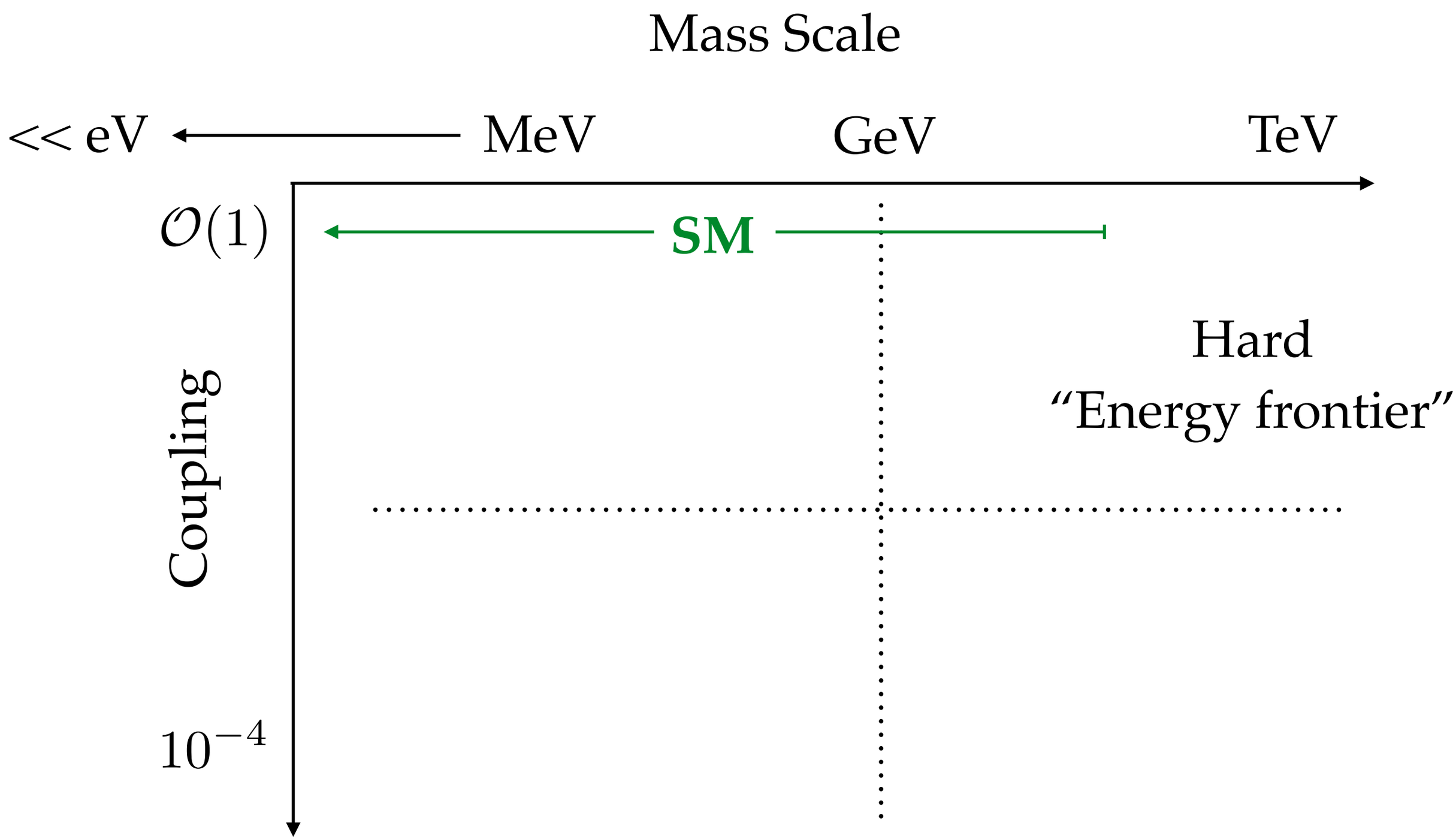
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Dark Sectors @ Fermilab

Gordan Krnjaic

FNAL PAC Meeting — June 11, 2021

How to look for new physics?



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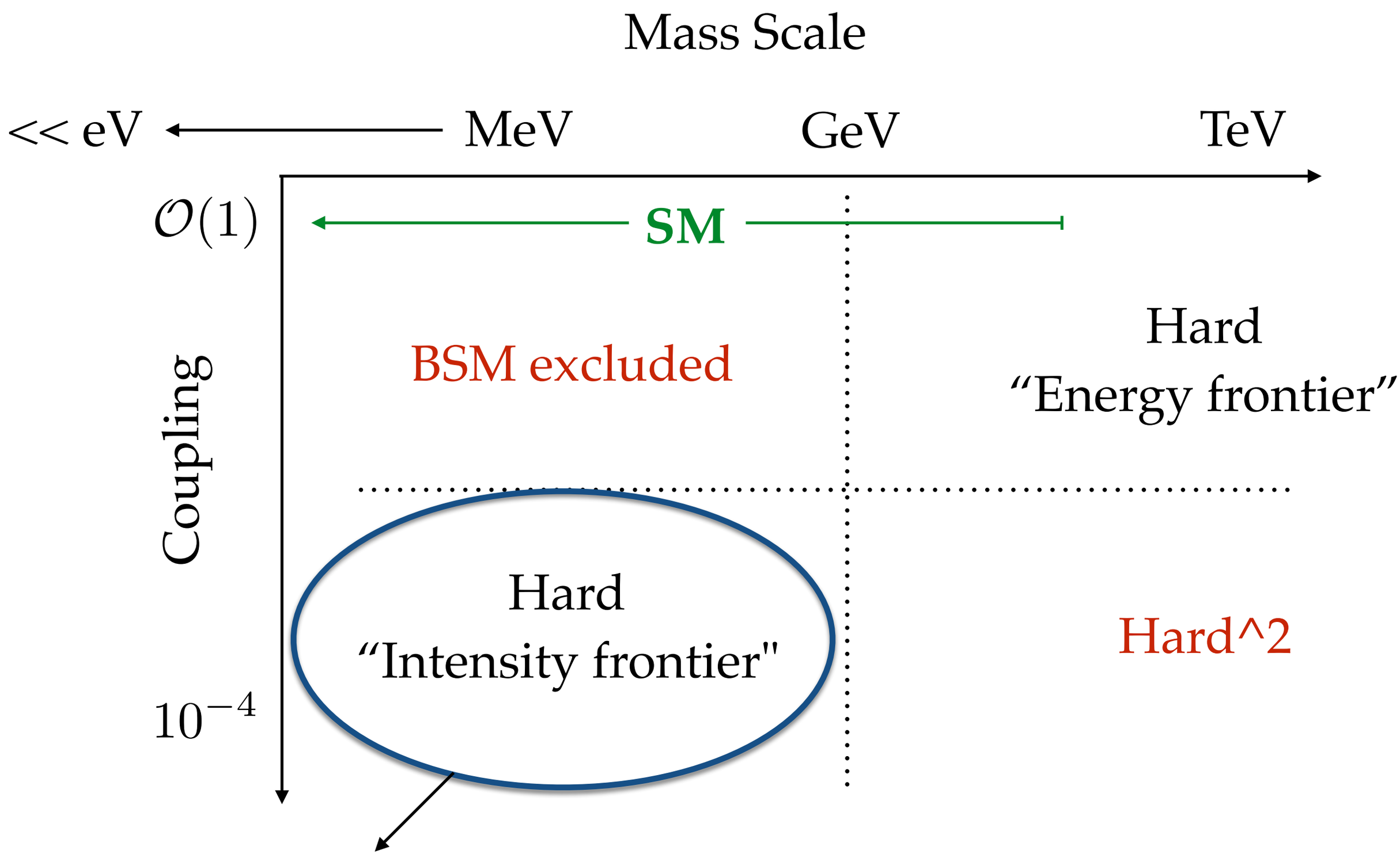
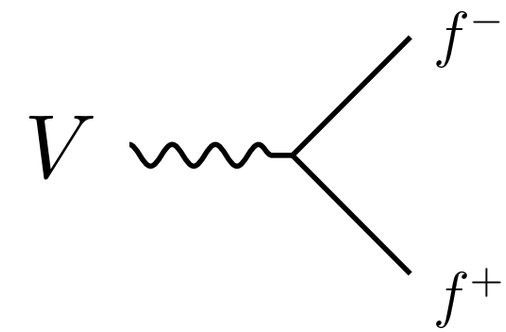


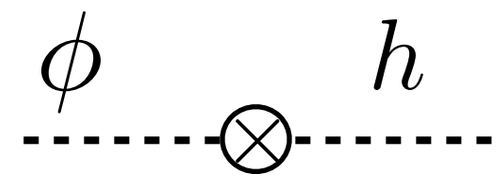
BSM: Smaller coupling, lower mass, **SM neutral**

Standard Model Portals

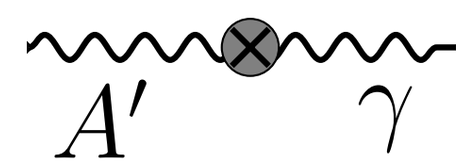
New U(1) gauge force $V_\mu \bar{f} \gamma^\mu f$



Scalar-Higgs mixing $\phi H^\dagger H \to \phi h$

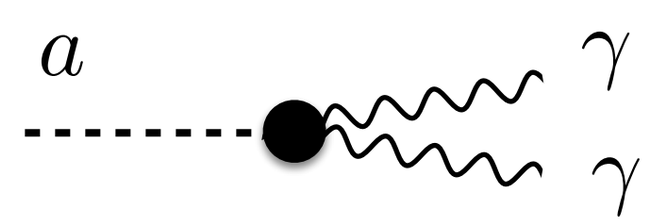


Photon-*A'* mixing $F'_{\mu\nu} F^{\mu\nu}$



Heavy neutral lepton LHN

Axion/ALP "portal" $\frac{a}{\Lambda} F_{\mu\nu} \tilde{F}_{\mu\nu}$



Standard Model Portals … to Dark Sectors

If cosmologically stable, these can all be DM

Wavelike, ultralight non-WIMP, non-thermal DM

Axions, ALPs, dark photons…

Haloscopes, cavity searches, light shining through wall

Standard Model Portals … to Dark Sectors

If cosmologically stable, these can all be DM

Wavelike, ultralight non-WIMP, non-thermal DM

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Haloscopes, cavity searches, light shining through wall

If short lived, can also mediate DM-SM interactions

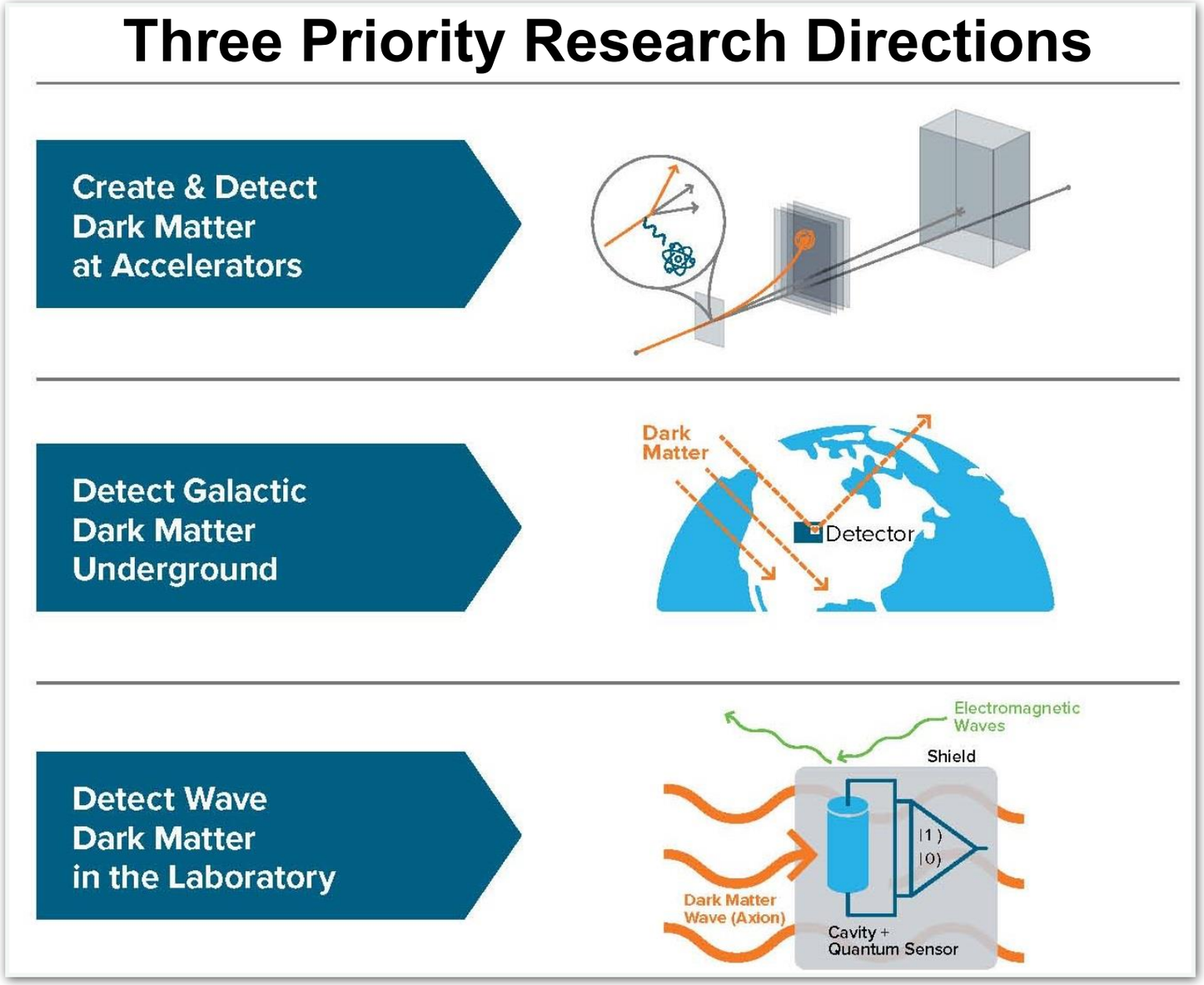
Particle-like light DM

Can be thermal (freeze out) or non-thermal (freeze in)

Accelerator production DM and/or mediators

Direct detection with non-traditional targets (electron/phonon)

