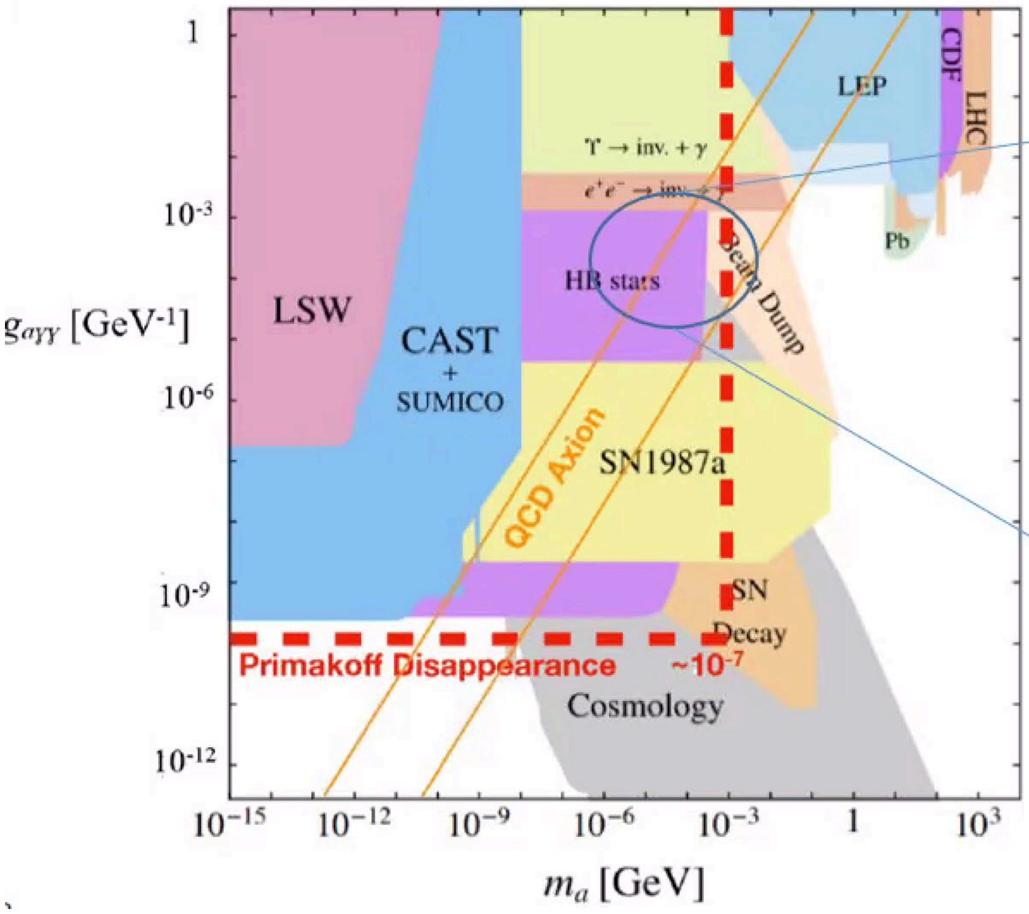


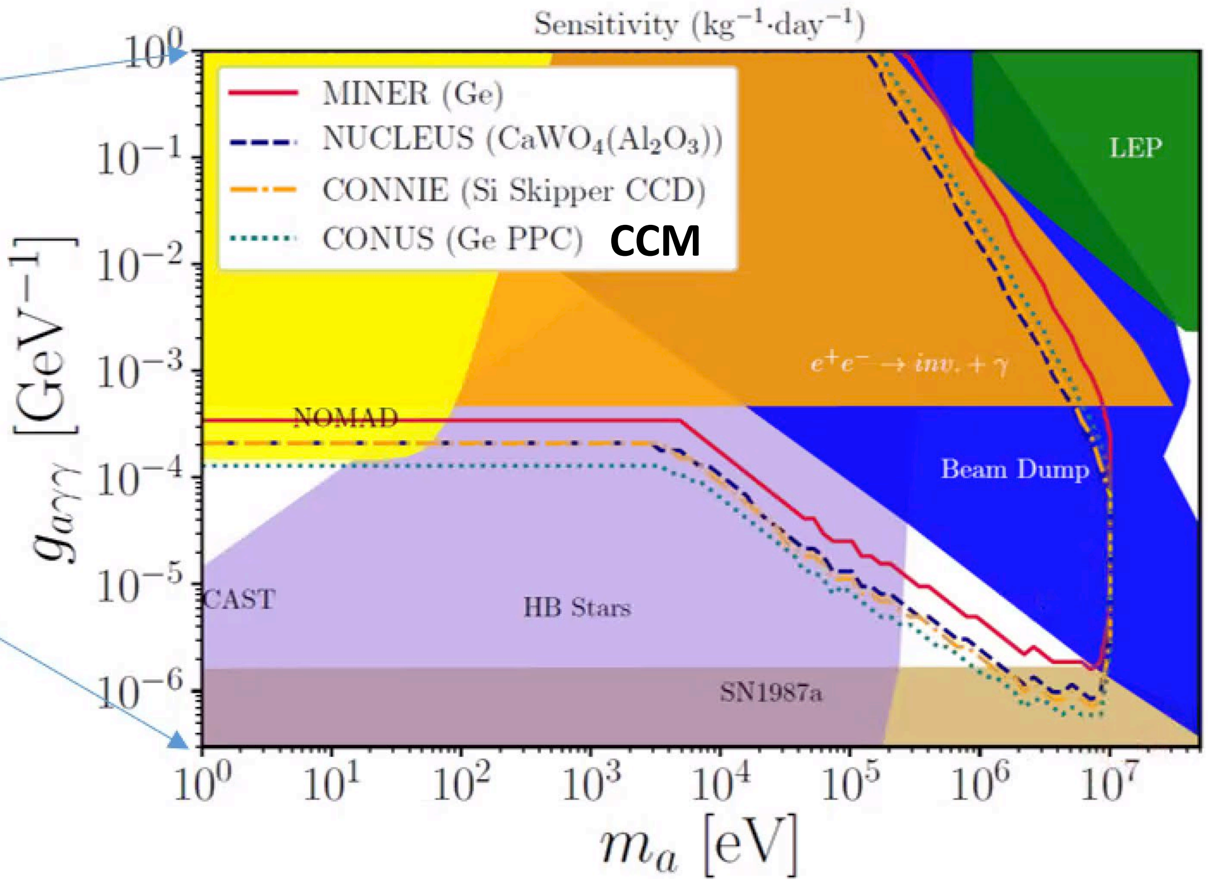
arXiv: 2112:09979 (submitted to PRD)

Dutta, Thompson (Texas A&M)

- CCM will probe untested regions of ALP parameter space around ~MeV, which is also consistent with the QCD Axion.

CCM Probing an interesting and overlooked ALP region around ~MeV motivated by QCD Axion

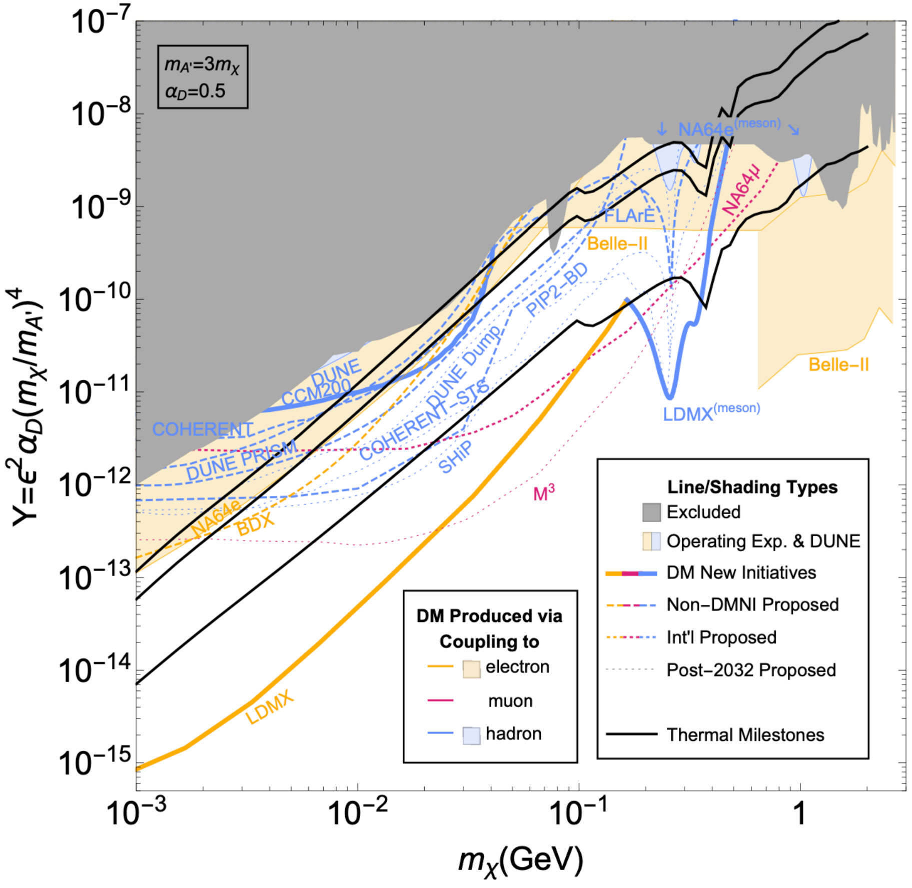




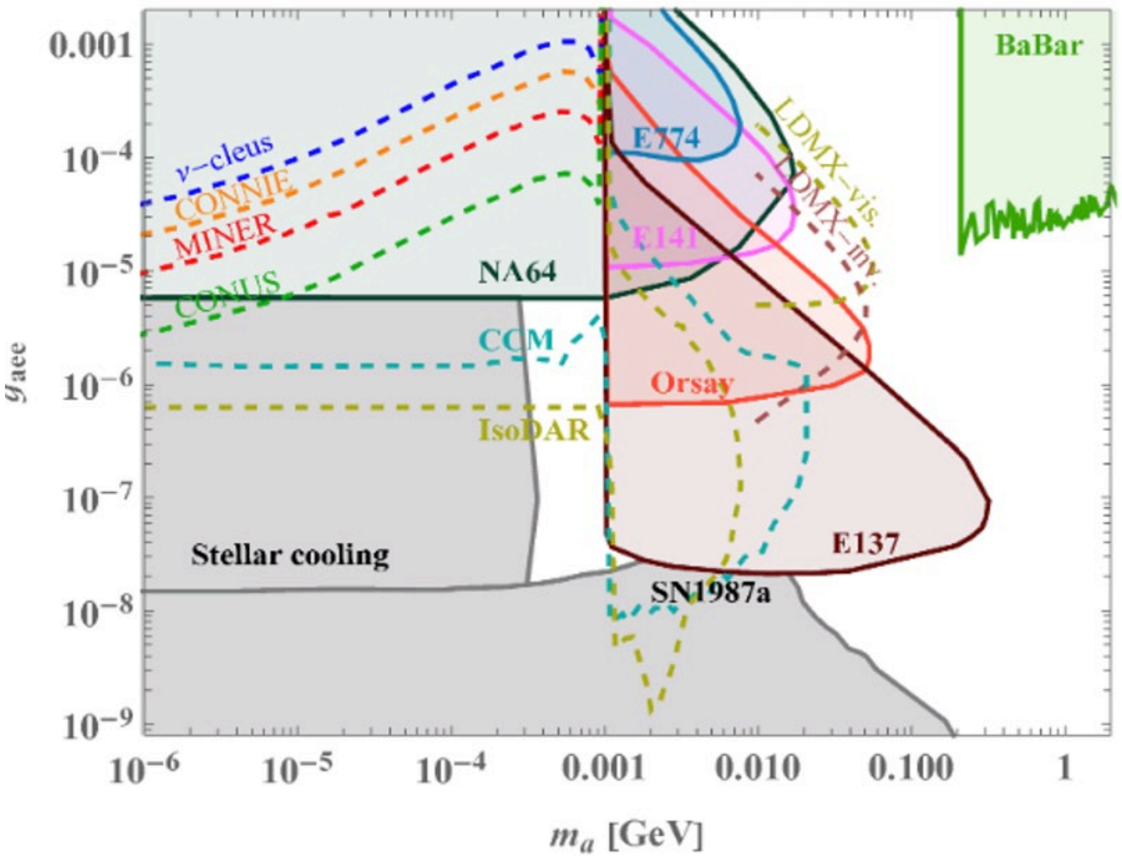
Rupak Mahaptra (TAMU)