BRN Priority Research Directions

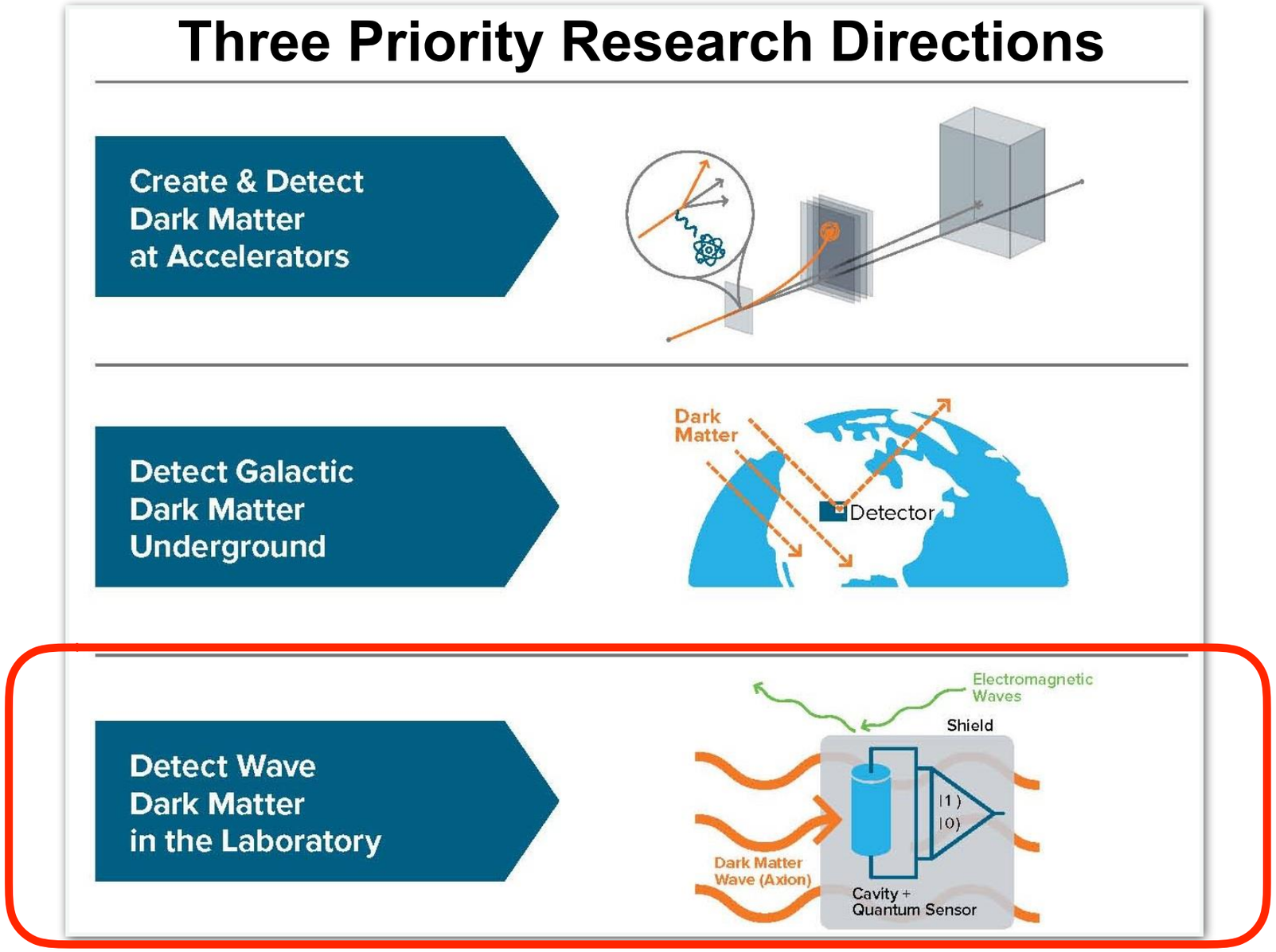


FNAL BRN report authors: Aaron Chou, Juan Estrada, Roni Harnik, Gordan Krnjaic, Nhan Tran

https://science.energy.gov/~/media/hep/hepap/pdf/201811/RKolb-HEPAP_201811.pdf

https://science.energy.gov/~/media/hep/hepap/pdf/201811/BRN_Dark-Matter-Brochure_HEPAP_201811.pdf

BRN Priority Research Directions



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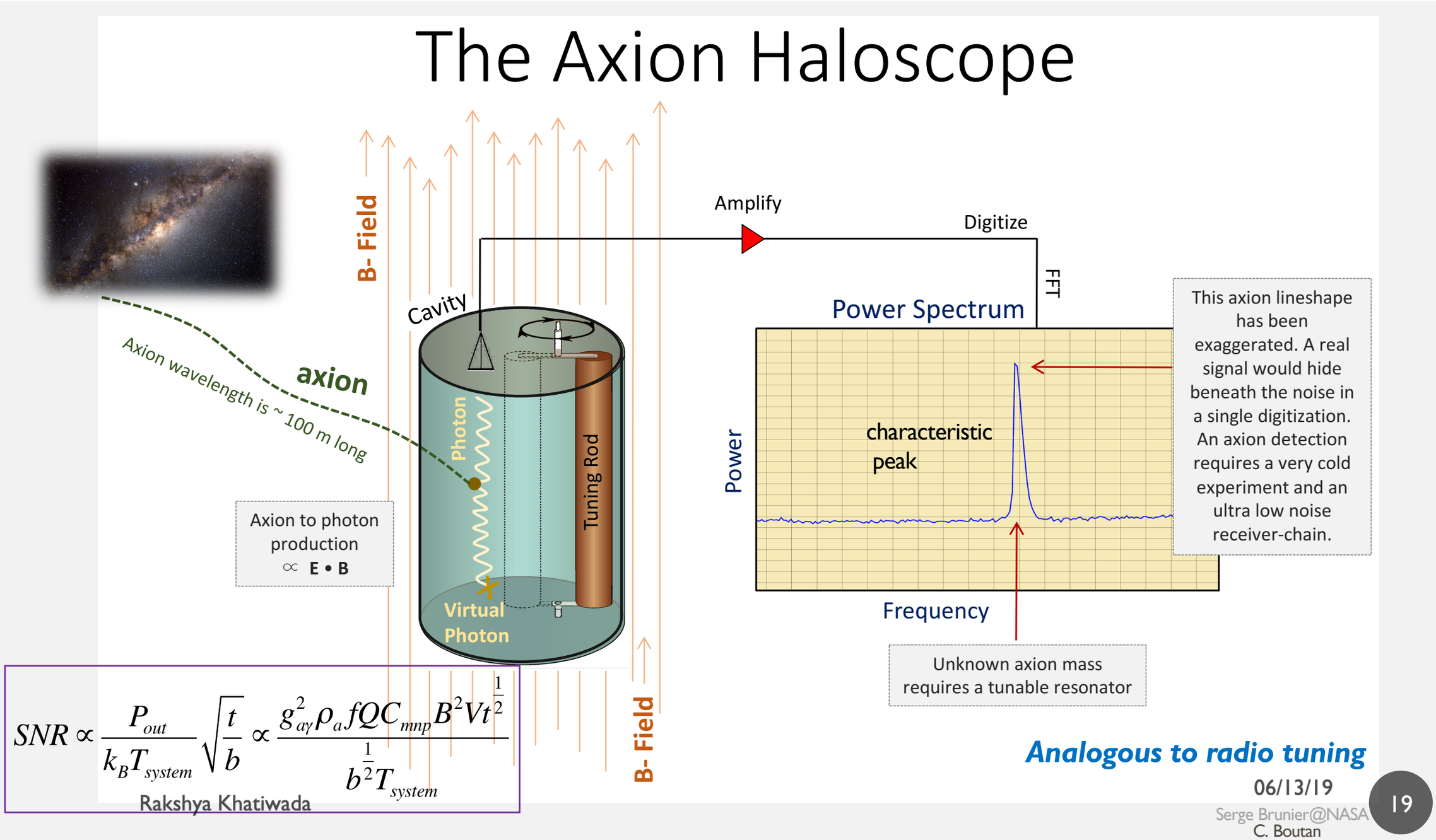
ADMX

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4}\, a\, F\tilde{F} = -g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}\,. \qquad a(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos m_a t$$



$$SNR \propto \frac{P_{out}}{k_B T_{system}}\sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

Rakshya Khatiwada

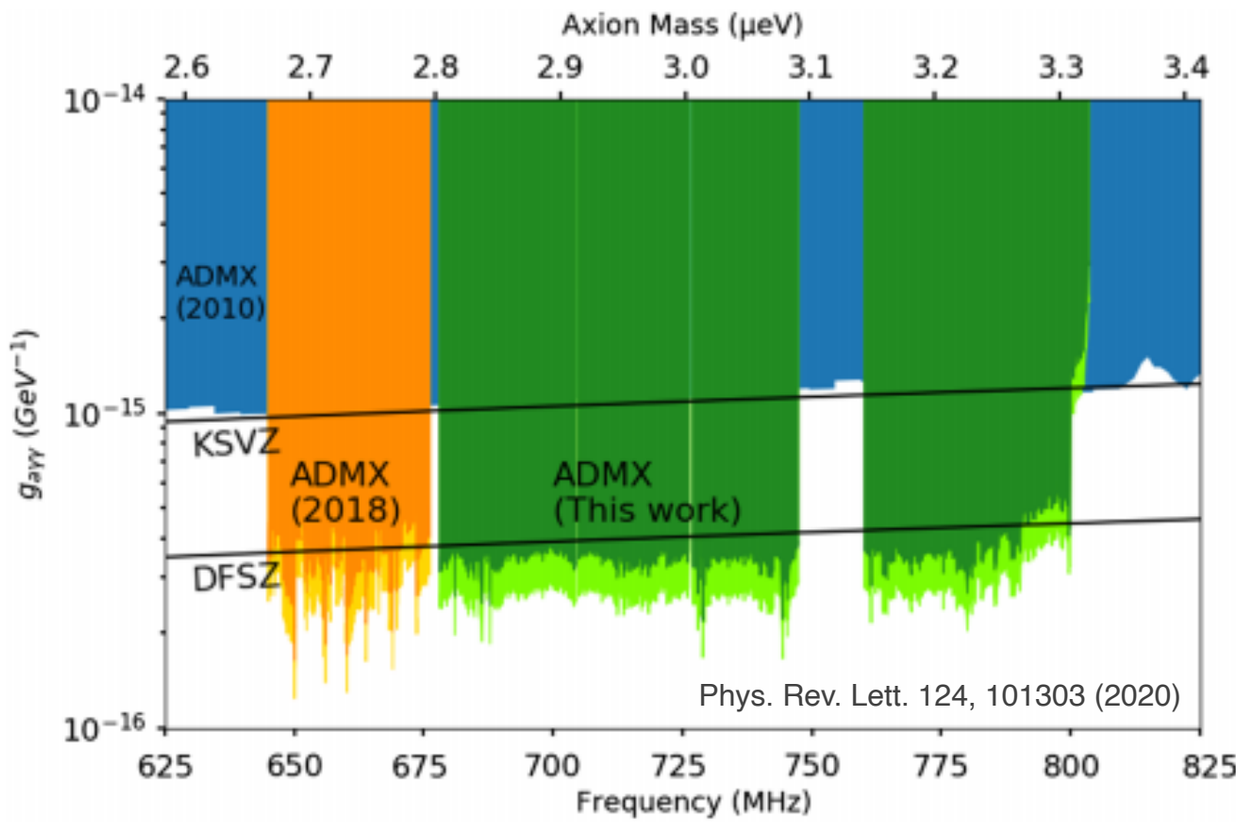
Slide: Rakshya Khatiwada

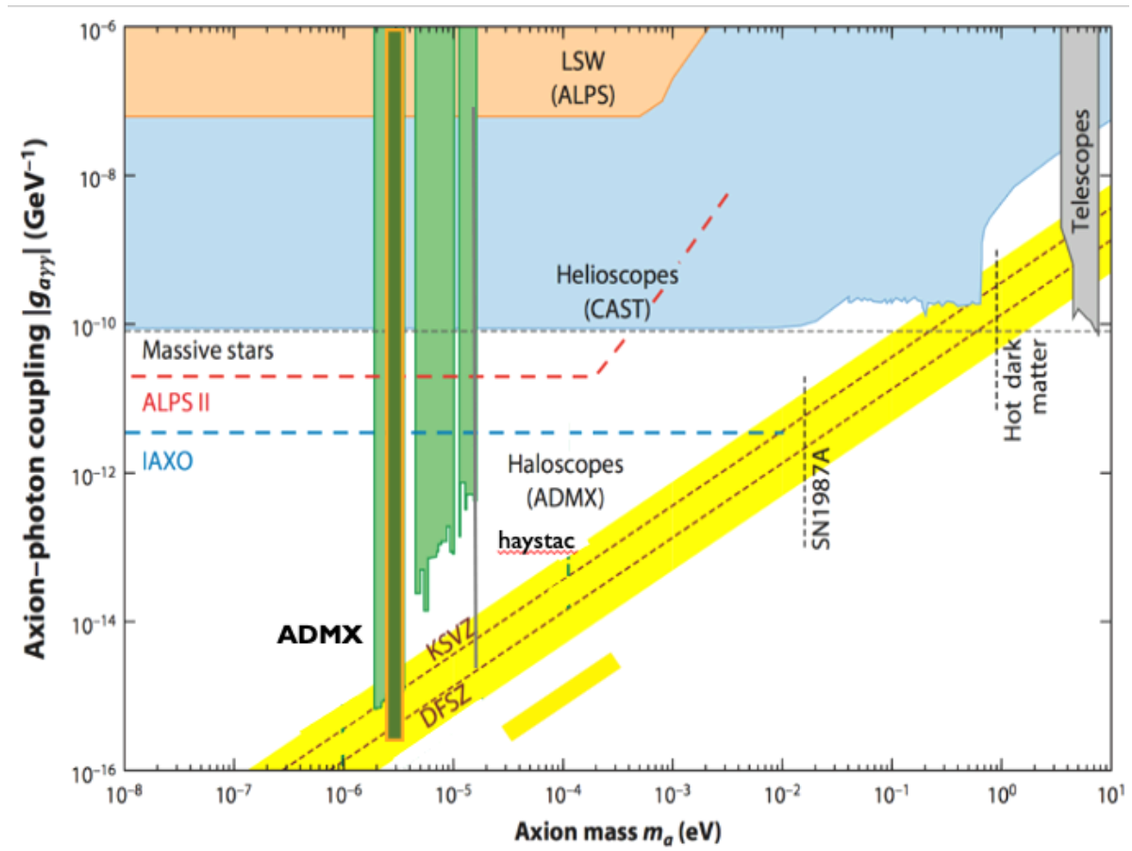
- Daniel Bowring, Aaron Chou, Rakshya Khatiwada, Andrew Sonnenschein

Slide: Rakshya Khatiwata

ADMX

- x4 more frequency covered than 2017
- DFSZ sensitivity -- 680 to 800 MHz
- Axion mass covered to this date: 2.66 to 3.3 μeV
  - Phys. Rev. Lett. 124, 101303 (2020)
- Currently taking > 4 μeV data (985 MHz)





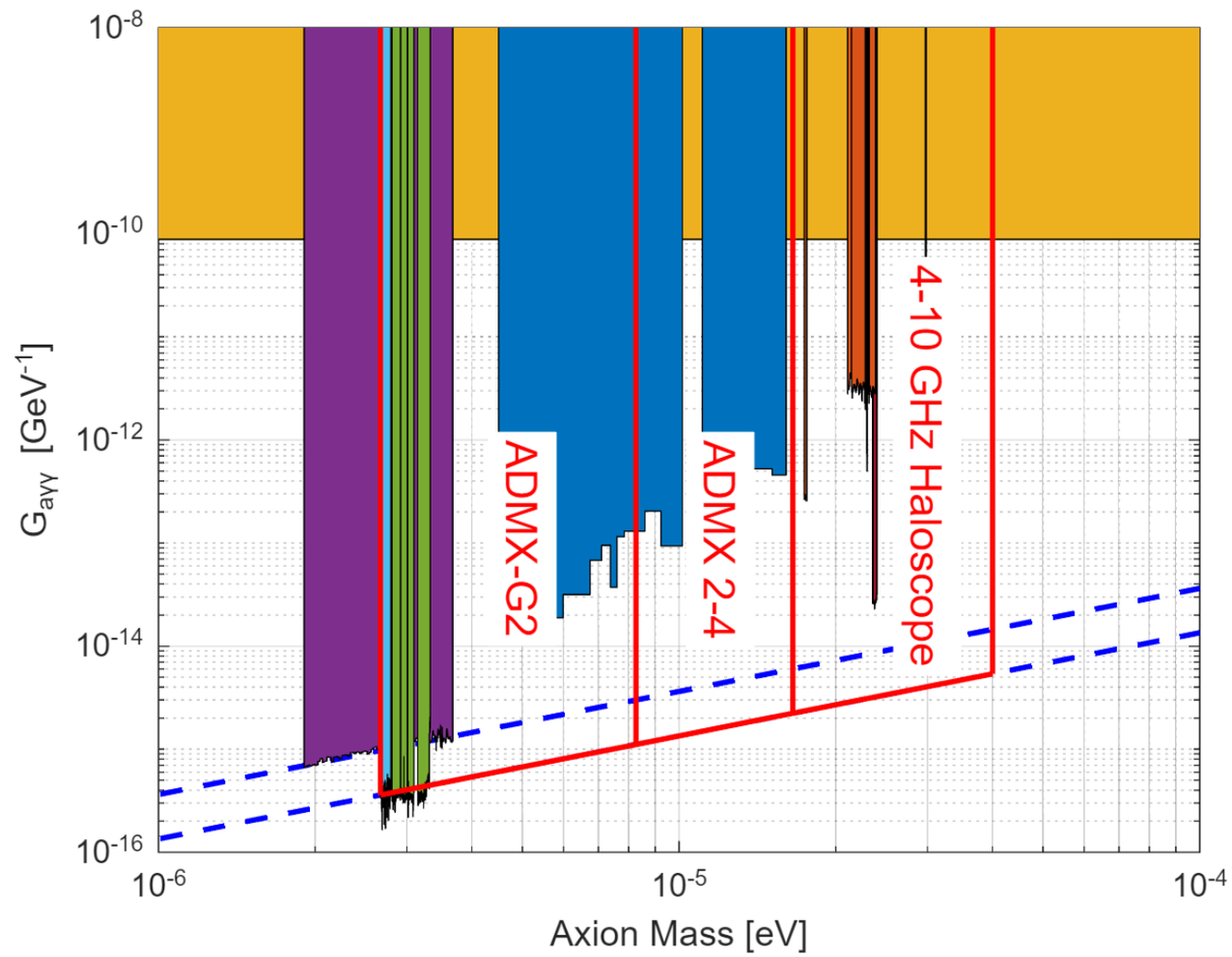
ADMX

ADMX G2 projected to reach 2 GHz by end 2023

DM New Initiatives funding for ADMX 2-4

Approaching predicted mass ~O(10 μeV) for post inflationary misalignment production

Klaer, Moore 1708.07521



https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0_Andrew_Sonnenschein-093.pdf

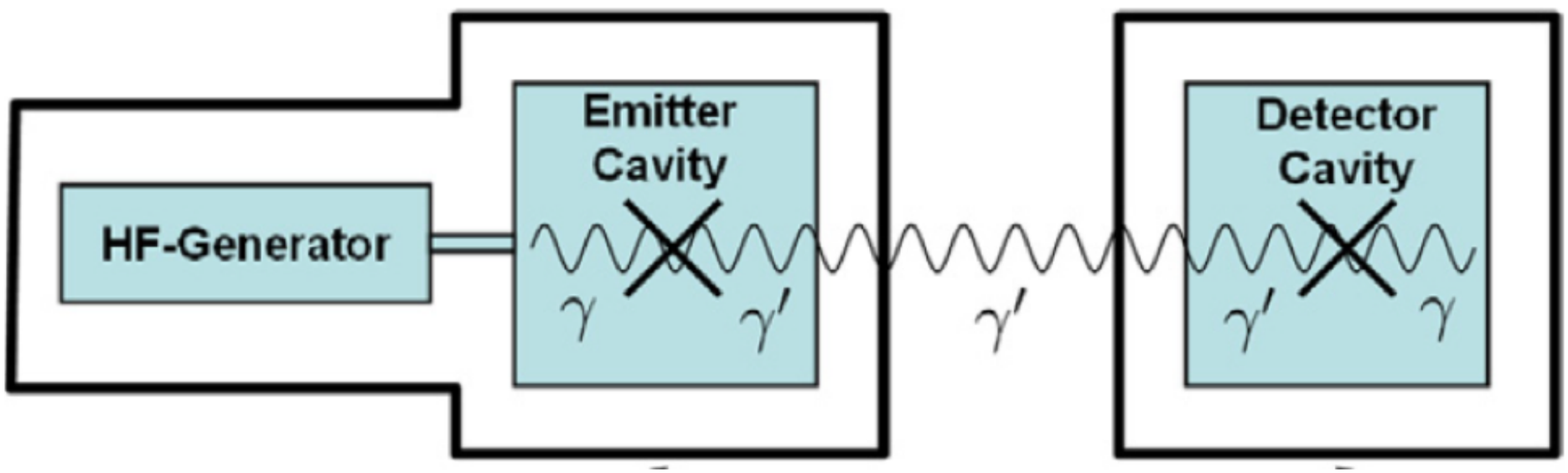
Slide: Anna Grassellino

Dark SRF

$$\mathscr{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A_\mu'^2 \ ,$$

Ultralight dark photon produced in SRF cavity via kinetic mixing

Identical shielded cavities, high Q > 1e11, many photons to source dark photon



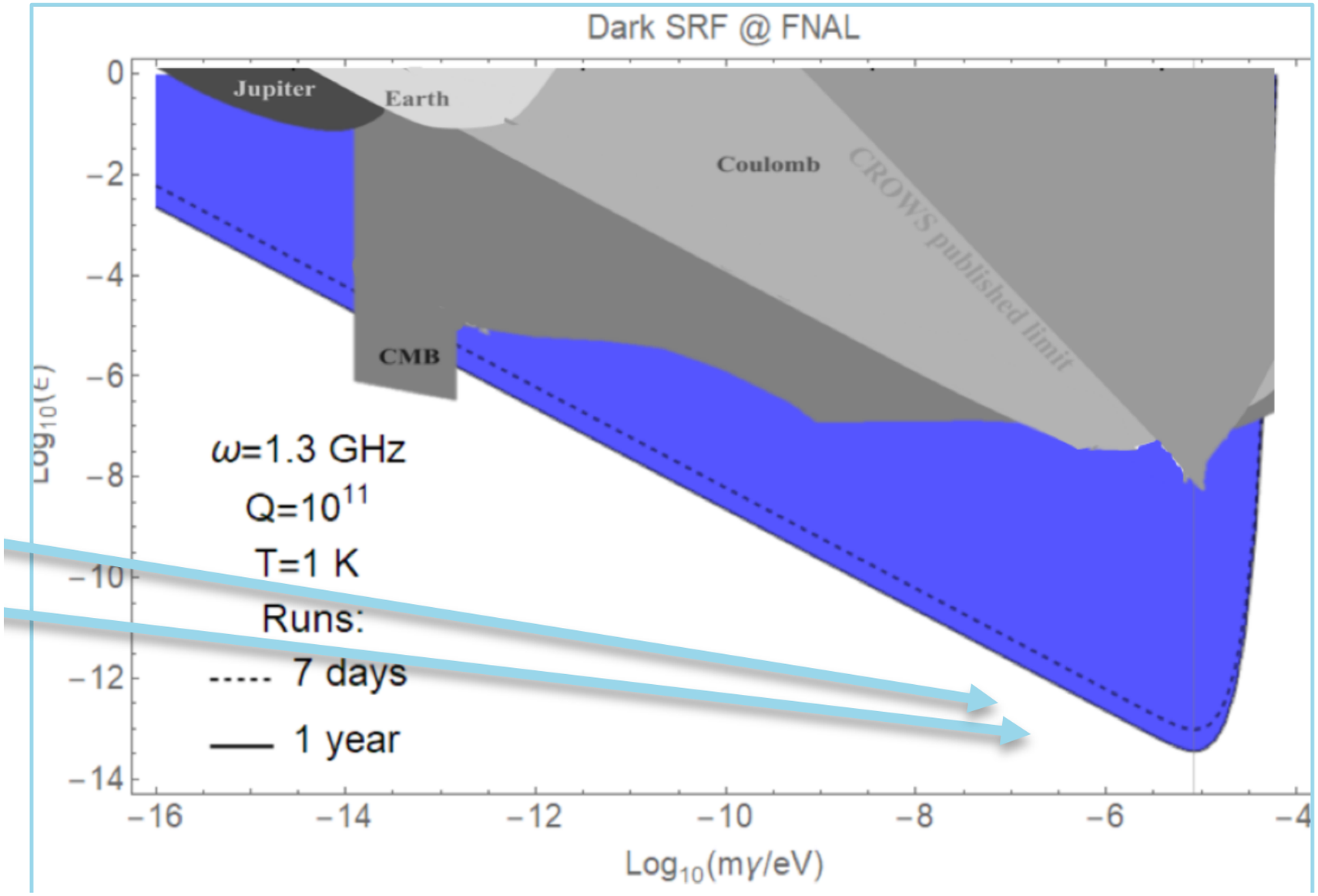
Dark photon passes through shielding and mixes back into visible in detector

https://indico.fnal.gov/event/19433/contributions/52137/attachments/32415/39710/DarkSRF.pdf

Slide: Anna Grassellino

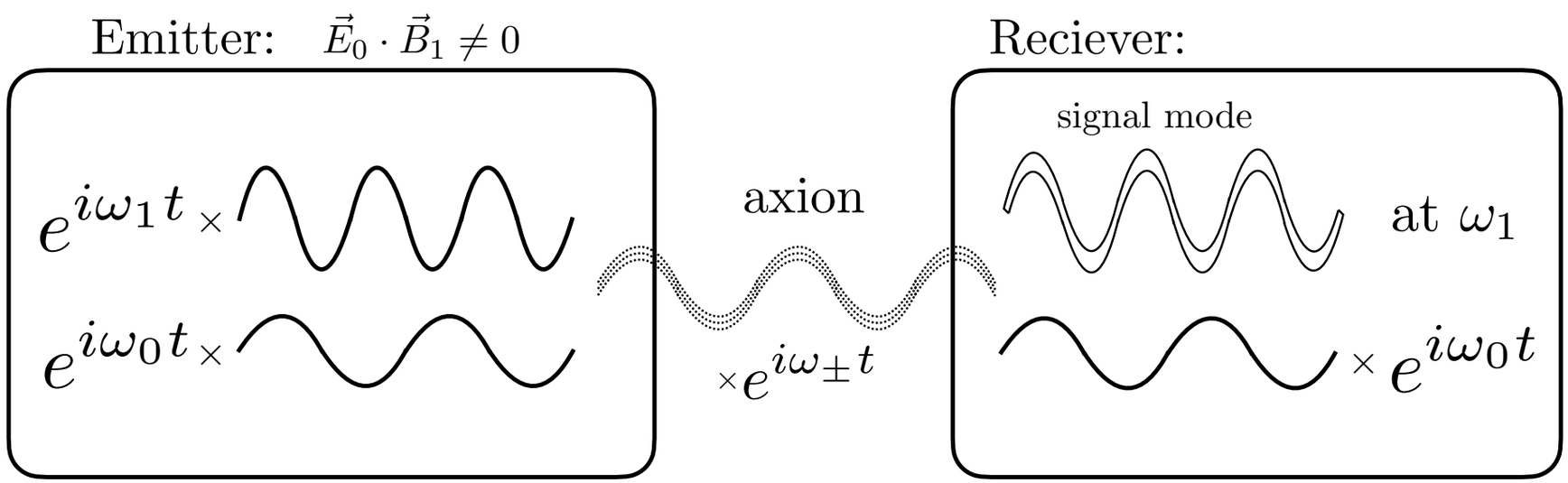
Dark SRF

$$\mathscr{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A_\mu'^2 \ ,$$



https://indico.fnal.gov/event/19433/contributions/52137/attachments/32415/39710/DarkSRF.pdf

SRF Cavities: Axion "Light Shining Through Wall"



$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4}\, a\, F\tilde{F} = -g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}\,.$$