CCM Impact: SNOWMASS 2022 (HEP Community Long Range Planning Report)

Dark Matter



Axions



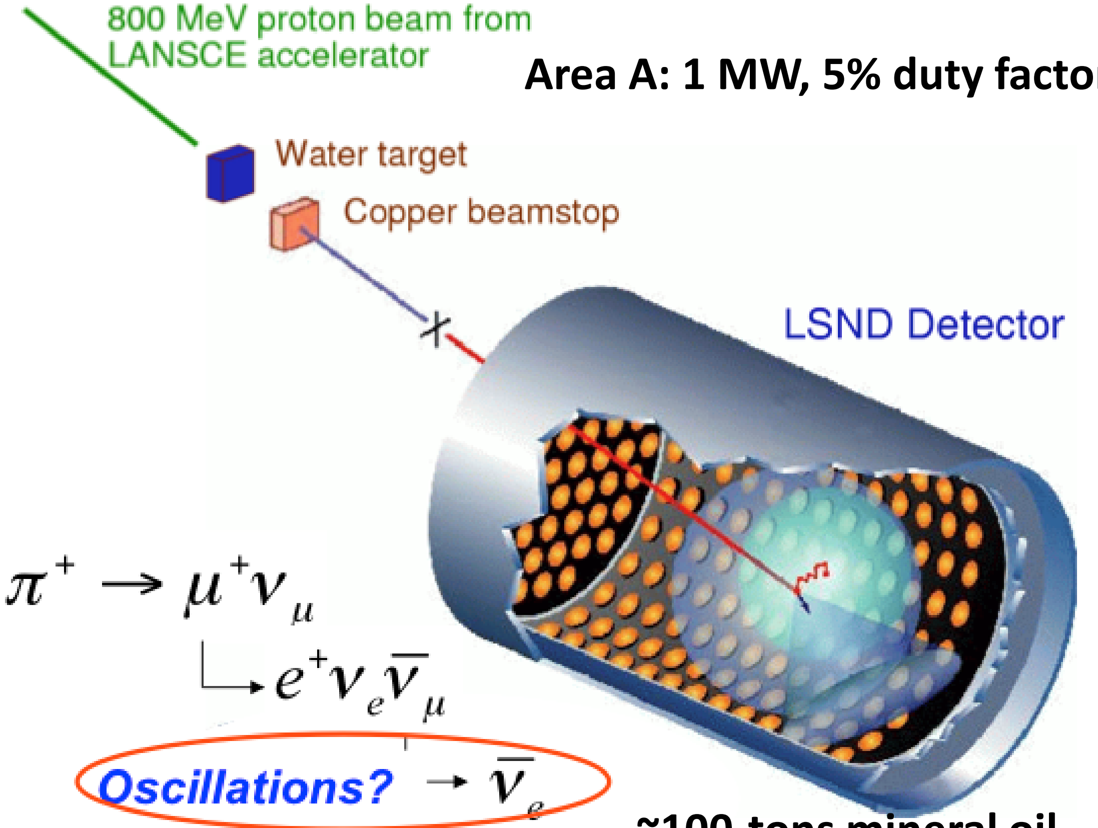
- **CCM is covering new dark sector parameter space near term, other experiments much further into the future and much more expensive!**

The LSND Experiment: Evidence for Oscillations

1995-1998

What makes CCM really exciting!

Area A: 1 MW, 5% duty factor



$\pi^+ \rightarrow \mu^+ \nu_\mu$

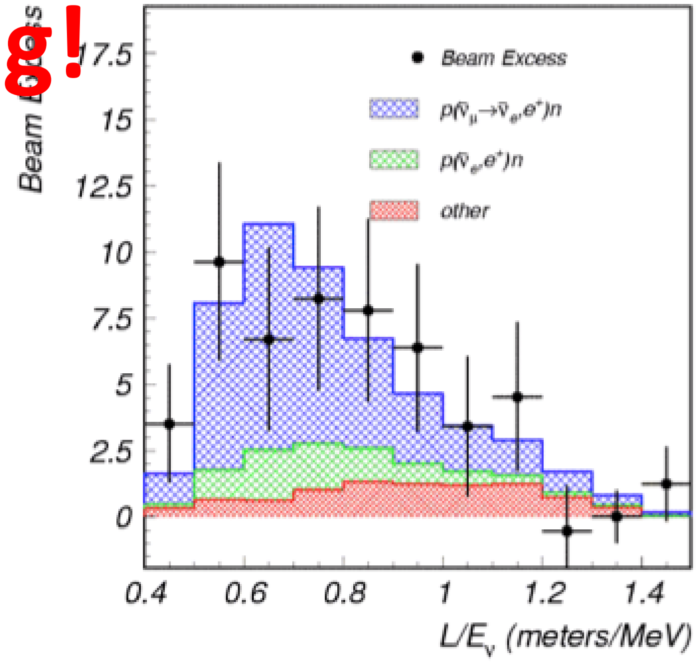
$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

Oscillations? $\rightarrow \bar{\nu}_e$

~100-tons mineral oil,
1200 8" PMT's

Signal: $\bar{\nu}_e\ p \rightarrow e^+\ n$

$\quad \hookrightarrow n\ p \rightarrow d\ \gamma(2.2\text{MeV})$



LSND took data from 1993-98
- 49,000 Coulombs of protons
- L = 30m and 20 < E_ν < 53 MeV

Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

- **CCM (100kW) and LSND (1MW) are both 800 MeV stopped pion source.**
- **CCM lower power, but PSR ~10^{-6} duty factor.**

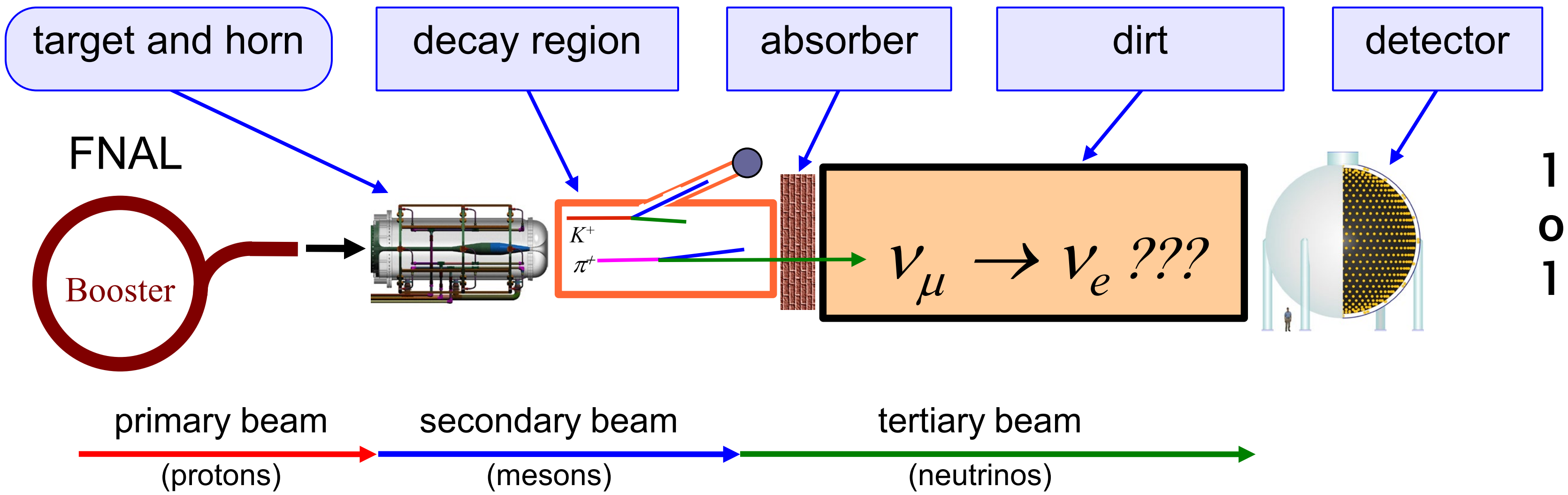
HARP recently announced measurements that confirm LSND $\bar{\nu}_e$ background estimate

MiniBooNE (2003-2018) was designed to test the LSND signal

Keep L/E same as LSND
while changing systematics, energy & event signature

$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$ ➔ Two neutrino fits

LSND:	E ~30 MeV	L ~30 m	L/E ~1
MiniBooNE:	E ~500 MeV	L ~500 m	L/E ~1

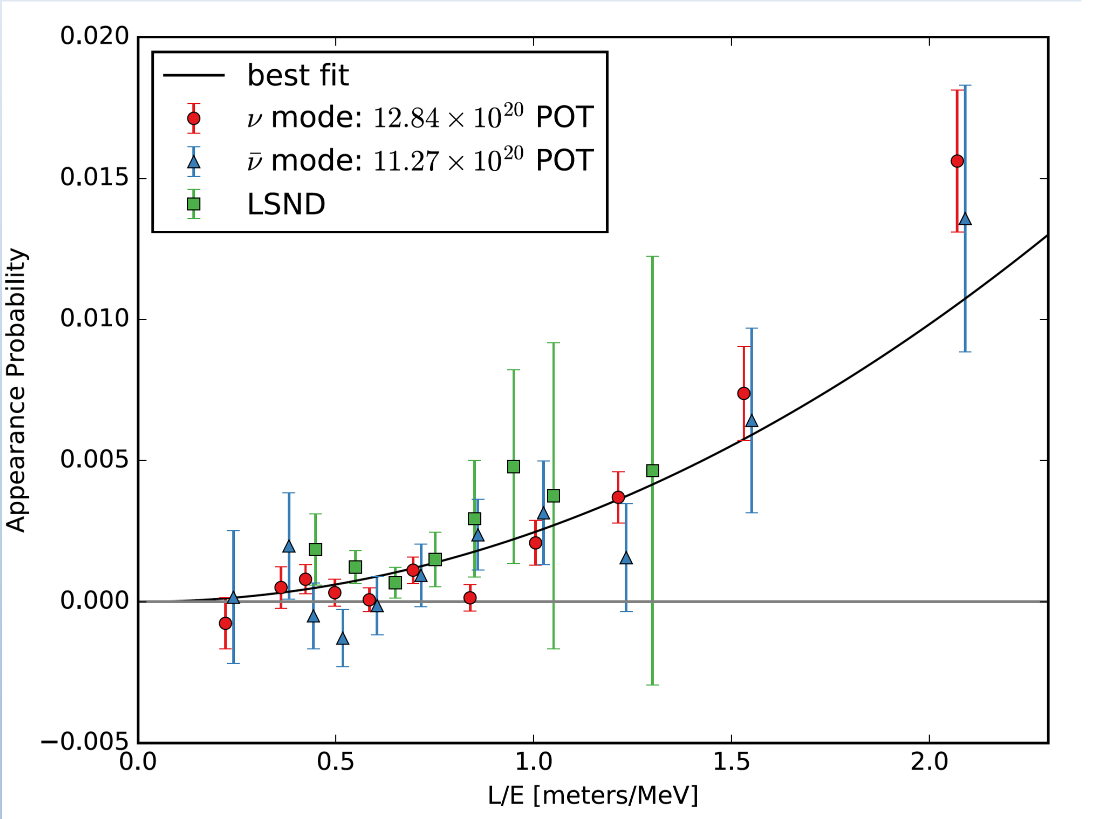


1-kton mineral oil detector, 1500 PMT's

Neutrino mode: search for $\nu_\mu \rightarrow \nu_e$ appearance with 6.5E20 POT ➔ assumes CP/CPT conservation
Antineutrino mode: search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance with 5.66E20 POT ➔ direct test of LSND

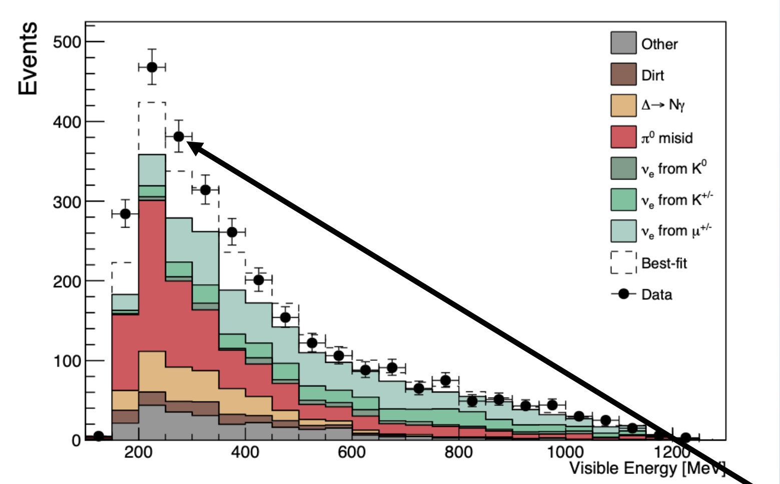
FNAL has done a great job delivering beam!

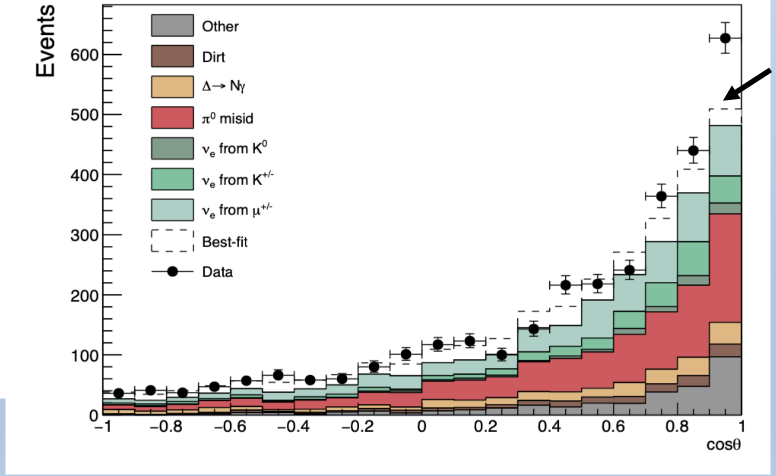
MiniBooNE New Oscillation Results Consistent with LSND



(or as beam dump scaling E_{excess}/E_{beam})

MiniBooNE neutrino mode 18.75E20 POT

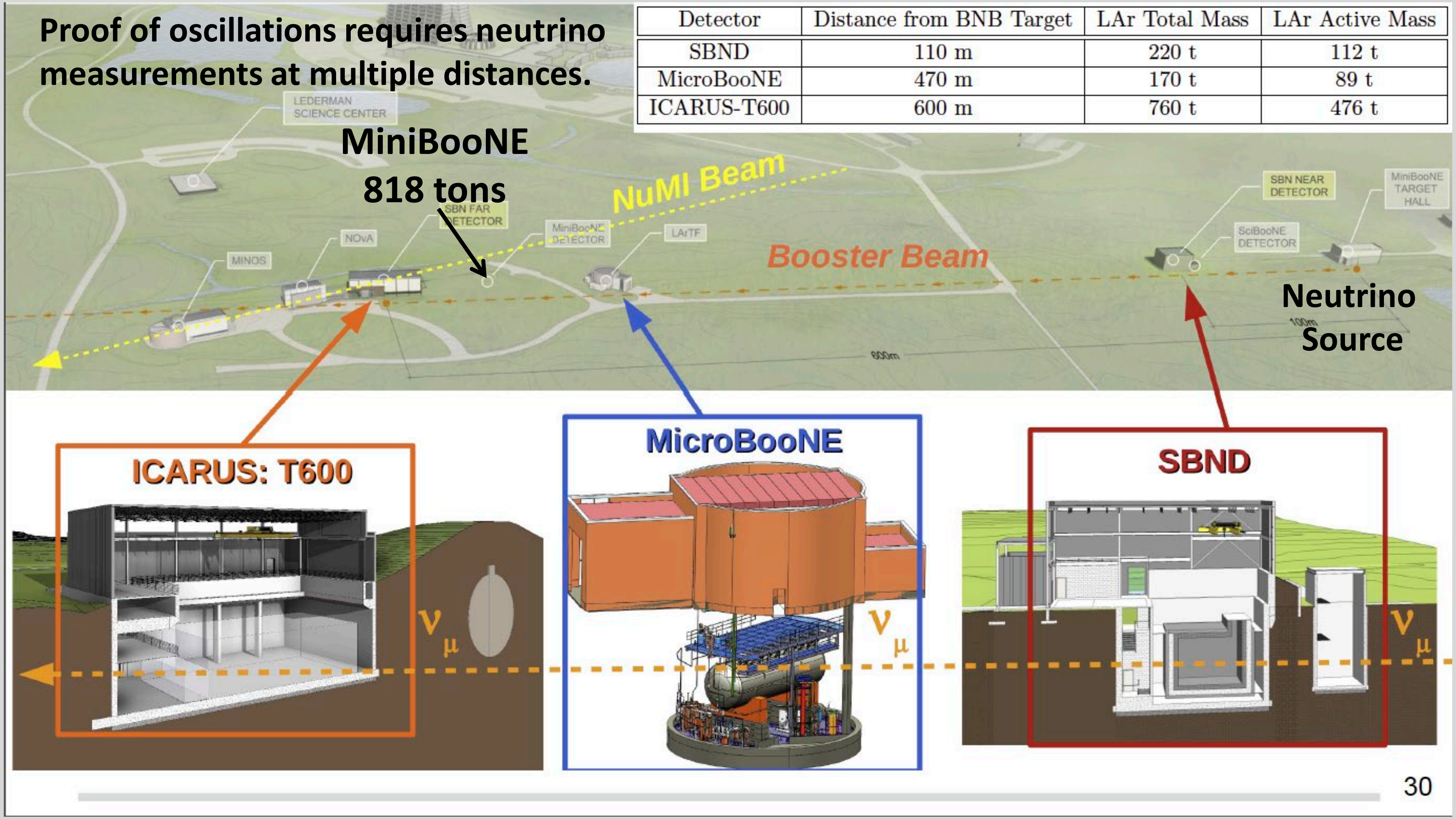




Sterile neutrino fits does not do well at low Evis and small angle

- **MiniBooNE is consistent with LSND excess, and combined is ~6σ**
- **The hunt is on for the nature of the excess, e.g. sterile neutrinos, dark sector, etc.**

LSND/MiniBooNE have motivated the DOE/HEP Short Baseline Neutrino (SBN) Program which will begin operations in 2019



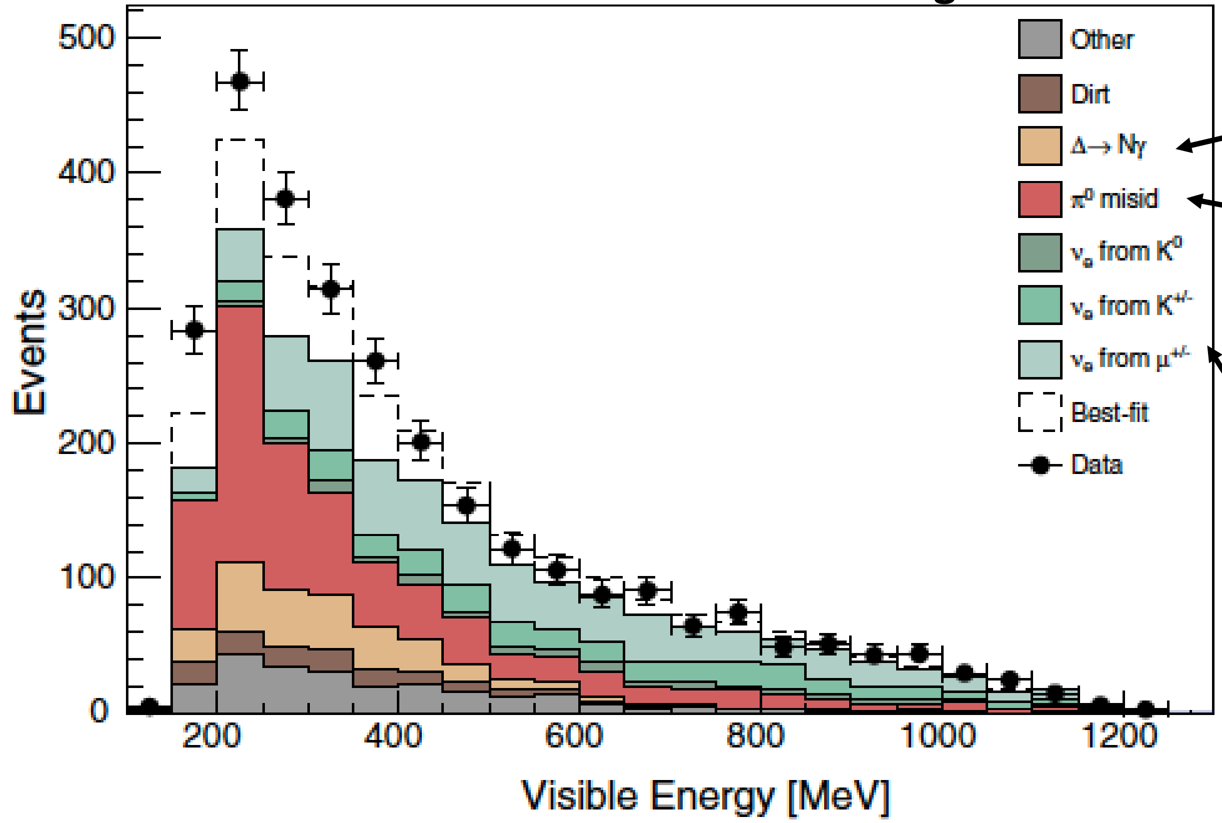
Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
SBND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t

- Initial results from MicroBooNE confirms MiniBooNE background estimates.
- Nature of the excess is stull up in the air!

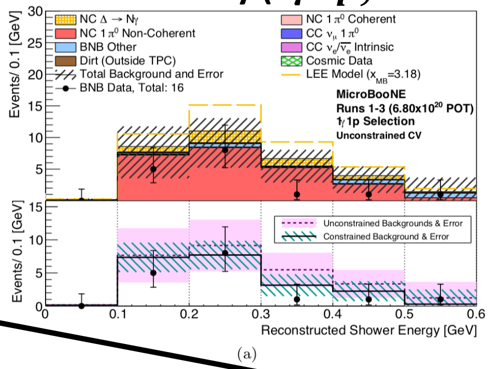
NEW! Explaining the MiniBooNE Excess – Recent MicroBooNE Results (arXiv 2110.00409 + 2110.14054 + other uB papers)

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

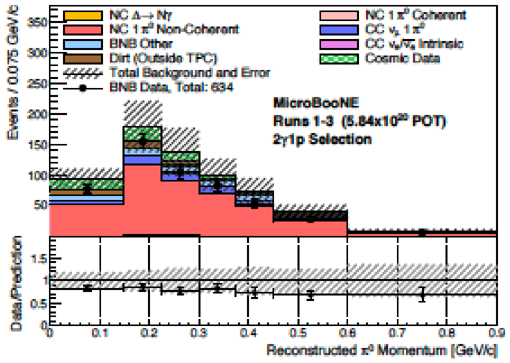
uB confirms MB standard model backgrounds



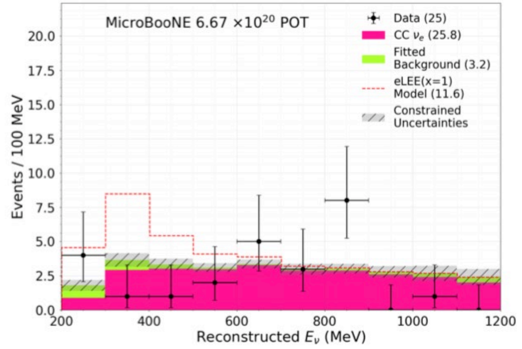
Delta Decay ($1\gamma1p$)



π^0 ($2\gamma1p$)



Intrinsic υ_e (1e1p)



Past Dark Sector Model problems explaining MB excess => coupled to neutral meson decays (POT scaling), but cannot explain excess rates from different run modes

MiniBooNE Anomaly

Can we correlate the excess to charged meson physics?