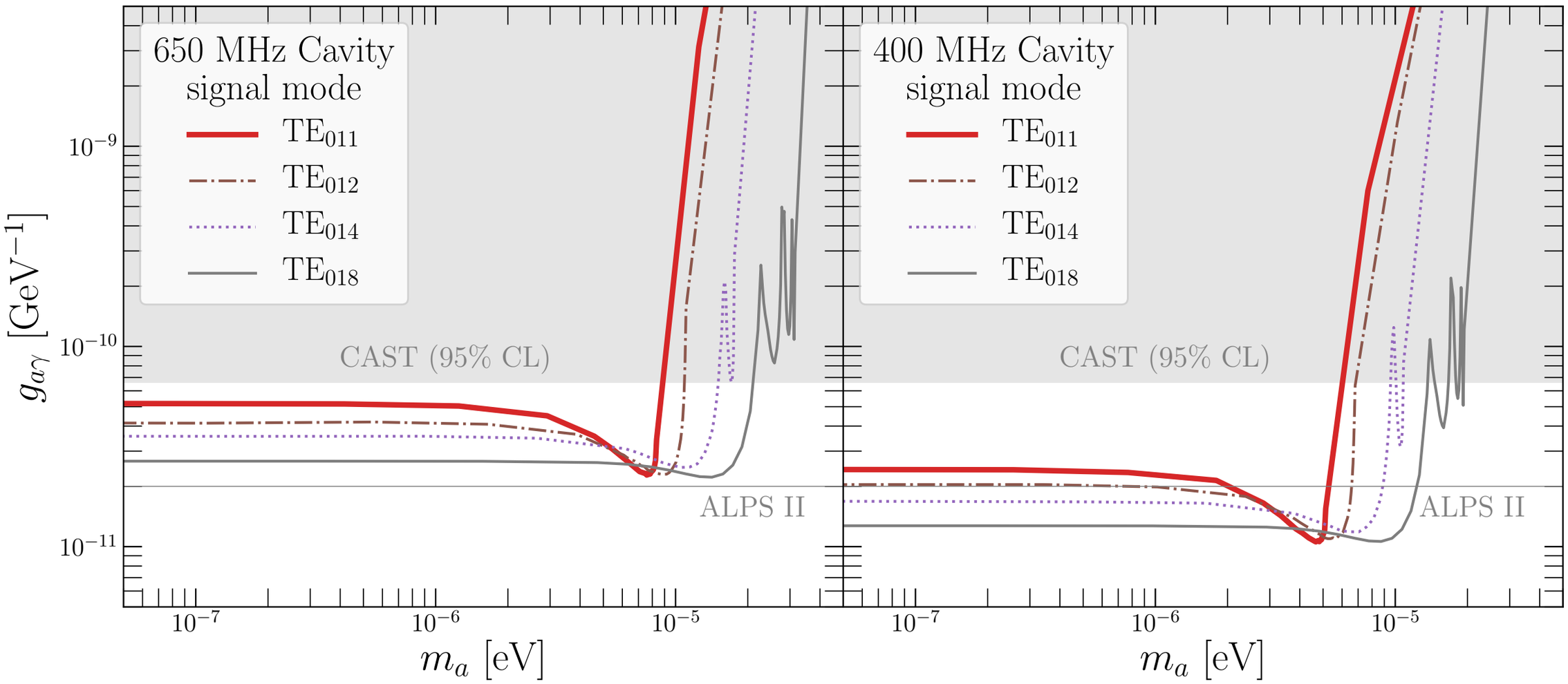
Axions/ALPs produced in emitter cavity sourced by 2 modes with nonzero E.B
High quality factor Q~ 1e10, large photon density sources rare axion production

Emitted with $\omega_a = |\omega_0 \pm \omega_1|$

Identical Receiver cavity with one of the two modes populated enables conversion

Gao, Harnik 2011.01350

SRF Cavities: Axion "Light Shining Through Wall"



Potential sensitivity for m < few GHz ALP masses

Gao, Harnik 2011.01350

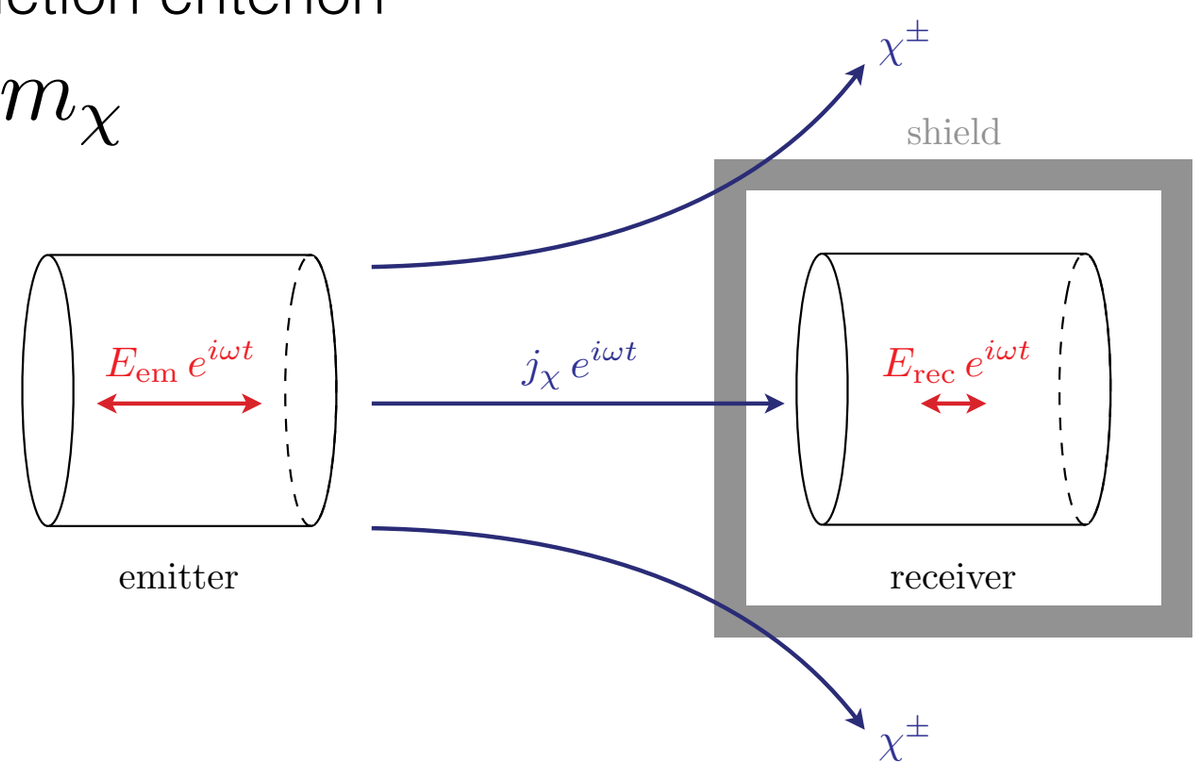
SRF Cavities: Millicharged Particles

Arise in models with ultra-light dark photons coupled to hidden X

$$\mathscr{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A_\mu'^2 \; + q_\chi A'_\mu \bar{\chi} \gamma^\mu \chi$$

Schwinger pair production criterion

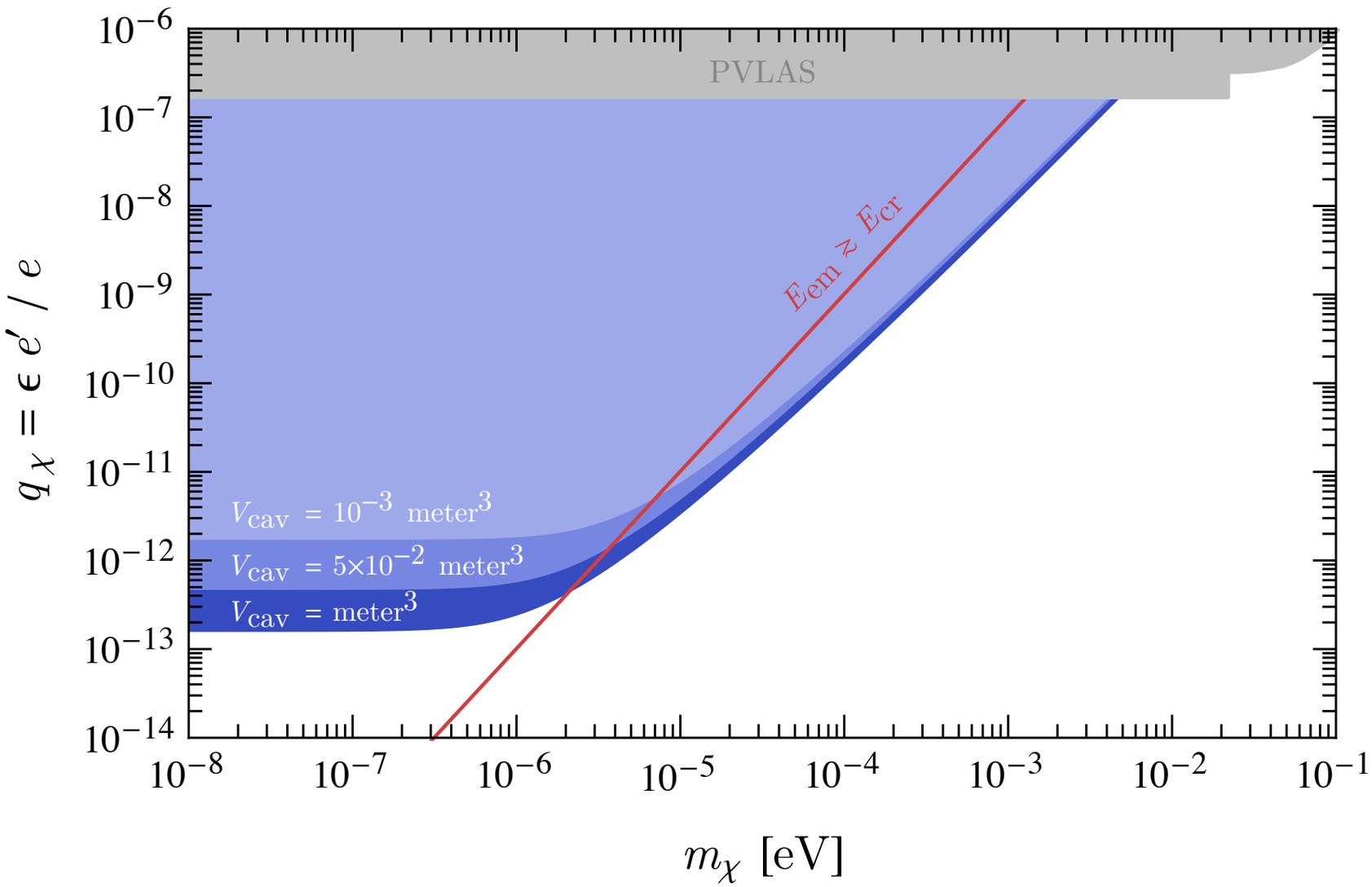
$$e q_\chi \, d\, E \sim m_\chi$$



Production of millicharged particles in emitter cavity (large E ~ 50 MV/m)
Shielded receiver cavity detects current from produced millichrages

Berlin, Hook 2001.02679

SRF Cavities: Millicharged Particles



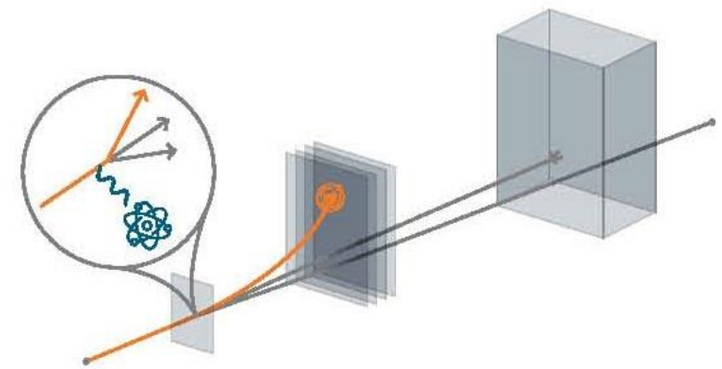
Schwinger pair production of ultralight millicharged particles

Berlin et. al. 1912.11048

BRN Priority Research Directions

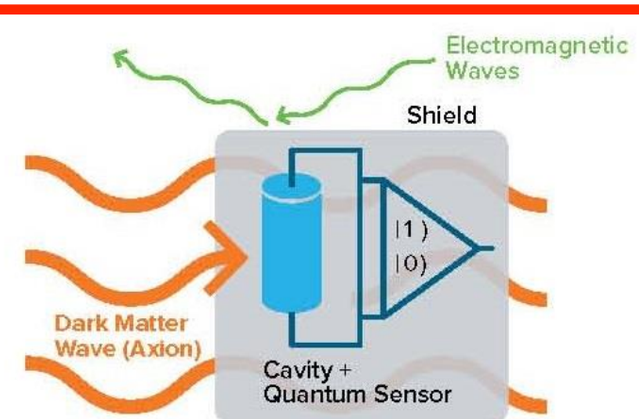
Three Priority Research Directions

Create & Detect Dark Matter at Accelerators



Detect Galactic Dark Matter Underground

Detect Wave Dark Matter in the Laboratory



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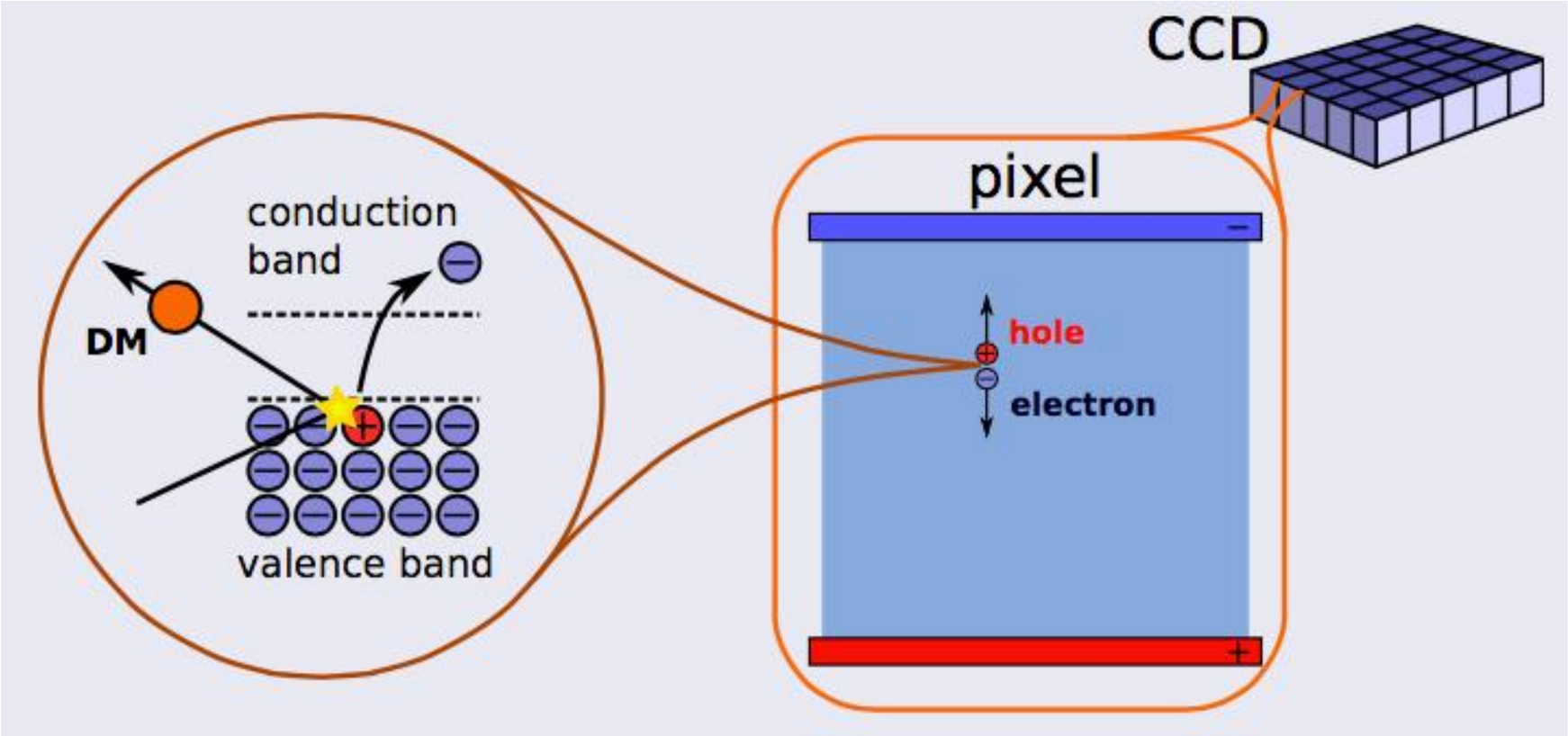
https://science.energy.gov/~/media/hep/hepap/pdf/201811/BRN_Dark-Matter-Brochure_HEPAP_201811.pdf

OSCURA/SENSEI

Electron recoils for sub-GeV dark matter

- We look for DM interactions with the electrons in a CCD
  - Benchmark models: DM-electron scattering, absorption
- Silicon bandgap gives us sensitivity to 1.2 eV excitations — if we can capture and resolve a single electron

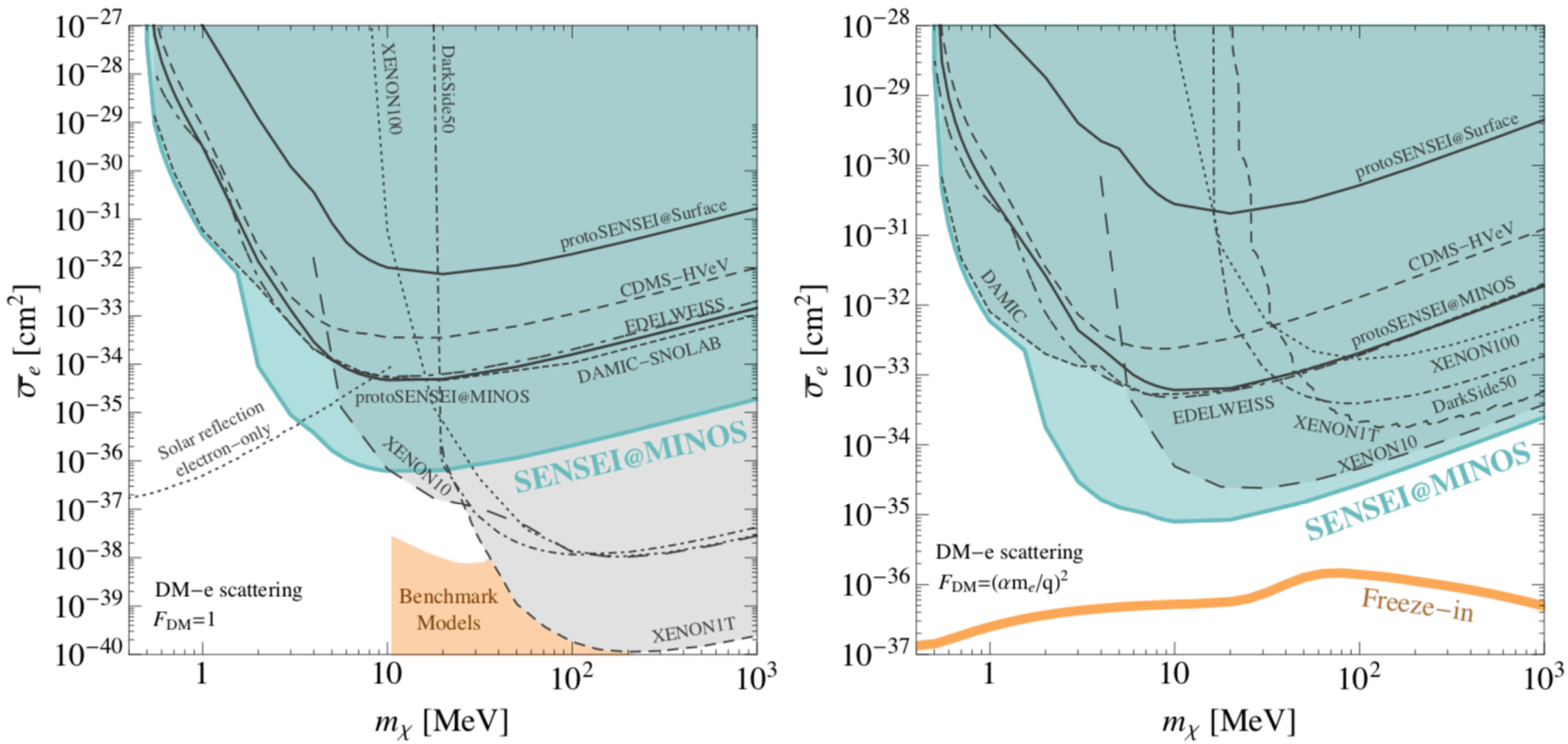


Fermilab:

- F. Chierchie, M. Cababie, G. Cancelo, M. Crisler, A. Drlica-Wagner, J. Estrada, G. Fernandez-Moroni, D. Rodrigues, M. Sofo-Haro, L. Stefanazzi, J. Tiffenberg

OSCURA/SENSEI

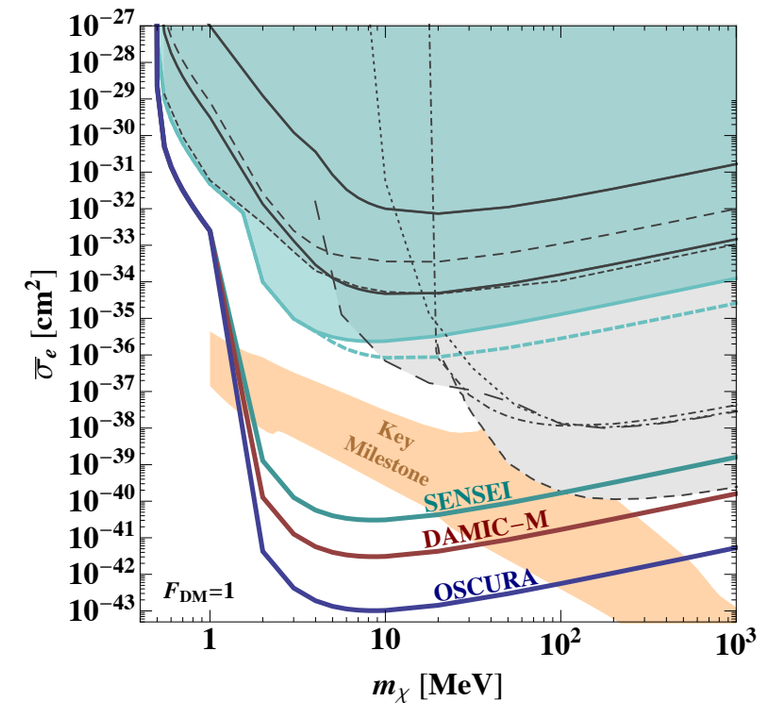
prototype 2.5 g experiment at MINOS (FNAL) using skipper-CCDs (SENSEI) is world leading again. Oscura will scale this successful technology. arXiv:2004.11378

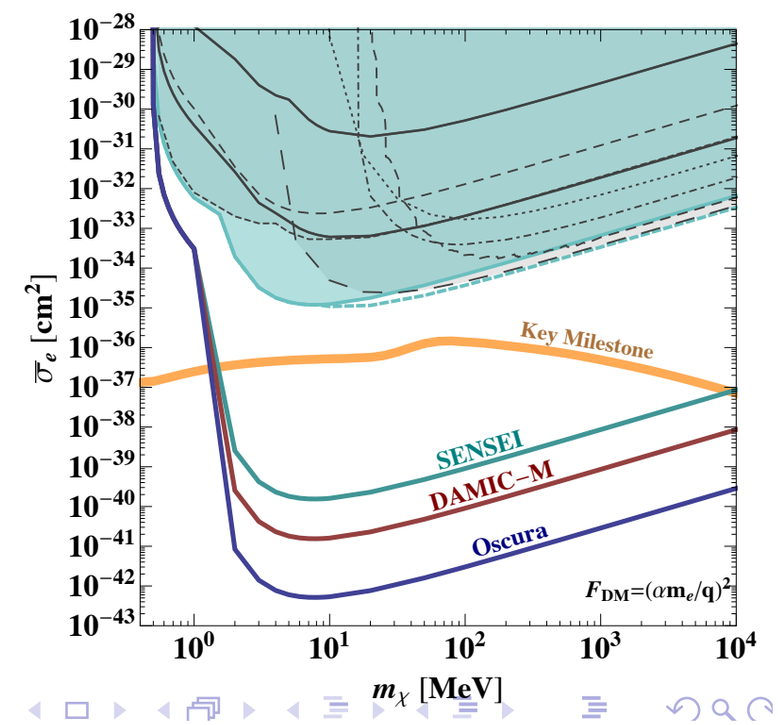


OSCURA/SENSEI (Future)

The future of Skippers

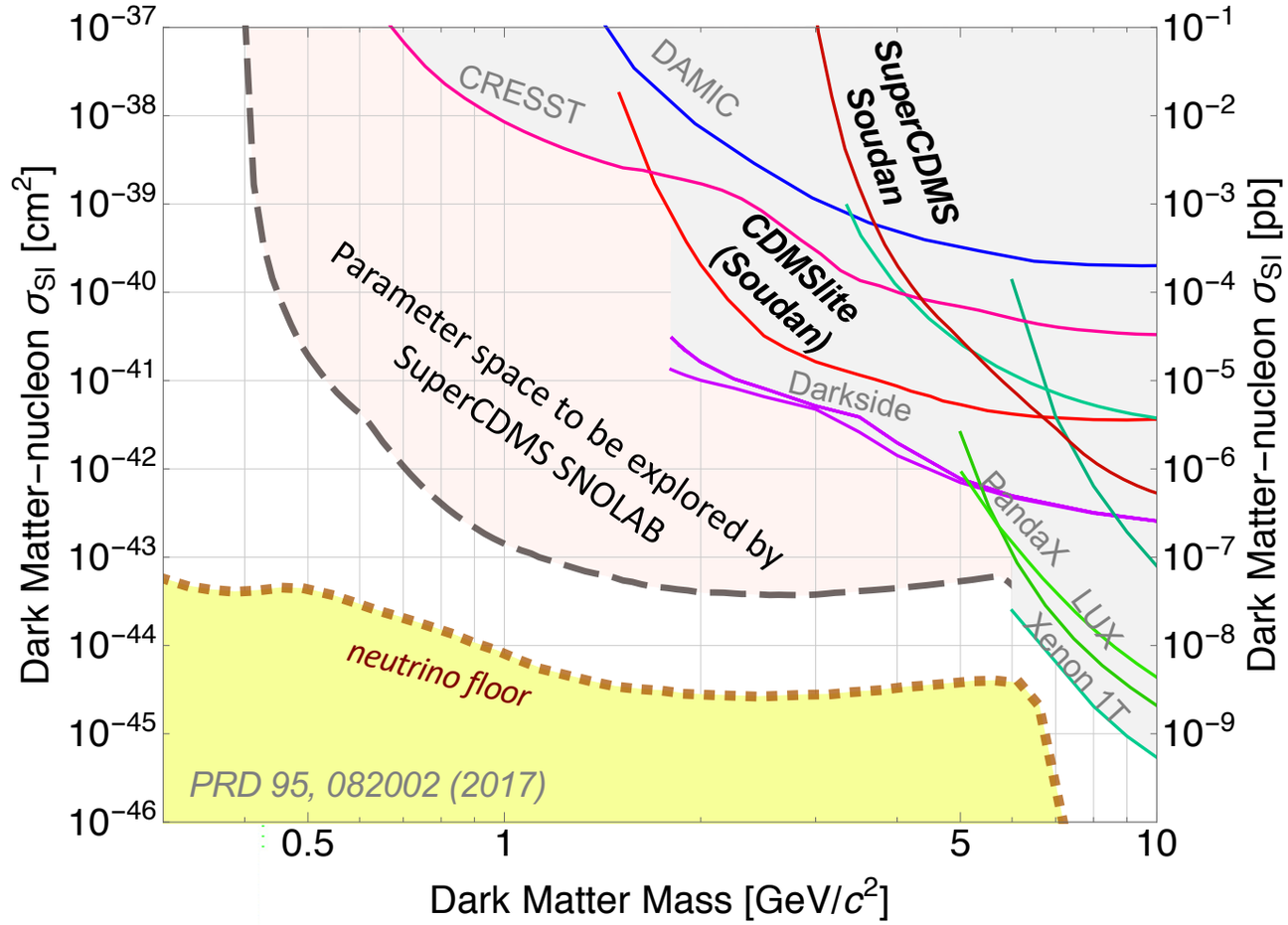
- We expect significant improvements in all measurement channels:
  - $1e^-$: better shielding $\rightarrow$ lower $1e^-$ rate
  - $2e^-$: reduced spurious charge $\rightarrow$ shorter exposures $\rightarrow$ lower coincidence rate
  - $3, 4e^-$: increased detector mass
- SENSEI@MINOS demonstrates that Skipper CCDs have the performance we need to reach theory targets
  - SENSEI@SNOLAB: 100 grams
  - DAMIC-M: 1 kg
  - Oscura: 10 kg

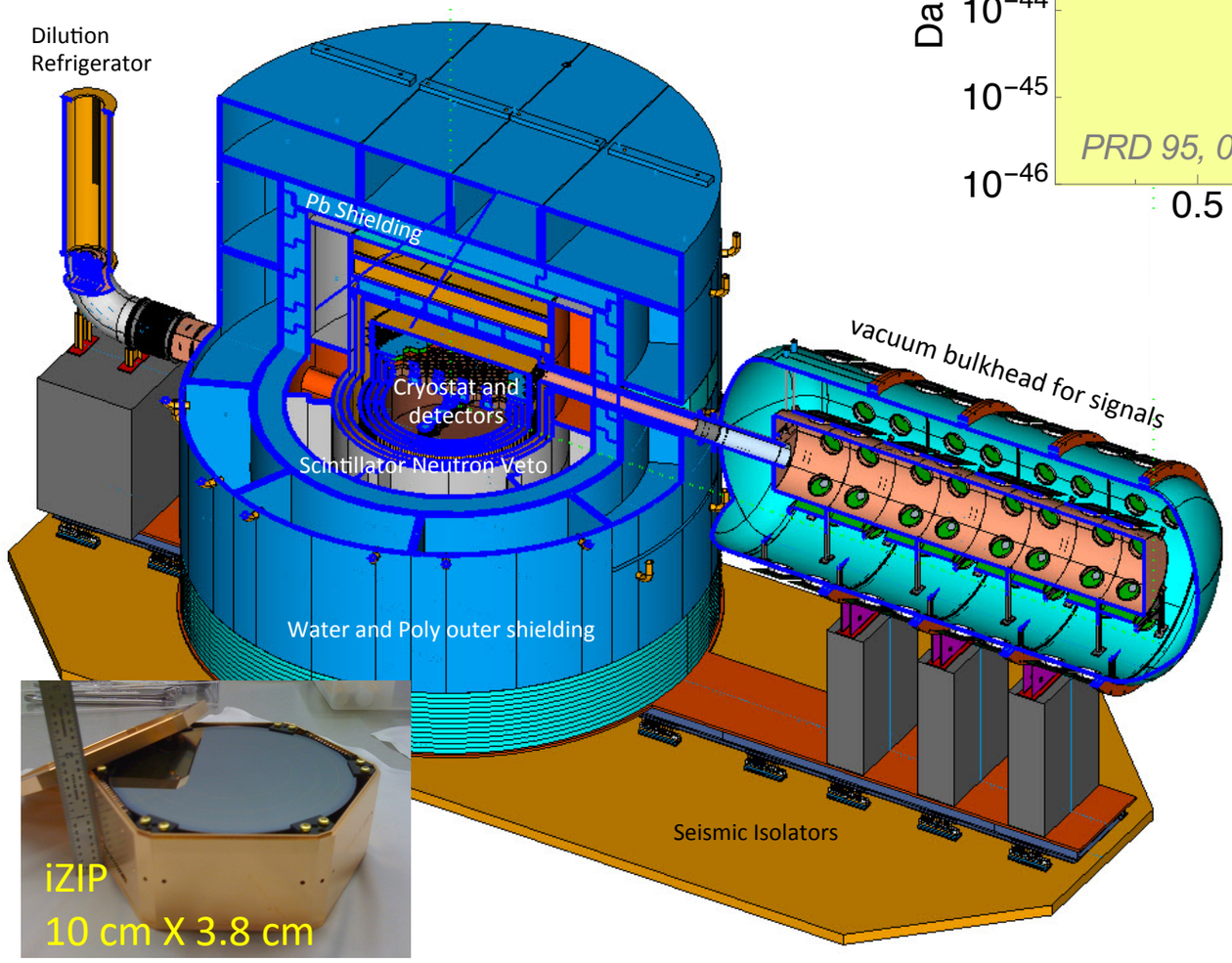




Super-CDMS SNOLAB

Will provide superb sensitivity to low mass WIMPs with Ge and Si operated in both HV and iZIP modes





Timeline:

- Construction and testing at Fermilab in 2019
- Install and Commission at SNOLAB in 2020
- First physics run in 2021!