- Excess events seen in neutrino mode
- Proportionally smaller in anti-neutrino mode
- No significant excess in the dump mode

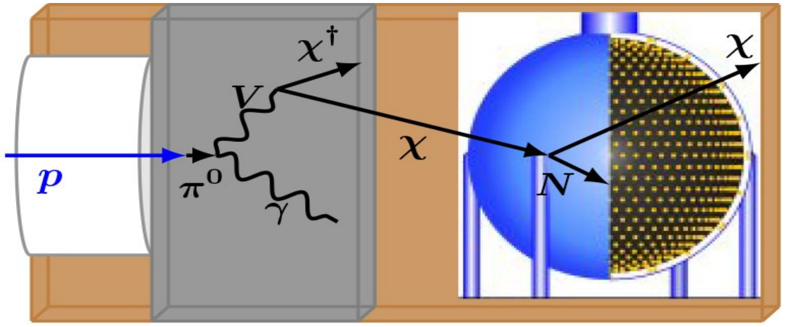
Solutions:

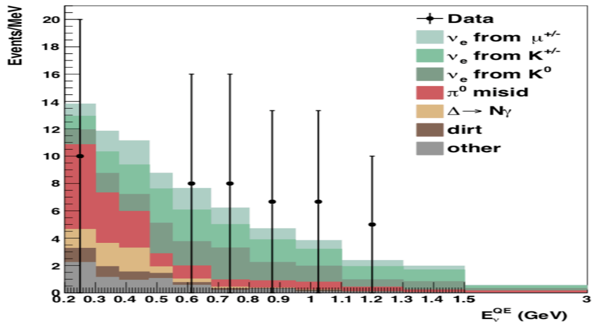
- Solutions in the neutrino sector or from DM sourced by π^0 & dark brem are popular
- However, the relative production of + vs. - mesons and their focusing by the magnetic horns could play a role in the asymmetry of the excess

- **MiniBooNE**, 2021 [2006.16883]
- **MiniBooNE**, 2019 [1807.06137]
- **MiniBooNE**, 2018 [1805.12028]

		Excess	POT	Mesons Focused?
Target Mode	Neutrino Mode	560.6±119.6	1.875E+21	π^+, K^+
	Anti-neutrino Mode	77.4±28.5	1.127E+21	π^-, K^-
Dump Mode		None	1.86E+20	None

pi0 are not focused by horn +/-on/off rates same





MB beam dump excess assuming POT scaling, expect 35.5 ± 7.6, measured -2.8 events

Phys. Rev. D **98**, 112004

NEW Model! Dark Sector particle coupling to charged meson decays can explain MiniBooNE/LSND excesses

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

Described by FNAL theorist as #1 Model!

Phys. Rev. Lett. 129 (2022) 11, 111803
(arXiv: 2110.11944)

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

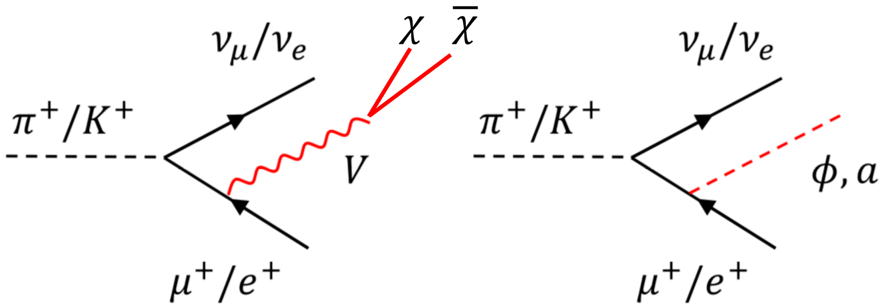


FIG. 1. Three-body charged meson decay into a scalar, pseudoscalar, or vector.

Detection involves gamma-like only final states

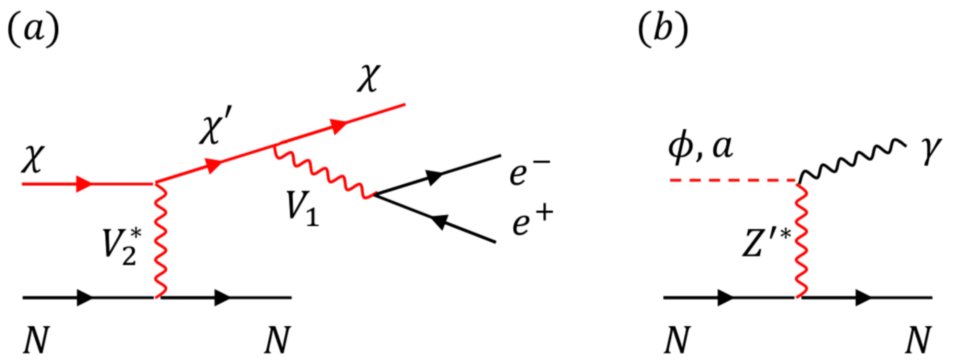
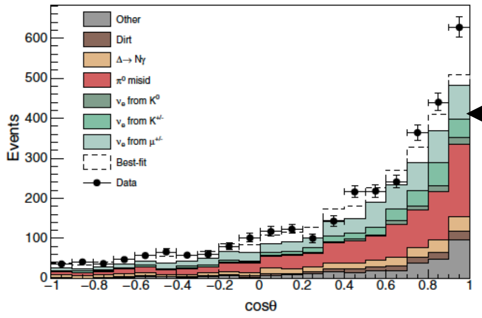


FIG. 2. (a): Dark-matter upscattering via a vector mediator. In the single-mediator scenario, $V_2 = V_1$. (b): "Dark Primakoff" scattering of a scalar ϕ or pseudoscalar a via a light Z'.

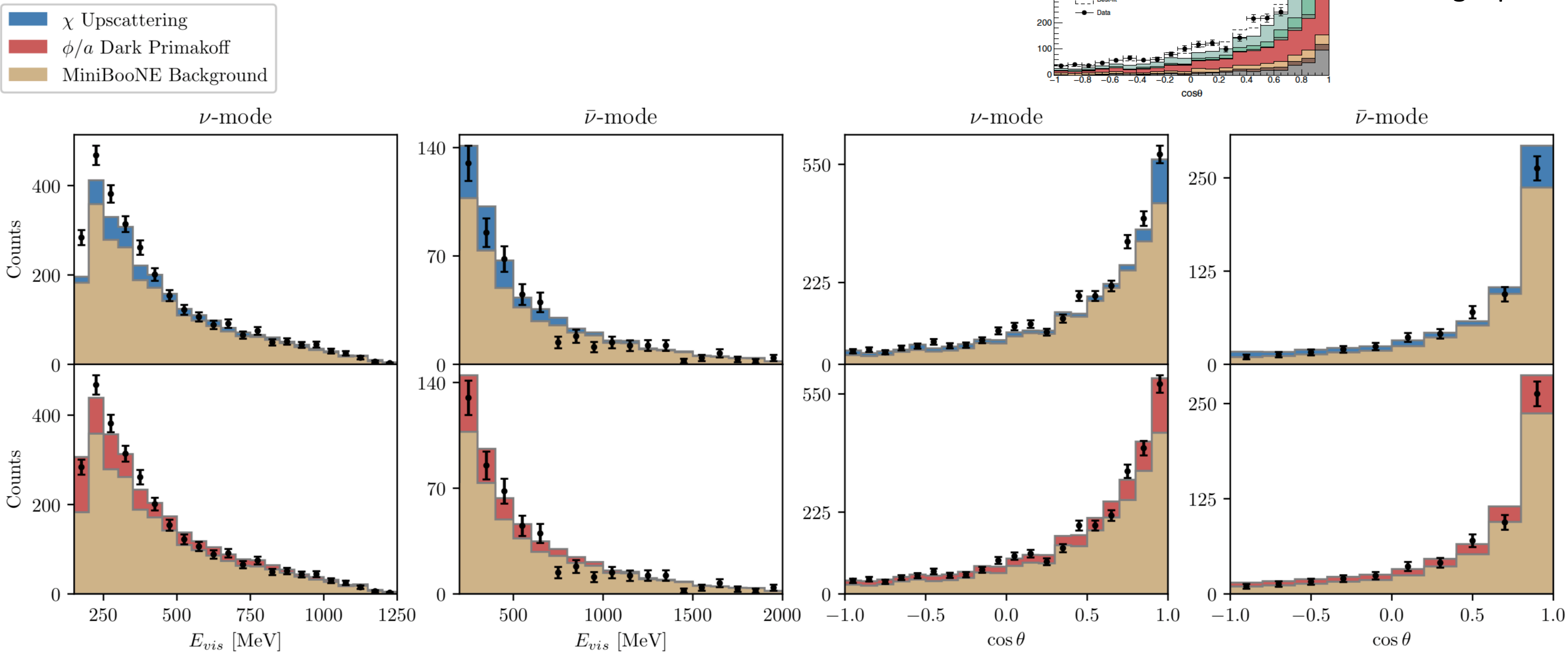
Coupling of dark sector particles to charged mesons (instead of π^0) decays focused by horn ensure correct event rates for neutrino, antineutrino, and beam dump modes.

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.

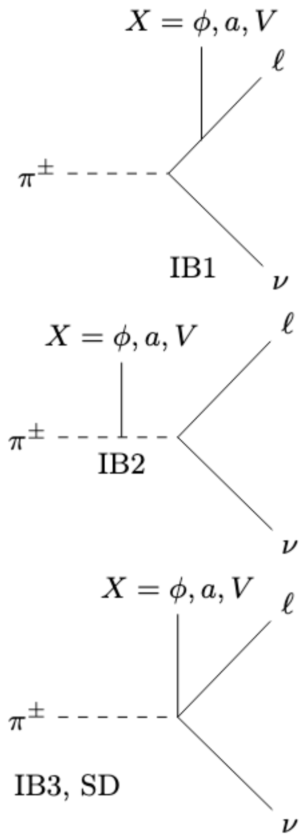
Fits MB event rates well (neutrino, anti-neutrino, beam dump), gets both visible energy and scatter angle better



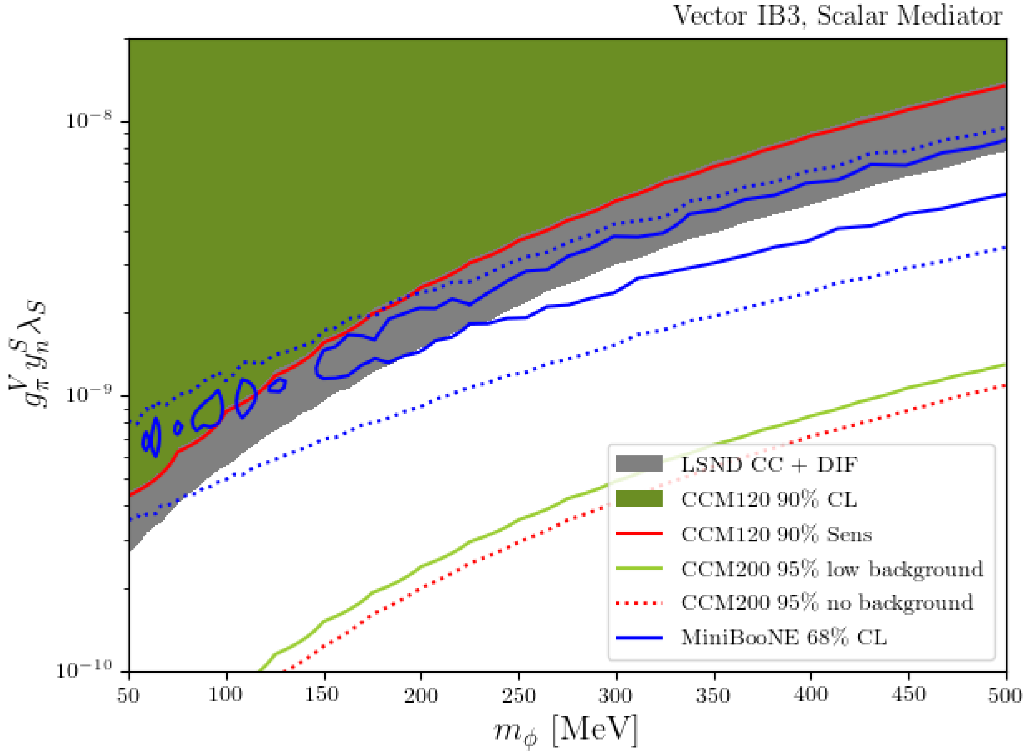
sterile nu model fit angle poorly

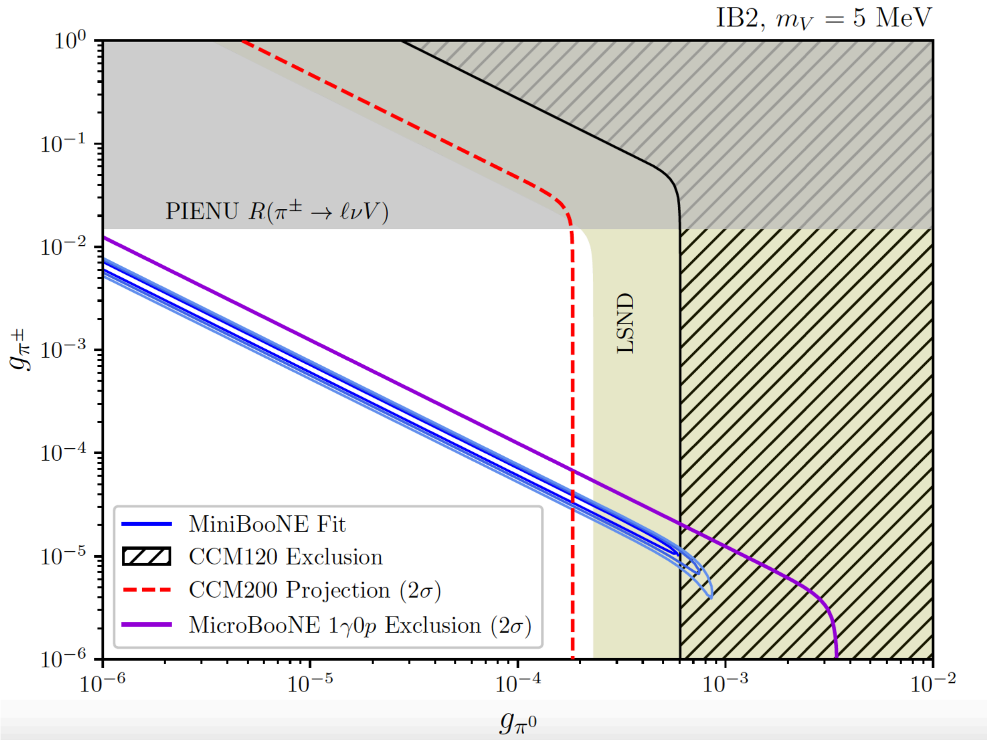


CCM Testing Dark Sector Interpretation of Short Baseline Anomalies in the next three years