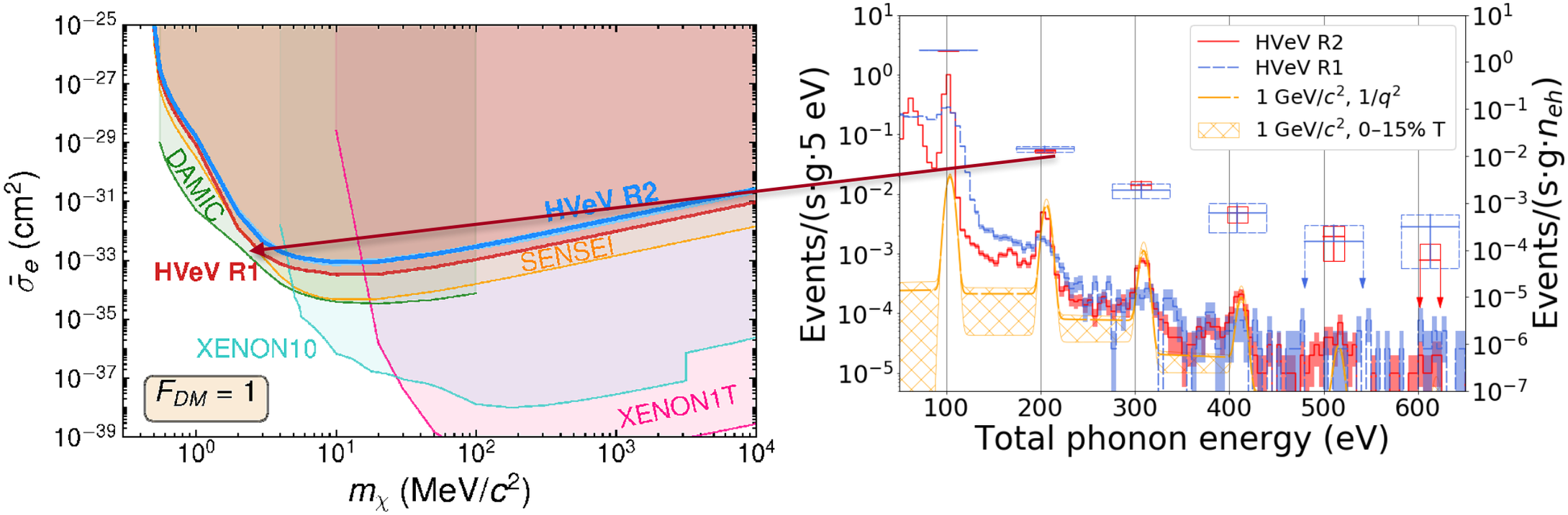
- Dan Bauer, Lauren Hsu, Noah Kurinsky, Pat Lukens

Super-CDMS HVeV (electron scattering)

Slide: Noah Kurinsky

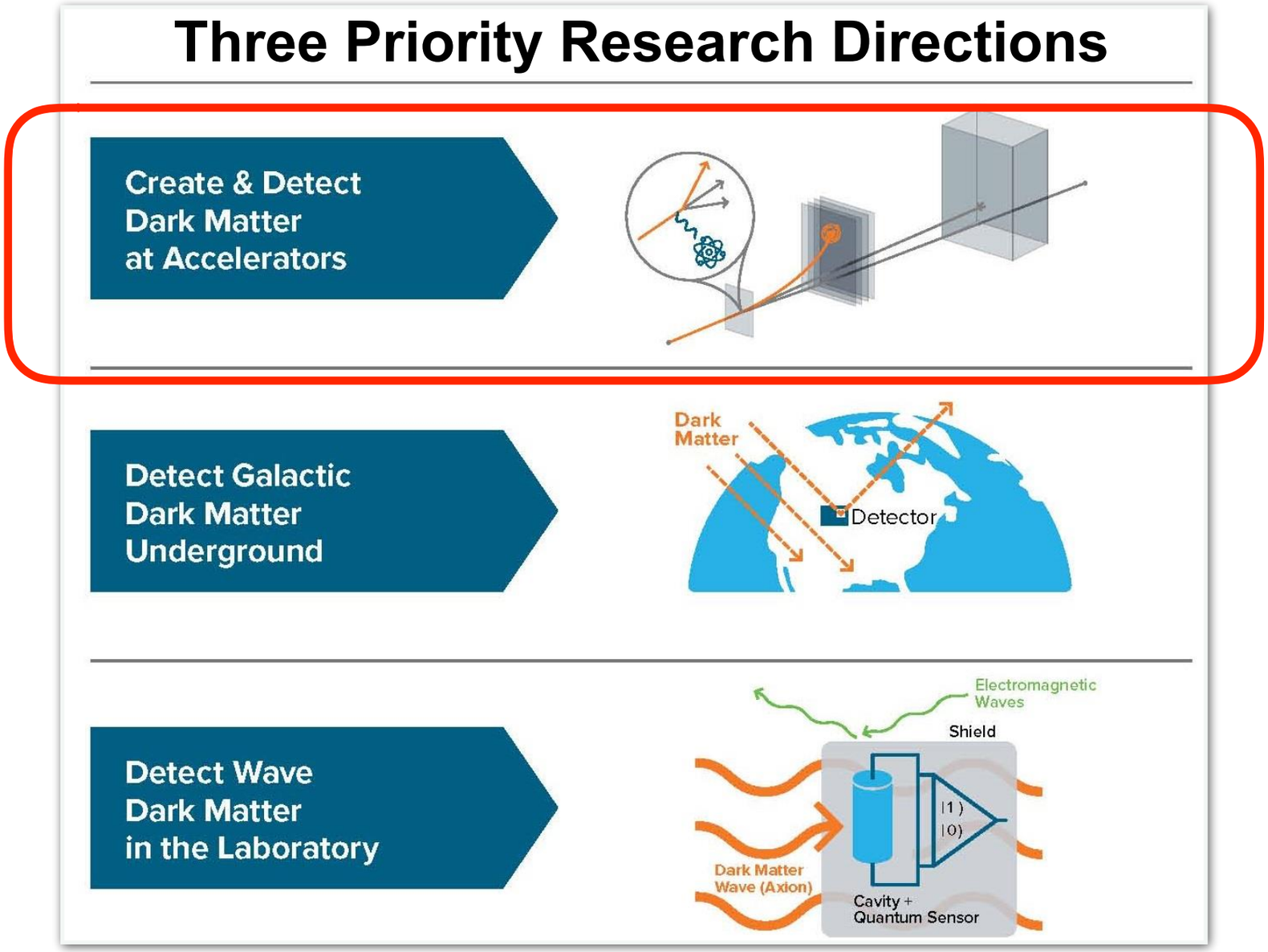
HVeV Run 2

SuperCDMS Collaboration 2020 (arXiv:2005.14067)
Supplemental Plots



- HVeV second run taken with 3 eV resolution detector over the course of 3 weeks:
  - 60V and 100V spectra show identical backgrounds; signal seen not voltage dependent
  - Different prototype, run in a different lab, in a different state
  - 0V data acquired with ~12 eV threshold, results still being analyzed
  - Rates in *every charge bin* consistent with Run 1…that is completely unexpected

BRN Priority Research Directions



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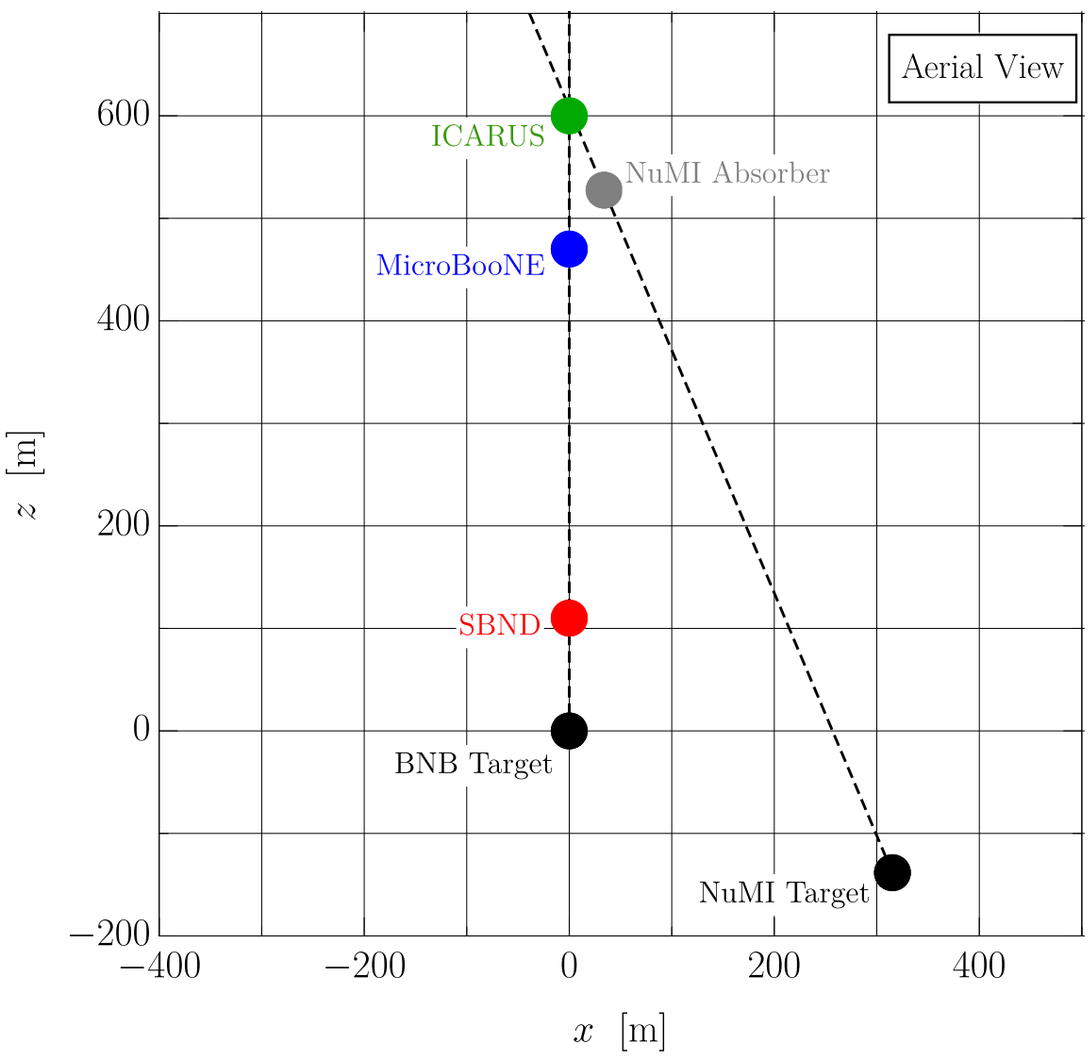
https://science.energy.gov/~/media/hep/hepap/pdf/201811/BRN_Dark-Matter-Brochure_HEPAP_201811.pdf

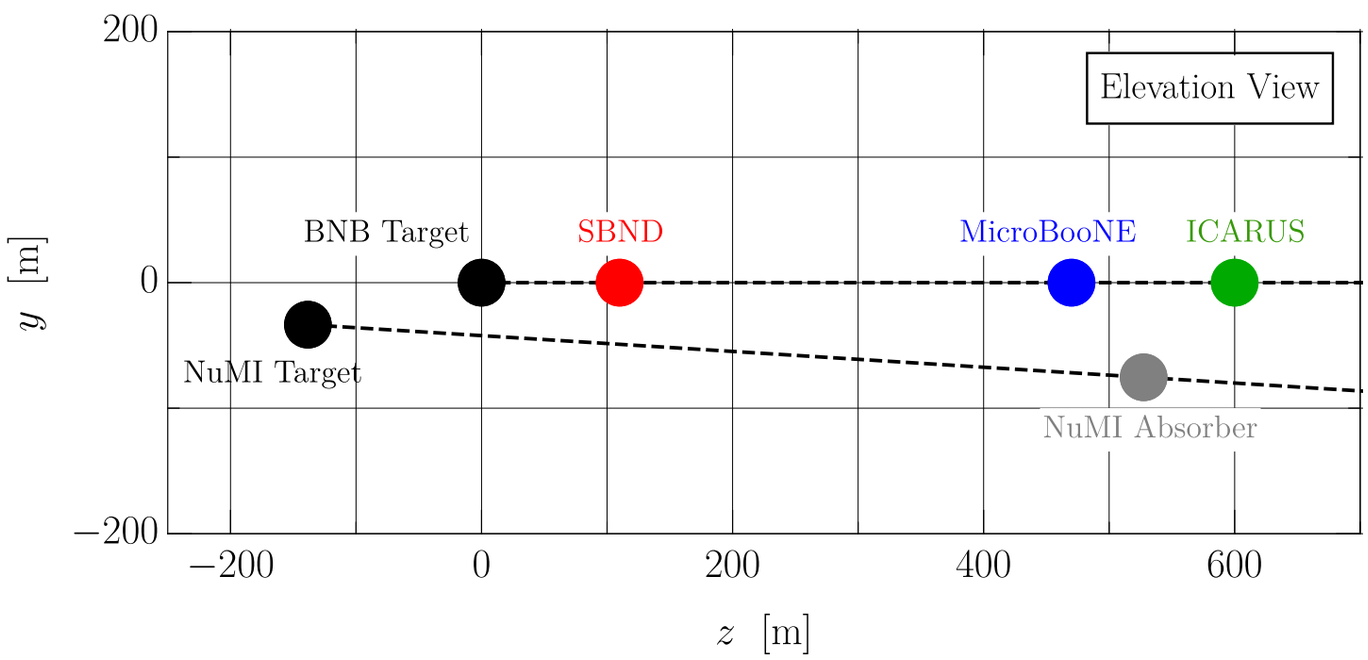
LDRD support
https://arxiv.org/abs/1804.00661
recent Pheno2021 talk

Proton Beams

SBN Experiments

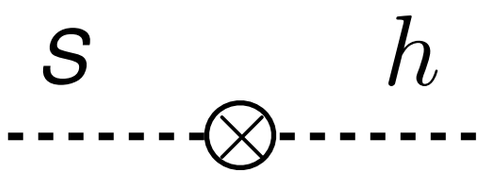
Batell, Berger, Ismail, 1909.11670



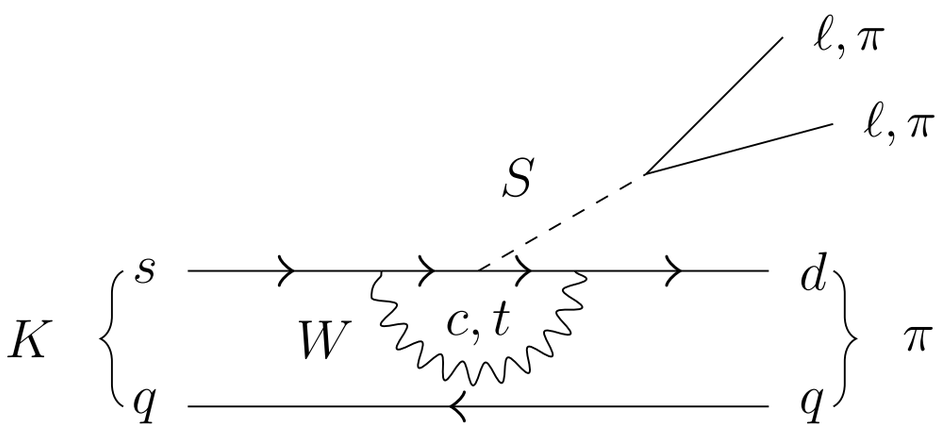


SBN Experiments (LLPs)

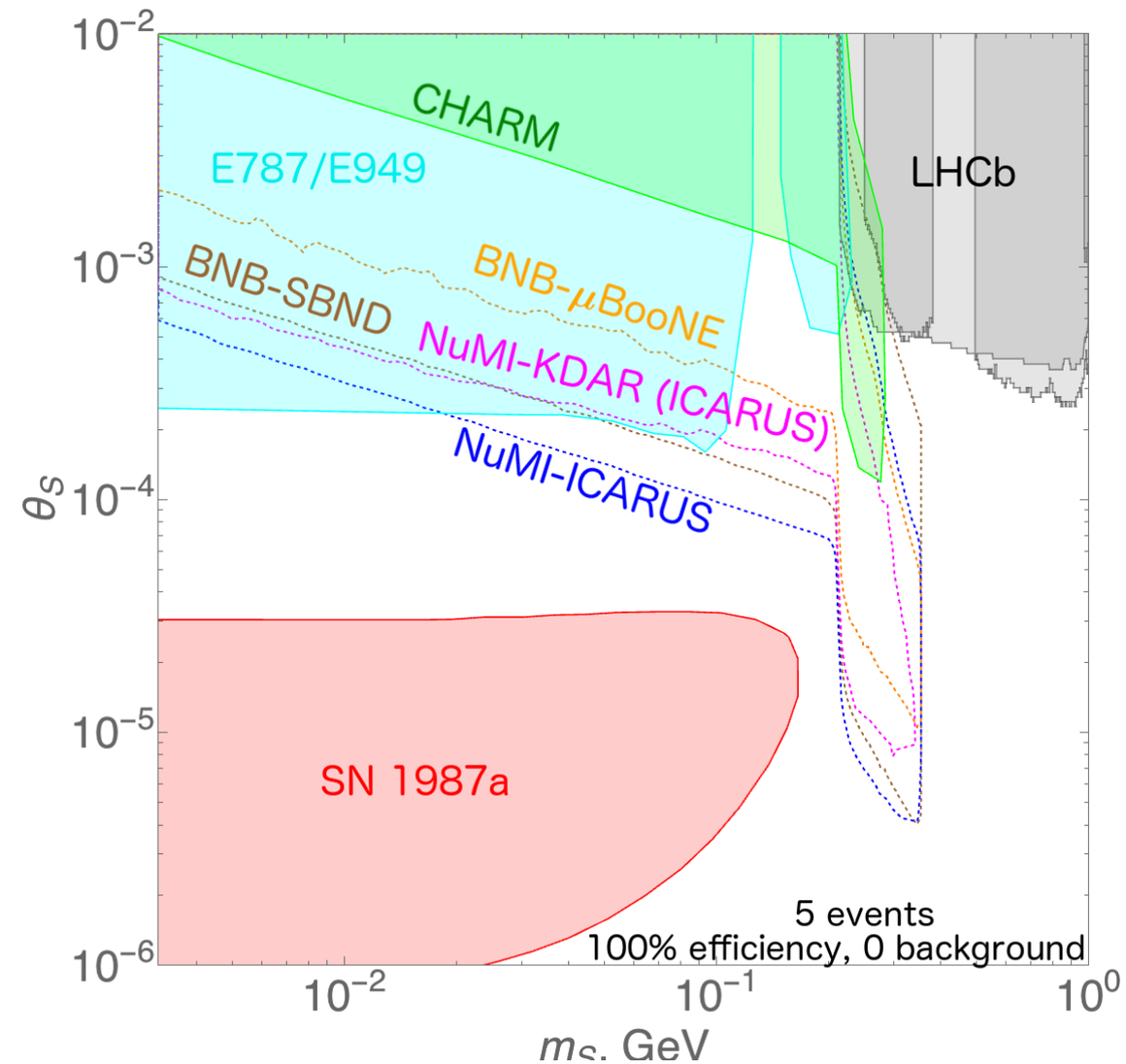
Batell, Berger, Ismail, 1909.11670



Higgs-mixed scalar boson
Long lived, visibly decaying



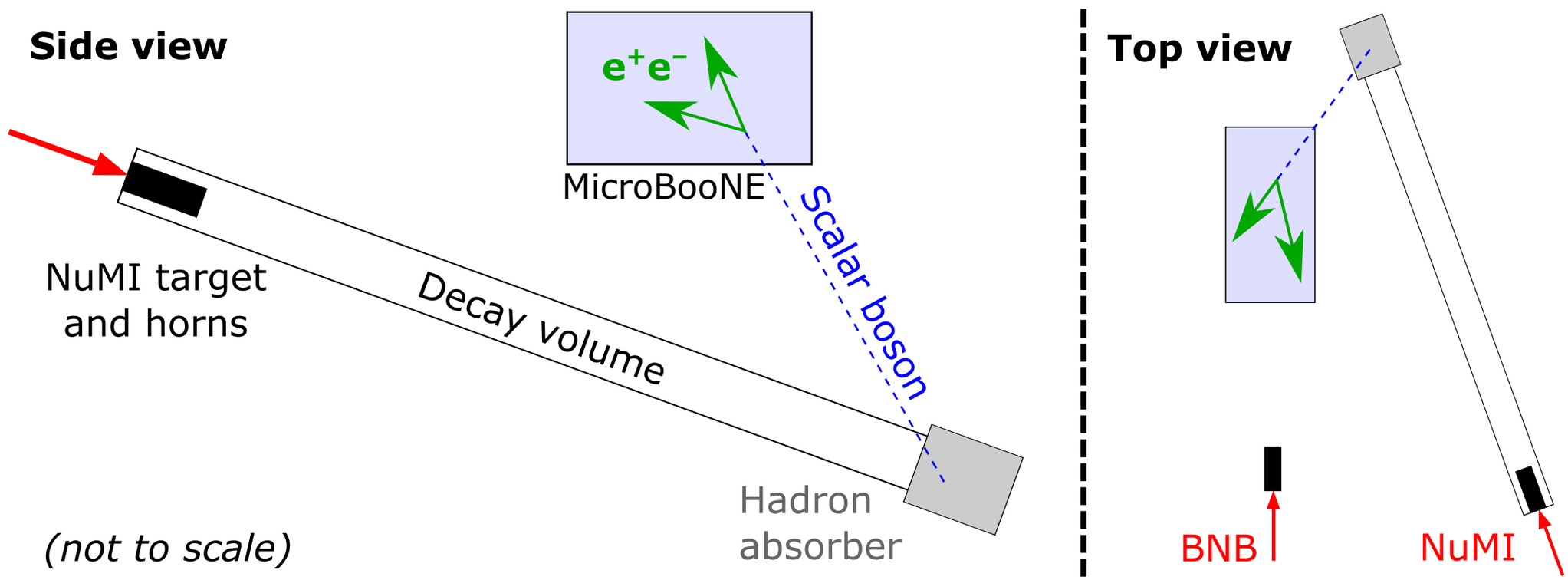
Proposed searches for rare meson decays inside beam dump



Projections for MicroBooNE, ICARUS, SBND
Searches involving 8 GeV (BNB) and 120 GeV proton (NuMI) beams

MicroBooNE (LLPs)

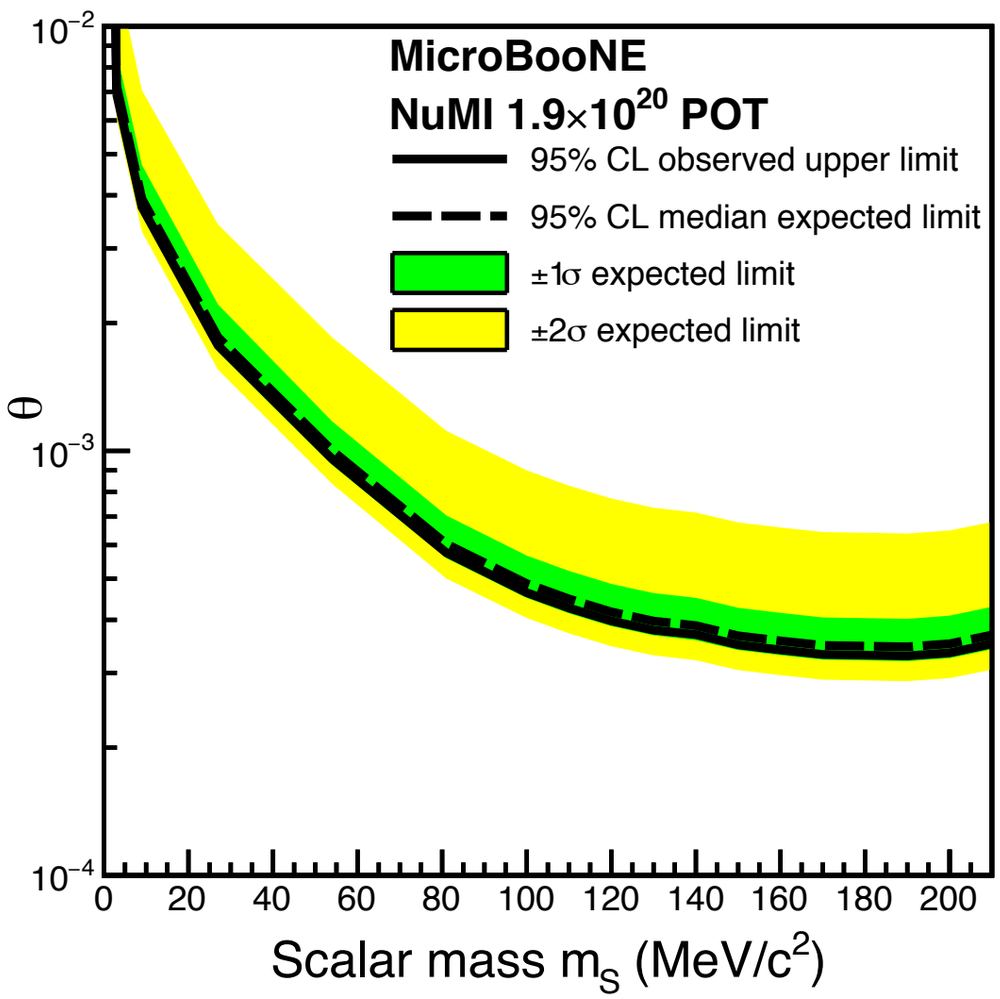
Batell, Berger, Ismail, 1909.11670
MicroBooNE Collaboration 2106.00568

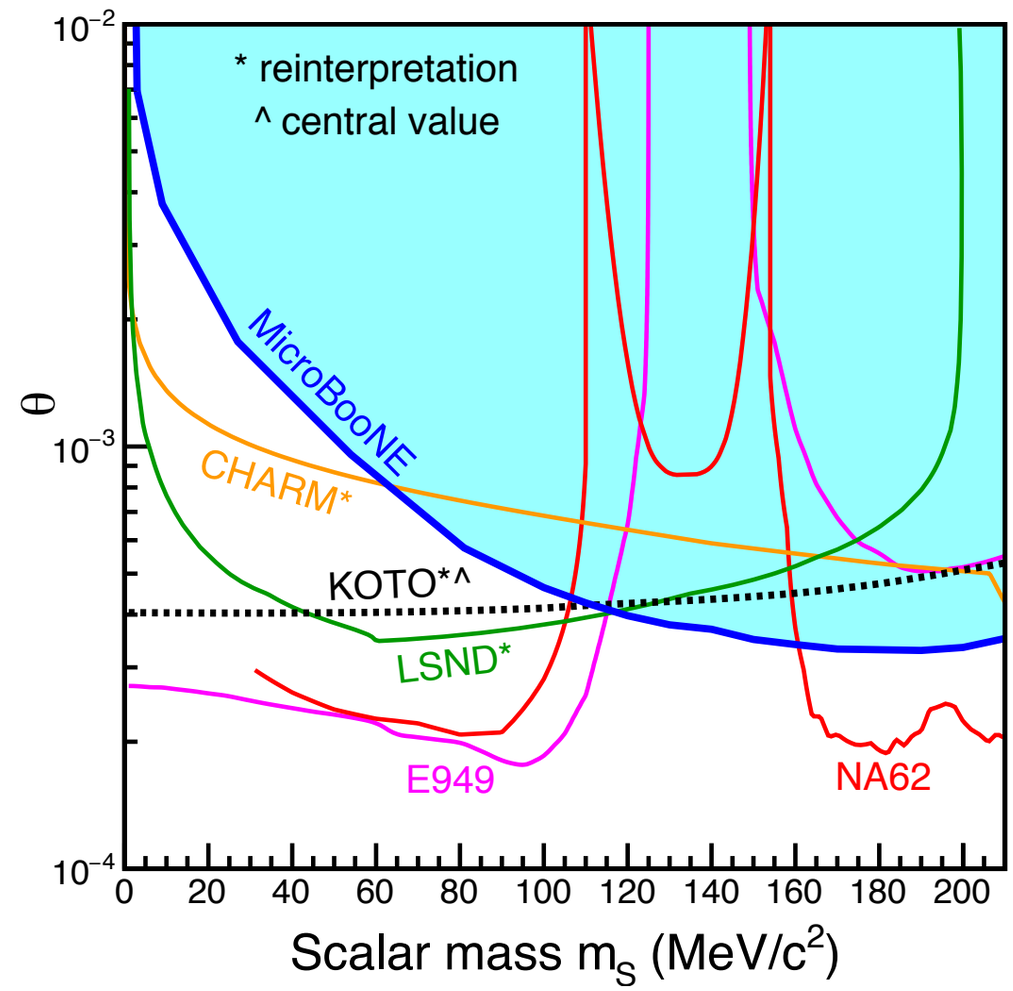


Sensitive to new long-lived particles decaying to e+e-
New search for Higgs-mixed scalar boson produced in absorber