Preliminary





A. Thompson (TAMU) – CCM paper in preparation

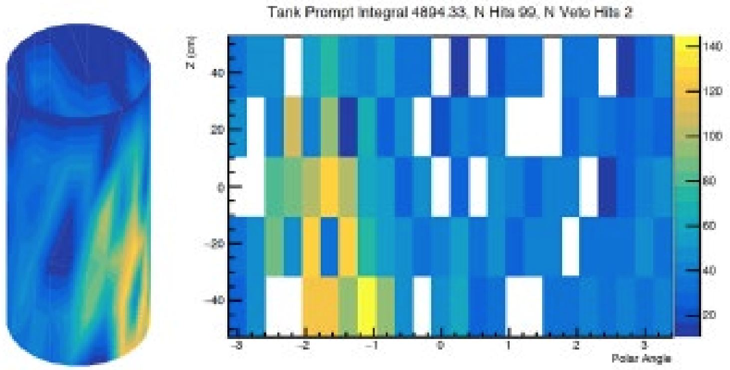
Planned CCM Analysis Upgrades:

Searching for Cherenkov signal in CCM on an event-by-event basis:

1) First event-by-event id of Cherenkov light.
    20% uncoated PMTs isolate prompt visible light.
    TPB will convert prompt UV Cherenkov light.
3) Reduce CCM backgrounds through pointing.
4) Improve light simulations in LAr detectors

Observering Cherenkov light in Scintillator detectors is of mch interest (NuDOT, Borexino, etc.).
Potentially could be used in large or ultra-large detector
Oil/water scintillator absorbs UV Cherenkov light
  – not true in LAr... More Cherenkov photons!
Other properties are very similar

Property	Water	LAr
Density (g/cm^3)	1	1.4
Radiation length (cm)	36.1	14.0
MIP dE/dx (MeV/cm)	1.9	2.1
Refractive index (visible)	1.33	1.24
Cherenkov angle	42^o	36^o
$d^2N/dEdx$ (eV^{-1}cm^{-1})	160	130



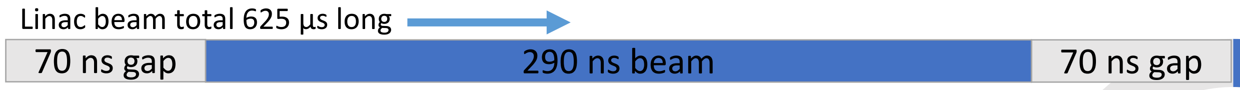
MIT led analysis

- **Cherenkov light rejects neutron backgrounds and provide event directionality wrt beam**

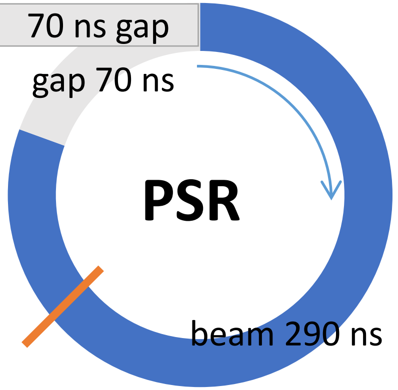
CCM Upgrade: Shorter Pulse Length at LANSCE Proton Storage Ring

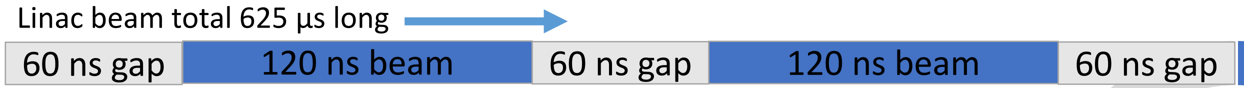
- Shorter Pulse at PSR provides
  - greater rejection power for BSM experiments
  - reduced uncertainties in neutron TOF/energy measurement
- Funded by LANL LDRD ER, starting this September
  - Beam development starting at the second year
- **Extensive and fast tracked LANSCE upgrades during this decade. One possibility is for PSR to have three times more intensity and 30 nsec beam width**

En-Chuan Huang (LANL)

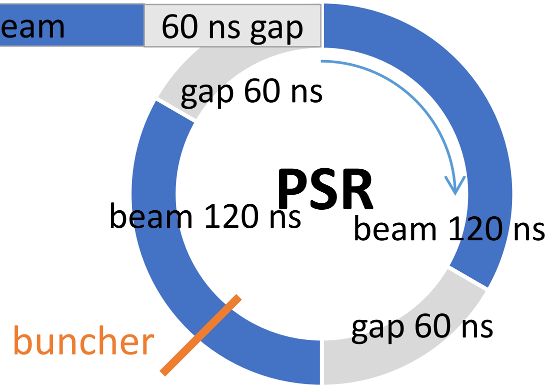


Current beam structure:
- PSR stacks one 290-ns pulse
- Beam is delivered to Lujan Center at 20 Hz
- Buncher runs at 2.8 MHz





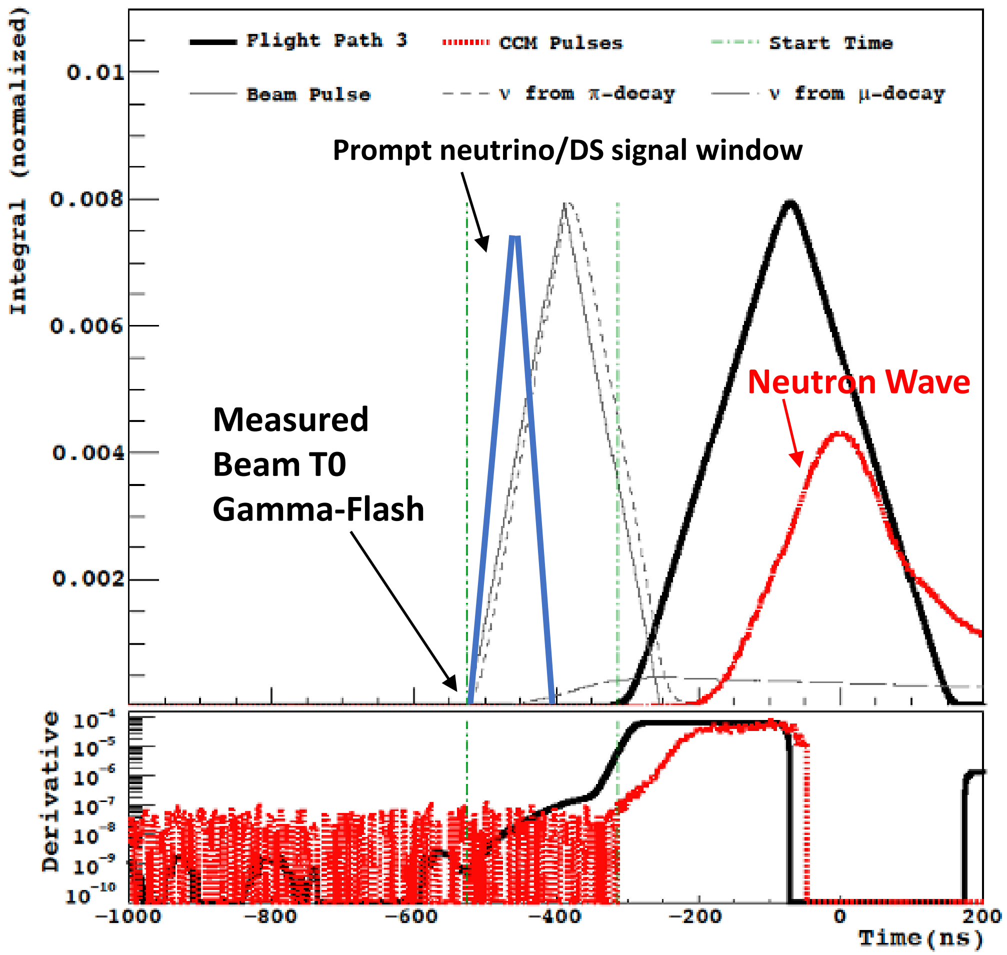
Proposed beam structure:
- PSR stacks two 120-ns pulse
- Two pulses are extracted at different time.
- Beam is delivered to Lujan Center at 40 Hz
- Buncher runs at 5.6 MHz



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

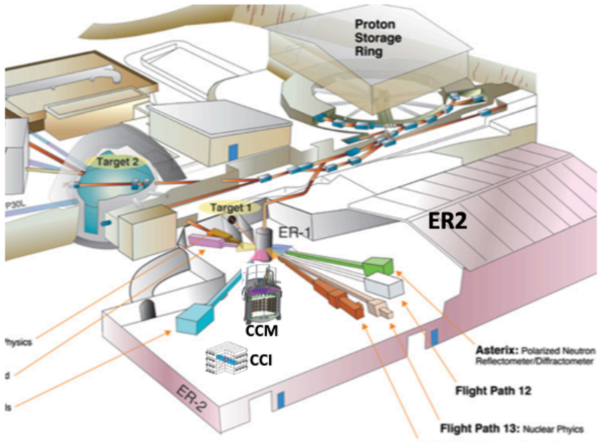
BSM signal tracks beam profile which would be very unique signature!

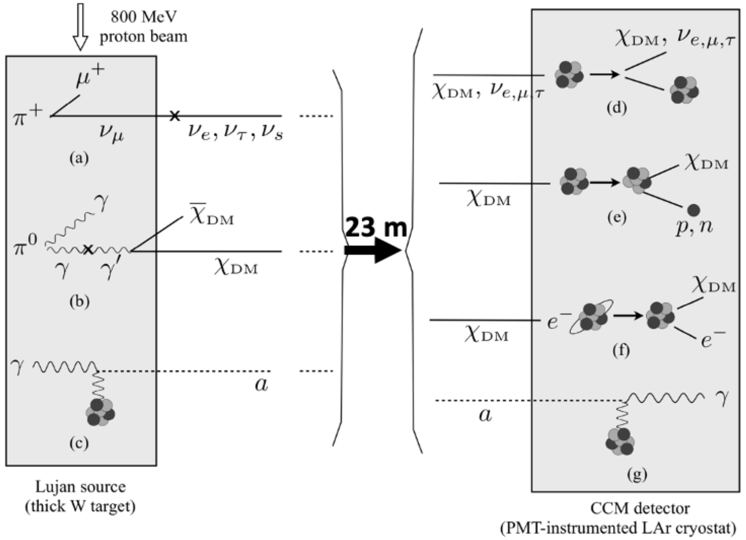
- If we shorten PSR pulse from 290 nsec to **120 nsec (Blue),** would increase signal efficiency and reduce random backgrounds, estimate increase **S/B (120 nsec) > 25**.
  - Factor ~2.5 reduction in random backgrounds from Ar39 and neutron activation
  - Factor ~10 reduction of EM events relative to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

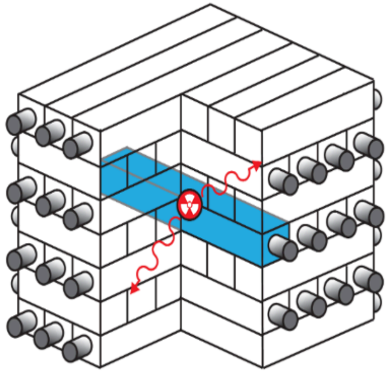
Future: Short Pulse and Coherent Cesium Iodide (CCI)

- AOT working to shorten Proton Storage Ring (PSR) pulse to 120 nsec, or more.
- Seeking LDRD, HEP, NSF, and Sloan funding to build a >1-ton CsI detector. Working with P-1, P-2, T, AOT, ISR, and with our TAMU partners.
- Exceptional sensitivity about order magnitude better than CCM for dark sector particle searches – low background, high event rate, extremely fast, compact detector. Complementary to CCM, especially if a signal is observed.

800 MeV protons, 100kW, 290 nsec pulsed beam





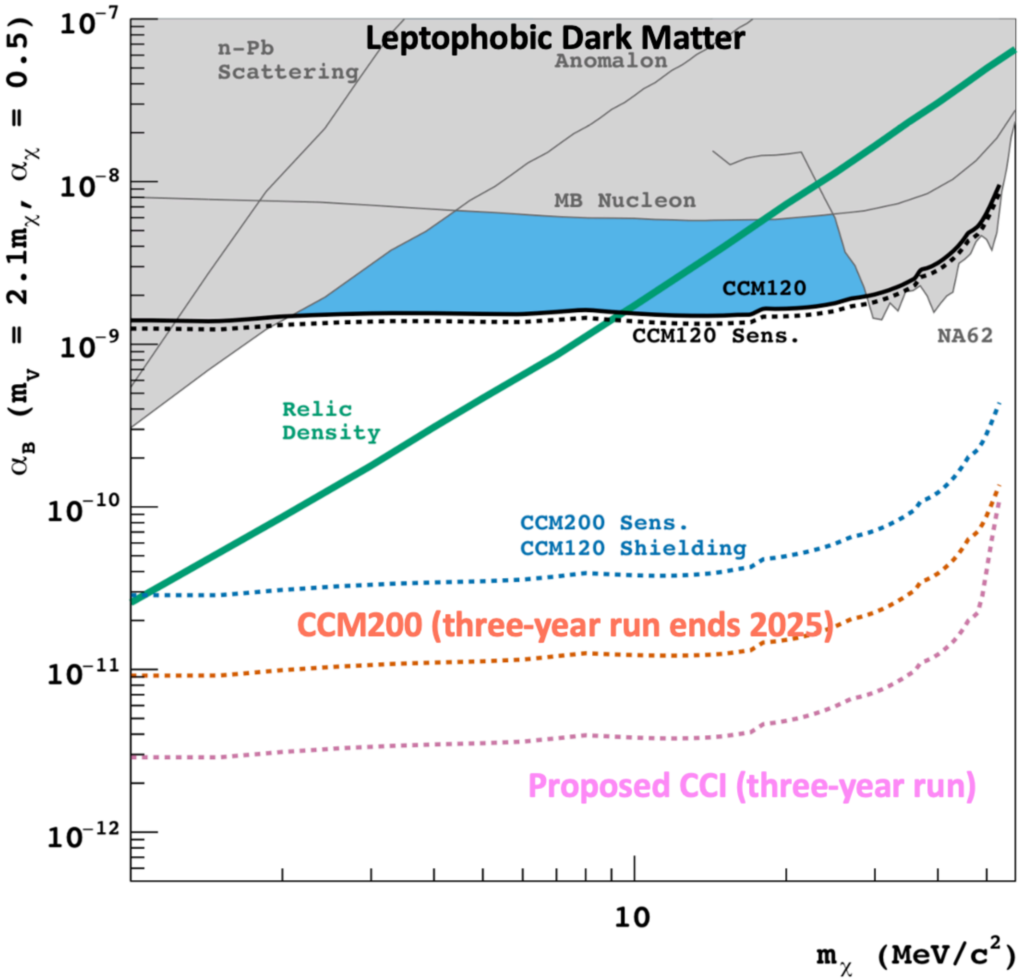


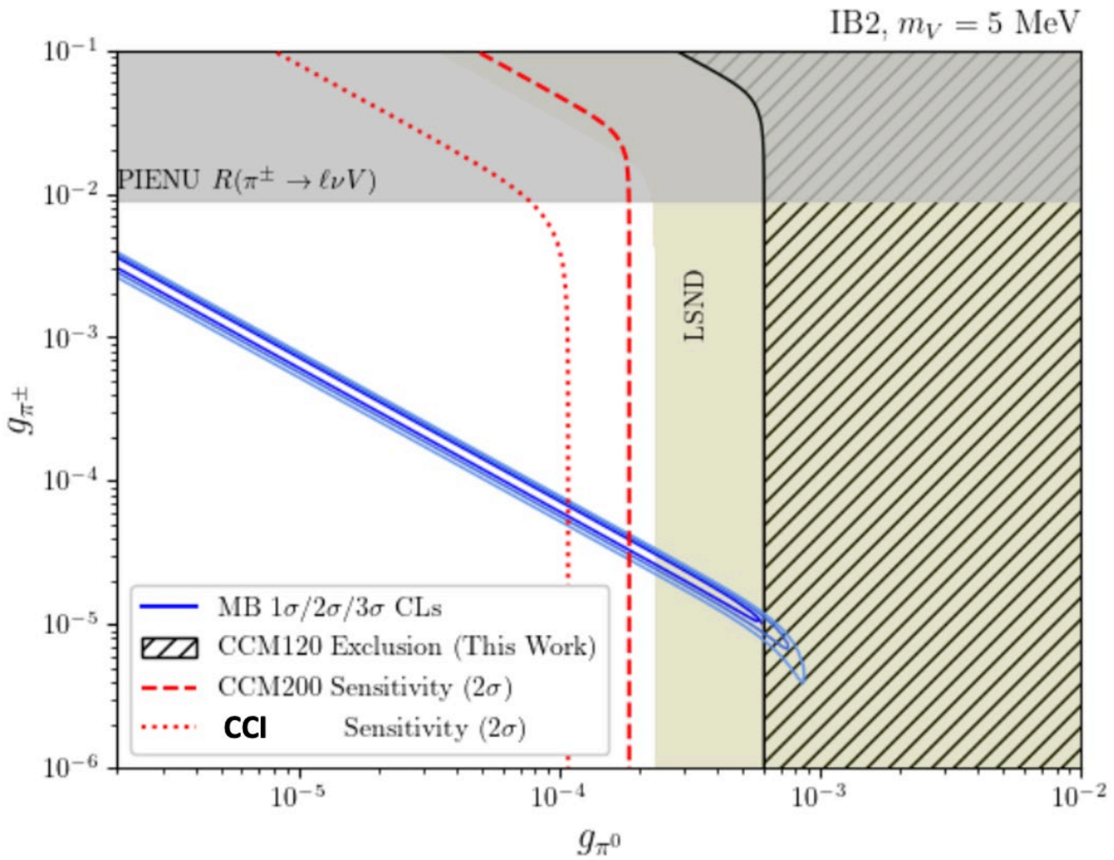
one-ton CCI (pure)

Extremely fast detector: Undoped CsI ~30 nsec scintillation time constant

LANSCE/CCM/CCI would remain competitive till the end of the decade.

CCM/CCI important input to testing dark matter, ALPs, and understanding short-baseline anomalies





Adrian Thompson (TAMU)

Low Energy nue CC cross sections for DUNE SN Search: Estimated event rates at CCM

$$N_{ev} = \phi \cdot N_T \cdot Exp \cdot \sigma \cdot \epsilon$$

Finally:

$$N_{ev} = (3.96\text{E+5 } \nu s^{-1} \ cm^{-2})(7.54\text{E+28})(1.34\text{E+7 s/year}) \times \begin{cases} 1.504\text{E-39 } cm^{-2} \times 0.5 & \text{(CEvNS)} \\ 1.908\text{E-40 } cm^{-2} \times 0.75 & \text{(CC)} \\ 1.759\text{E-41 } cm^{-2} \times 0.75 & \text{(NC)} \end{cases}$$

Includes detection efficiency

	Total events/year*
CEvNS (ν_μ)	300.82
CC (ν_e)	57.25
NC (ν_μ)	5.28

Marisol Chavez (UNAM-Mexico)

*6 months of running, at 23 m, for 5 tons. E_ν =30 MeV.

Three year CCM run will result in ~16% nue CC cross section measurement, flux average around ~35 MeV, includes background subtraction and flux errors

Summary: New Exciting Opportunities for Accelerators!

- **Exciting decade** as 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.
- **LANSCE and CCM are leading accelerator dark sector searches.** Unique features make it ideal - fast beam time and high power, robust detector design, key experimental and theoretical personnel, outstanding institutional support (LDRD, Lujan, AOT, HPC, PDO/ALDPS).
- **CCM successfully built by LDRD funds and beginning a three-year HEP funded run** that will directly probe a rich list of dark sector physics and test the dark sector interpretation of the MiniBooNE excess. Expect many new CCM results in the next 2-3 years building on our already successful publication record.
- **Developing follow on experiment CCI and upgrades to LANSCE-PSR** that can continue the dark sector leadership throughout this decade.

Backups: The Neutrino/DS Scatters Here!

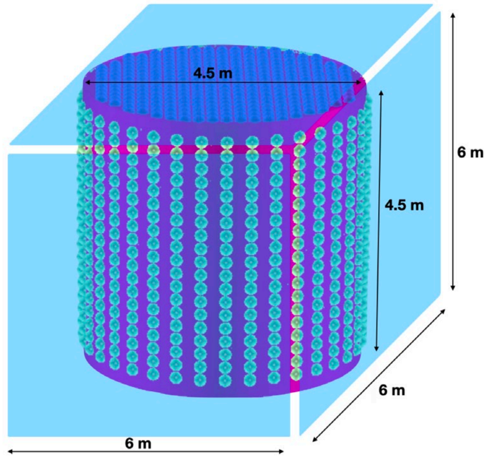
New Dedicated Facility: FNAL Proton Beam Dump @ 1 GeV: PIP2-BD

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

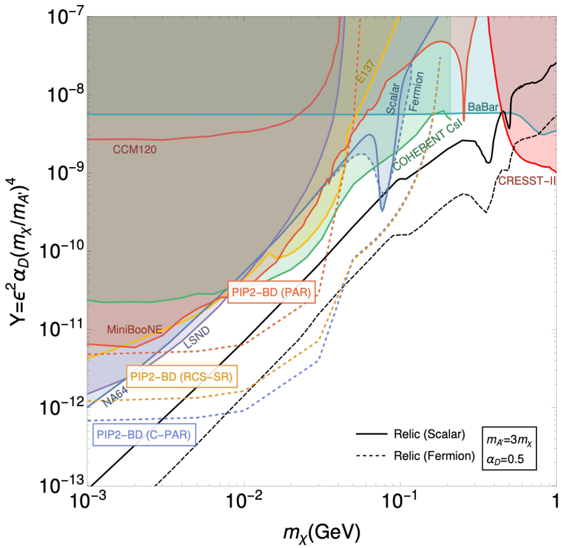
- Same technology as CCM-200

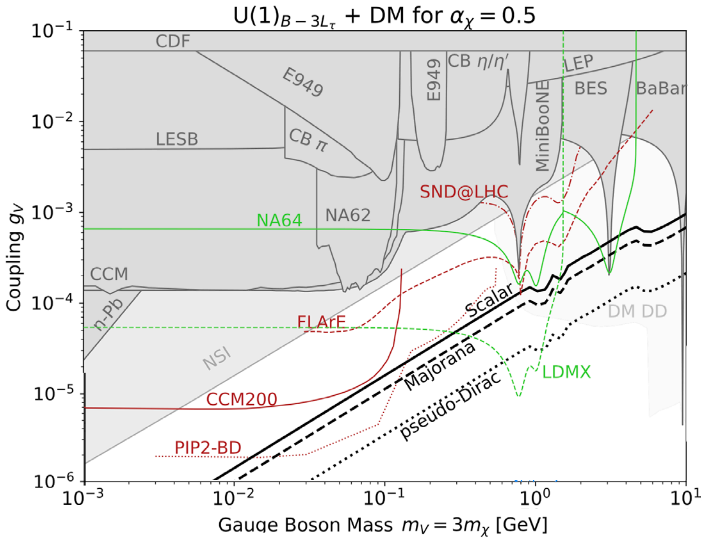
World-leading dark sector sensitivity, especially to hadrophilic dark matter, ALPs

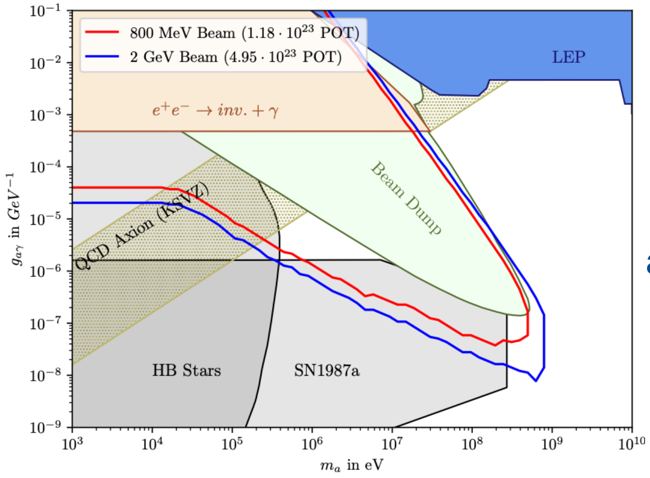
- Also supports definitive active-sterile neutrino oscillation search, neutrino cross sections measurements, etc.



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

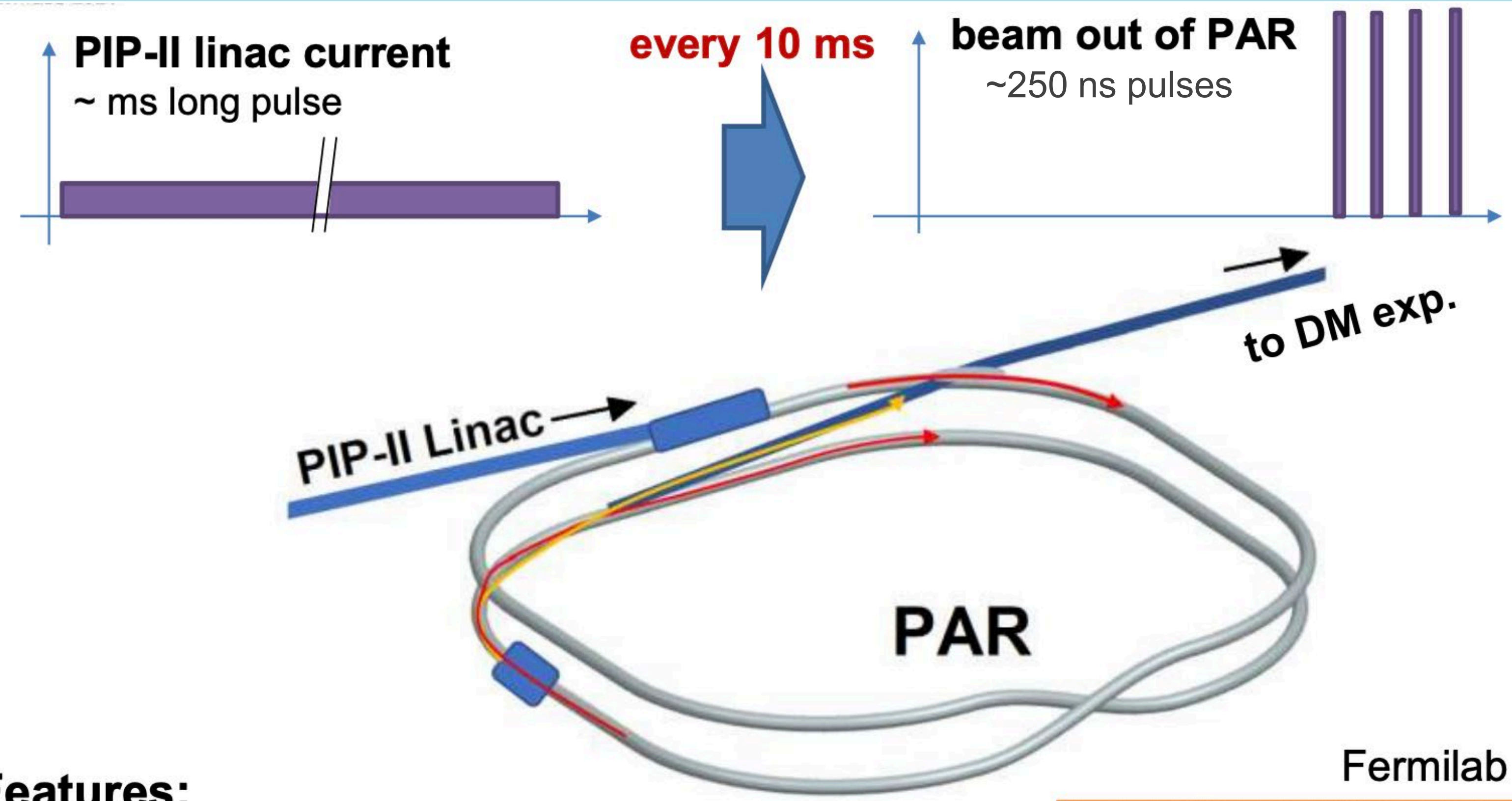






arXiv:2203.08079

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)

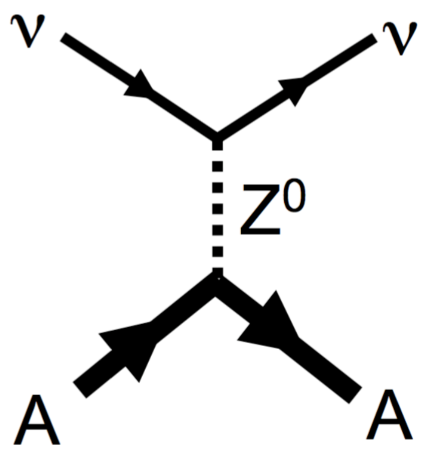
Fermilab

Slide from Kate Scholberg

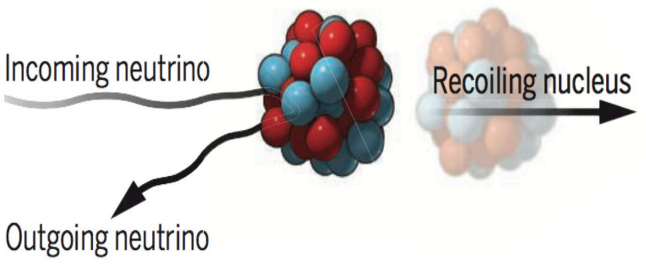
Coherent elastic neutrino-nucleus scattering (CEvNS)

ν + A → ν + A

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



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

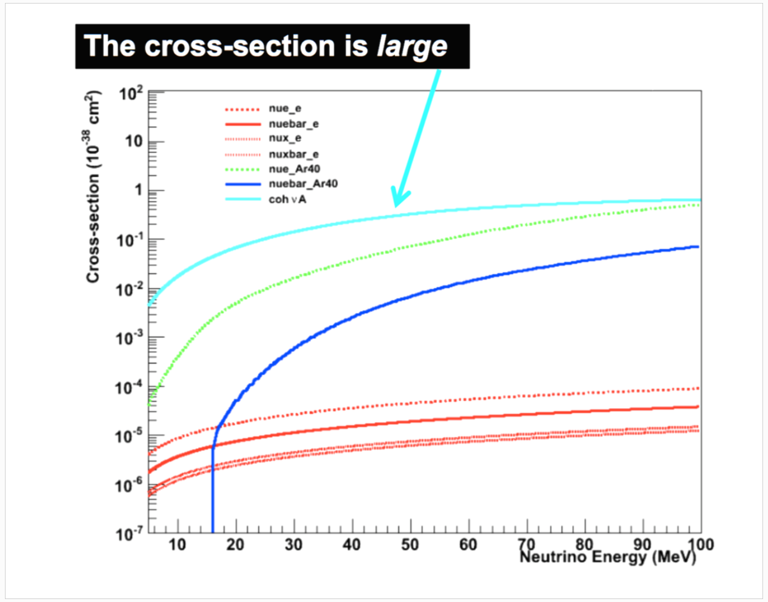


- **Low energy nucleus recoil E ~ 10’s keV**
- Well-calculable cross-section in SM: SM test, probe of neutrino NSI
- Dark matter direct detection background
- Possible applications (reactor monitoring)

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

$$\propto N^2$$

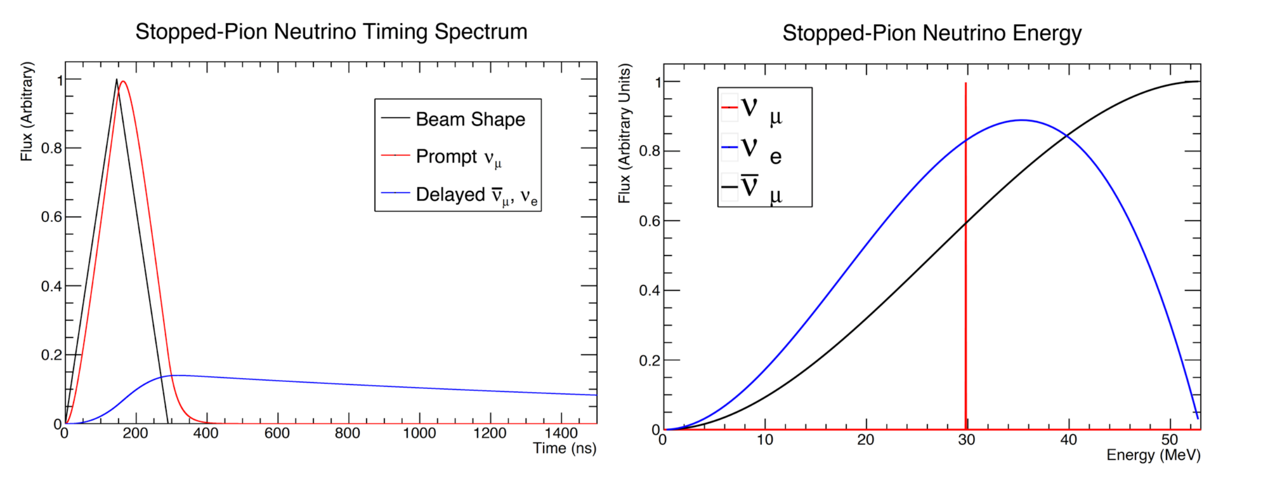
Expected CAPTAIN-Mills LAr Event Rates for Three Years



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



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

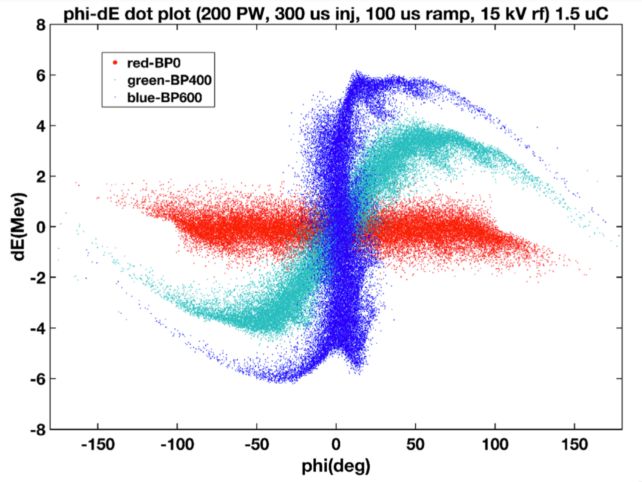
Colorado argon will be at the heart of dark matter exper

1 of 2

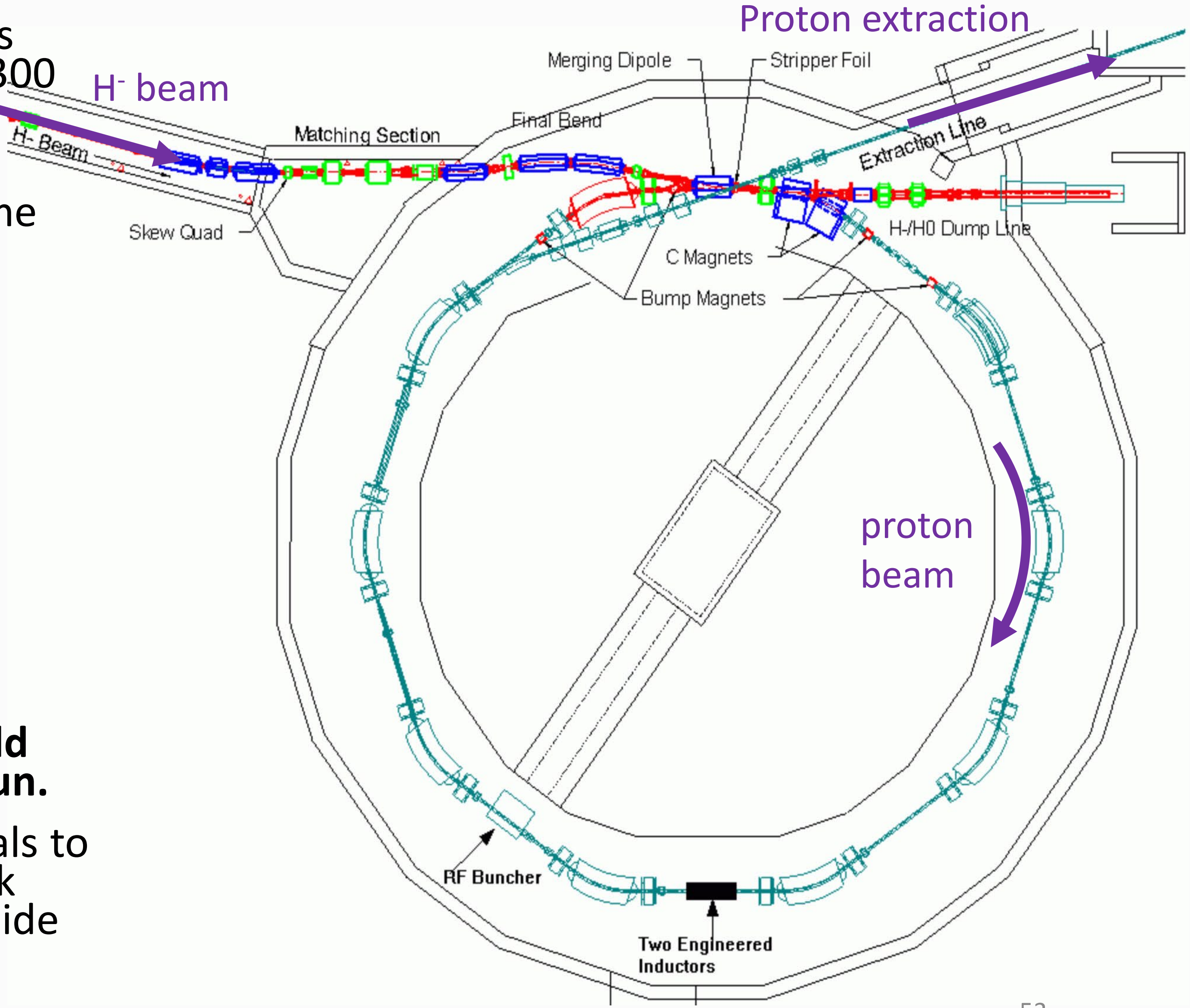
Kinder Morgan plant operator Joe Buffington, left, and operations supervisor Stan Mannis look over Fermilab's argon-extraction unit that they call "a little plant within our plant" north of Cortez.

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

- 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



Phenomenological Model

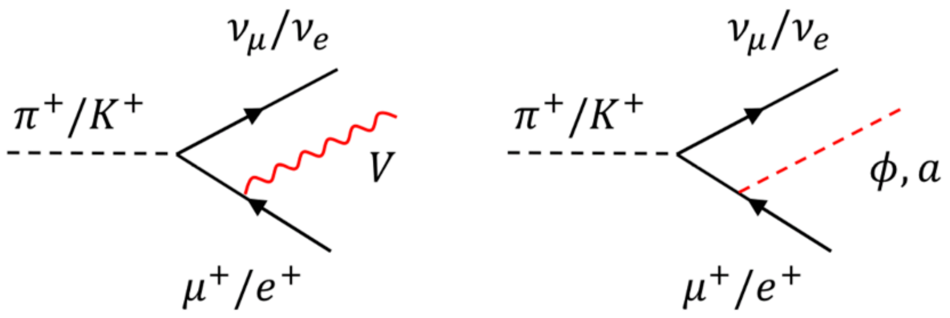
Long-lived Scalar or Pseudoscalar

$$\mathscr{L}_S \supset g_\mu \phi \bar{\mu}\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4}\phi F'_{\mu\nu}F^{\mu\nu} + i\kappa Z'_\mu \phi \partial^\mu \phi^* + \frac{1}{2}m_\phi^2 \phi^* \phi + \frac{1}{2}m_Z^2 Z'_\alpha Z'^\alpha + \text{h.c.}$$

$$\mathscr{L}_P \supset i g_\mu a \bar{\mu}\gamma^5 \mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4} a F'_{\mu\nu}\tilde{F}^{\mu\nu} + i\kappa Z'_\mu a \partial^\mu a^* + \frac{1}{2}m_a^2 a^* a + \frac{1}{2}m_Z^2 Z'_\alpha Z'^\alpha + \text{h.c.}$$

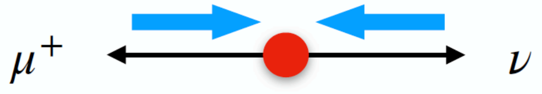
Vector Coupling (dark photon)

$$-\mathcal{L}_{V,\text{int}} \supset e(\epsilon_1 V_{1,\mu} + \epsilon_2 V_{2,\mu})J^\mu_{\text{EM}} + (g_1 V_{1,\mu} + g_2 V_{2,\mu})J^\mu_D + (g'_1 V_{1,\mu} + g'_2 V_{2,\mu})J'^\mu_D$$

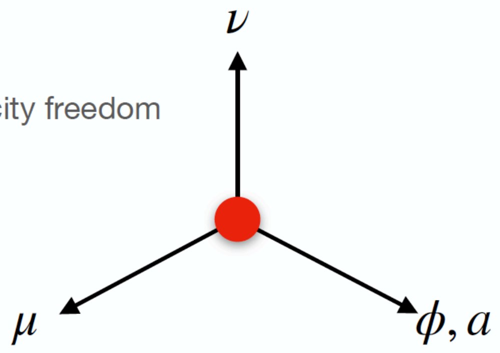


- Scalar or pseudo scalar coupled to muons permits the 3-body decay of the charged mesons
- The 3-body decay ***isn't necessarily phase-space suppressed;***

2-body: Only one helicity combination selected out



3-body: helicity freedom



Decay rates can be larger than standard two body decays

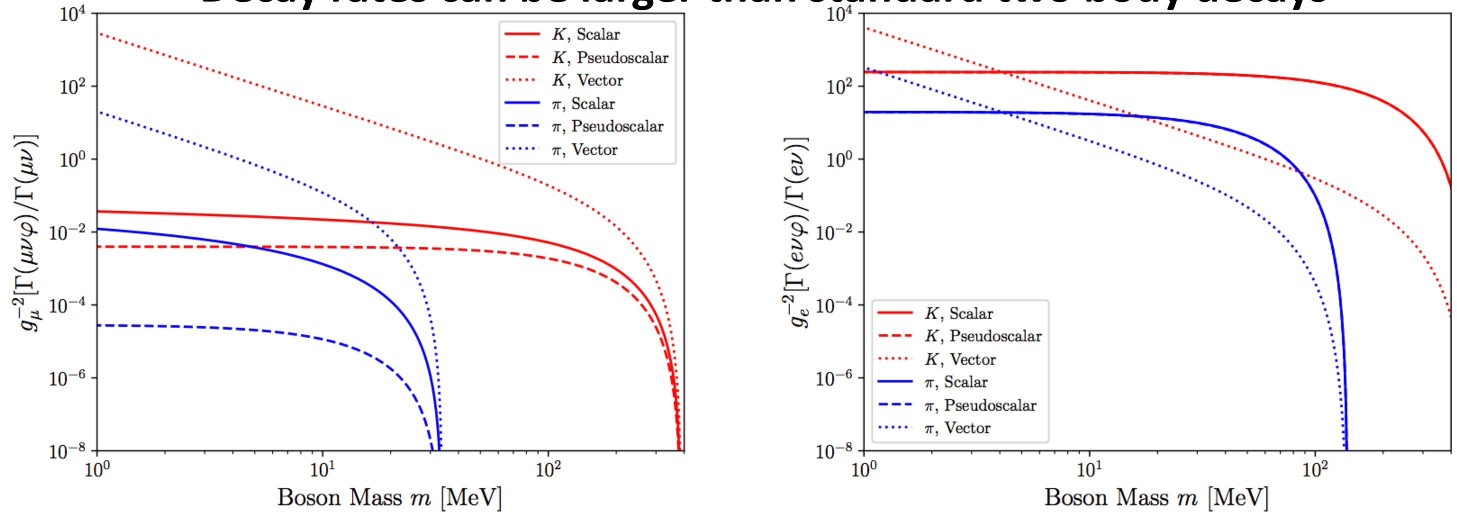


FIG. 5. Branching ratios for the three-body production of scalars, pseudoscalars, and vectors ($\varphi = \phi, a, V$) whose mass is m via the decay of a charged meson with mass $M(= m_\pi, m_K)$, relative to their corresponding two-body decay. The charged meson decays involve a muon (left panel) or an electron (right panel).

DSCMD Model predicts high energy gamma-rays in CCM

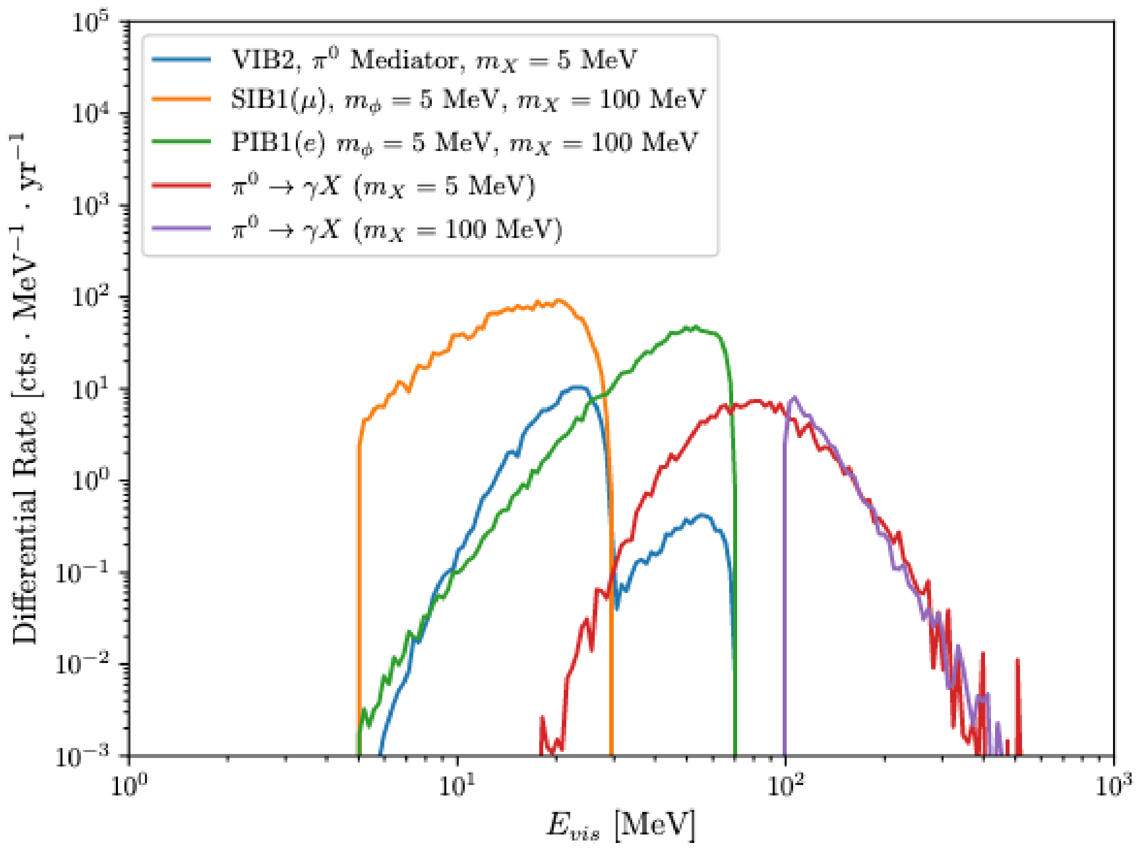


FIG. 5. Differential rate spectra for various decay models coming from $\pi^+ \to \ell\nu X$ and $\pi^0 \to \gamma X$ decays at rest.