MicroBooNE Collaboration 2106.00568

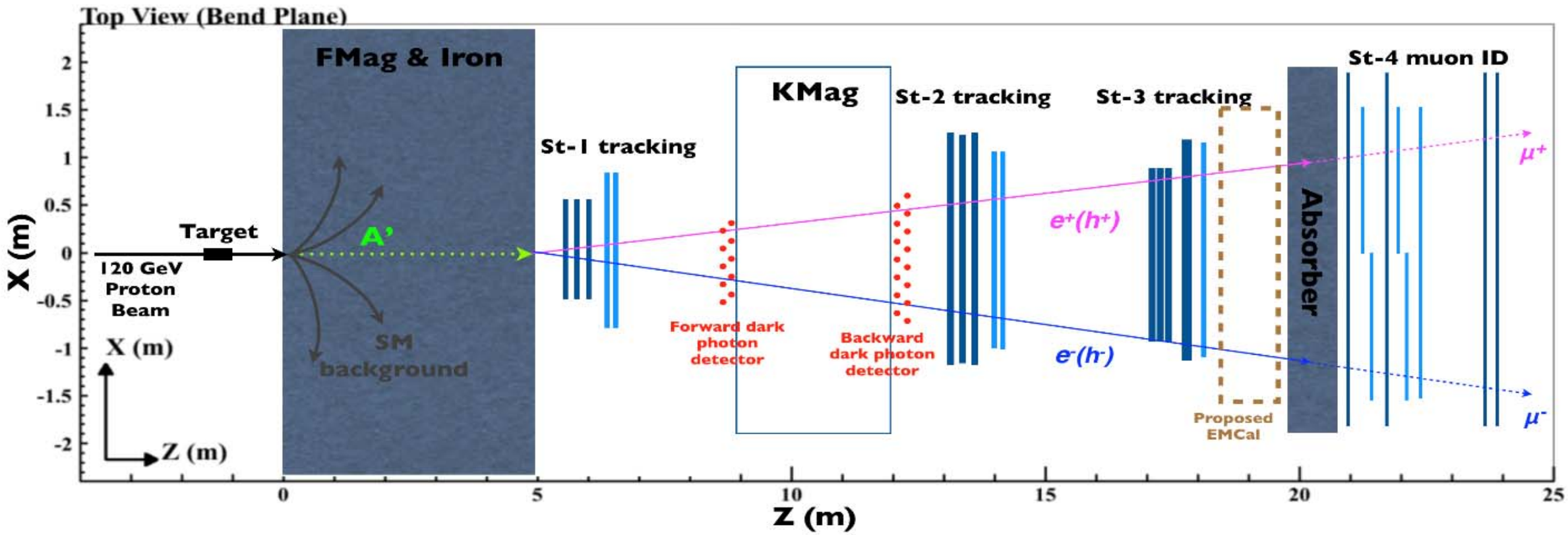
MicroBooNE (LLPs)





World leading results from a modest run in ~ 100 MeV mass range

DarkQuest (LLPs)

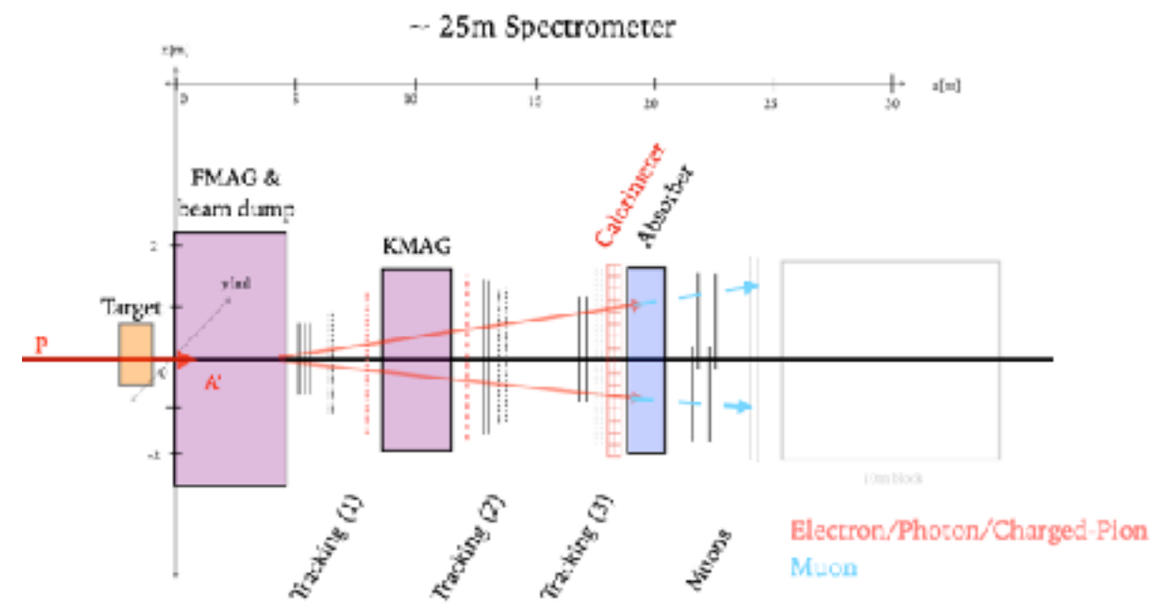


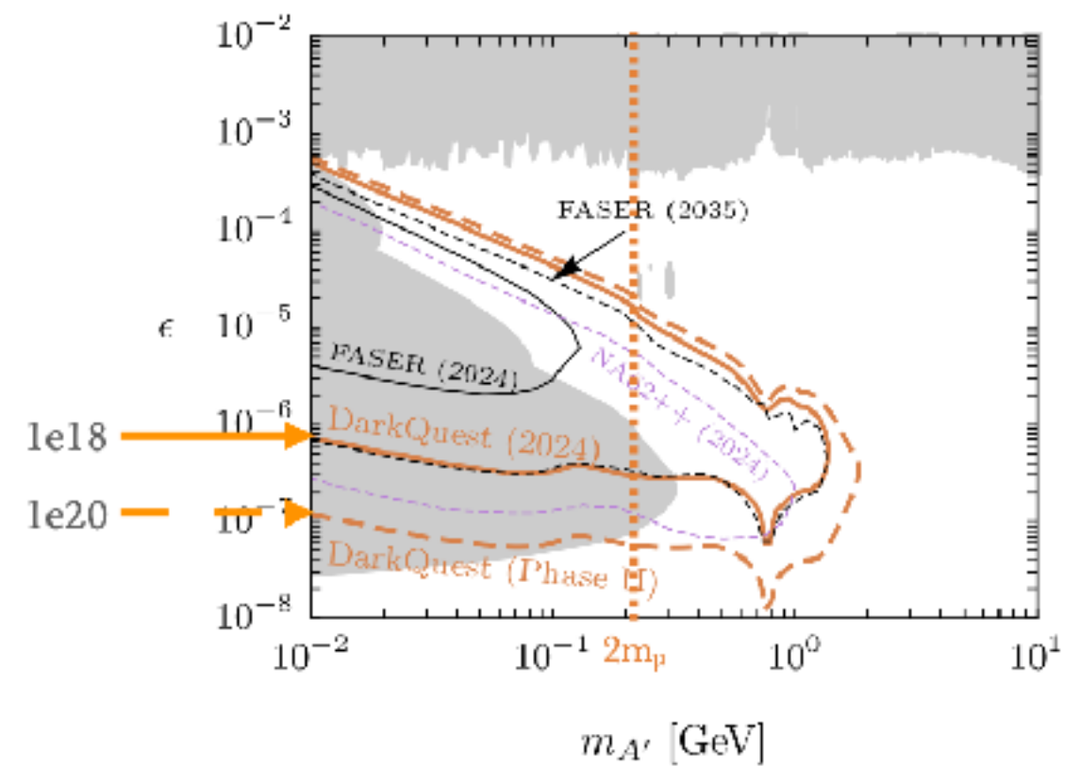
Berlin, Gori, Schuster, Toro 1804.00661

LDRD support
https://arxiv.org/abs/1804.00661
recent Pheno2021 talk

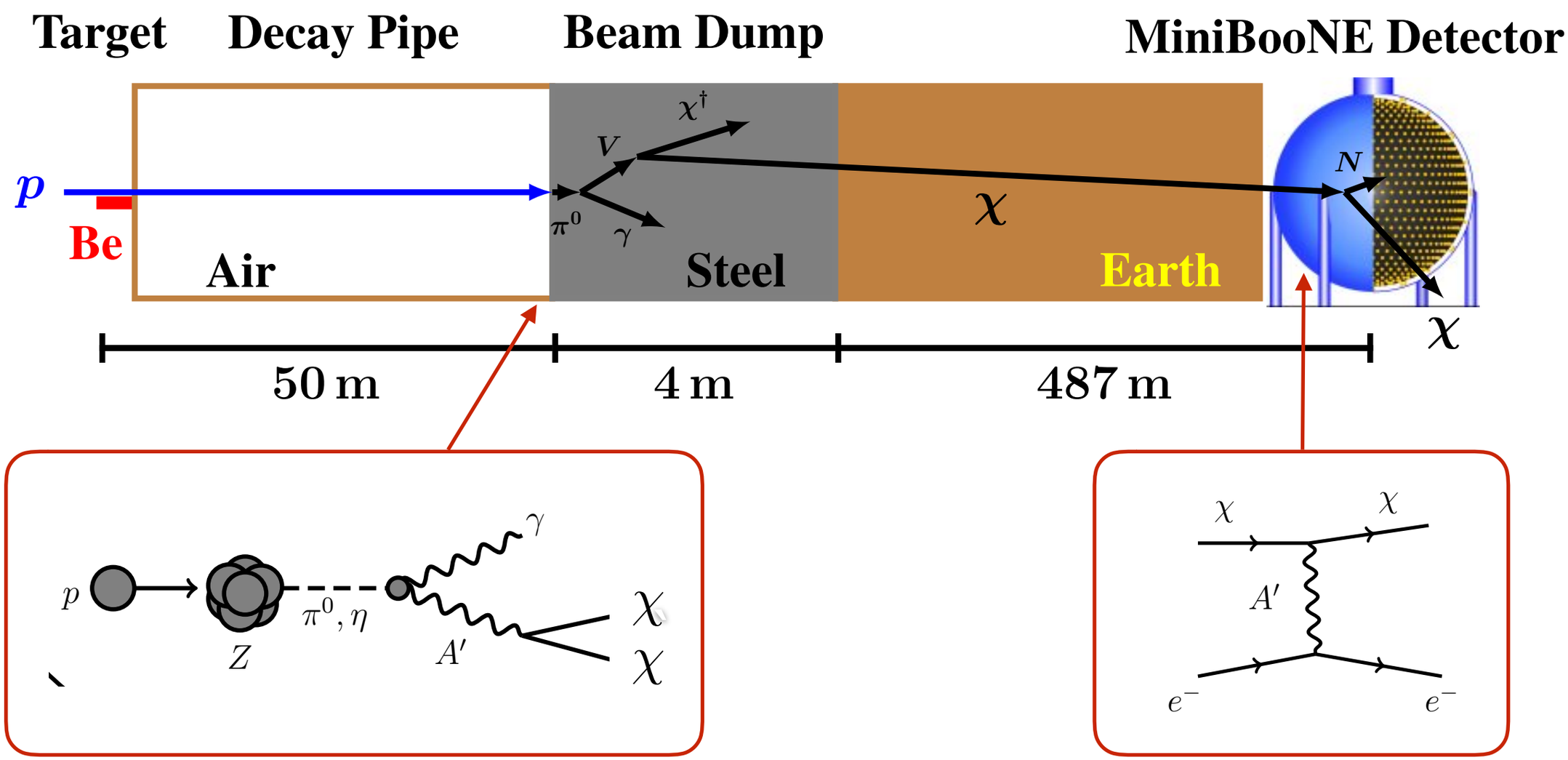
DarkQuest

- **Motivation**
  - Search for sub-GeV dark mediators in the **visible** final state
    - 120 GeV proton beam dump at FNAL
  - Covers new phase space due to **unique SpinQuest beam dump configuration**
    - Extends SpinQuest spectrometer with EMCal
- **Status**
  - DarkQuest members (FNAL, BU, MIT, LANL, JHU) integrating w/SpinQuest collaboration
    - FNAL: N. Tran, Y. Feng (PD), C. Mantilla Suarez (PD), A. Berlin (PD, theory), N. Blinov (PD, theory), Y.D. Tsai (PD, theory) involved in detector design and physics studies
  - Physics studies and design on-going
    - Project cost modest, < ~500k
  - Exploring funding opportunities both internal and external to FNAL, targeting FY24-25 physics run





MiniBooNE-DM



Batell, Pospelov, Ritz 0903.0363

Dobrescu, Friuguele 1410.1566
Kahn, Krnjaic, Thaler, Toups 1411.1055
Izaguirre, Kahn, Krnjaic, Moschella 1703.06881
De Gouvea, Fox, Harnik, Kelly, Zhang 1809.06388
Berlin, Kling 1810.01879
Di Romeri, Kelly, Machado 1903.10505
De Niverville, Tsai, Liu 1908.07525

Fermilab theory involvement in proton beam dump DM searches

MiniBooNE-DM

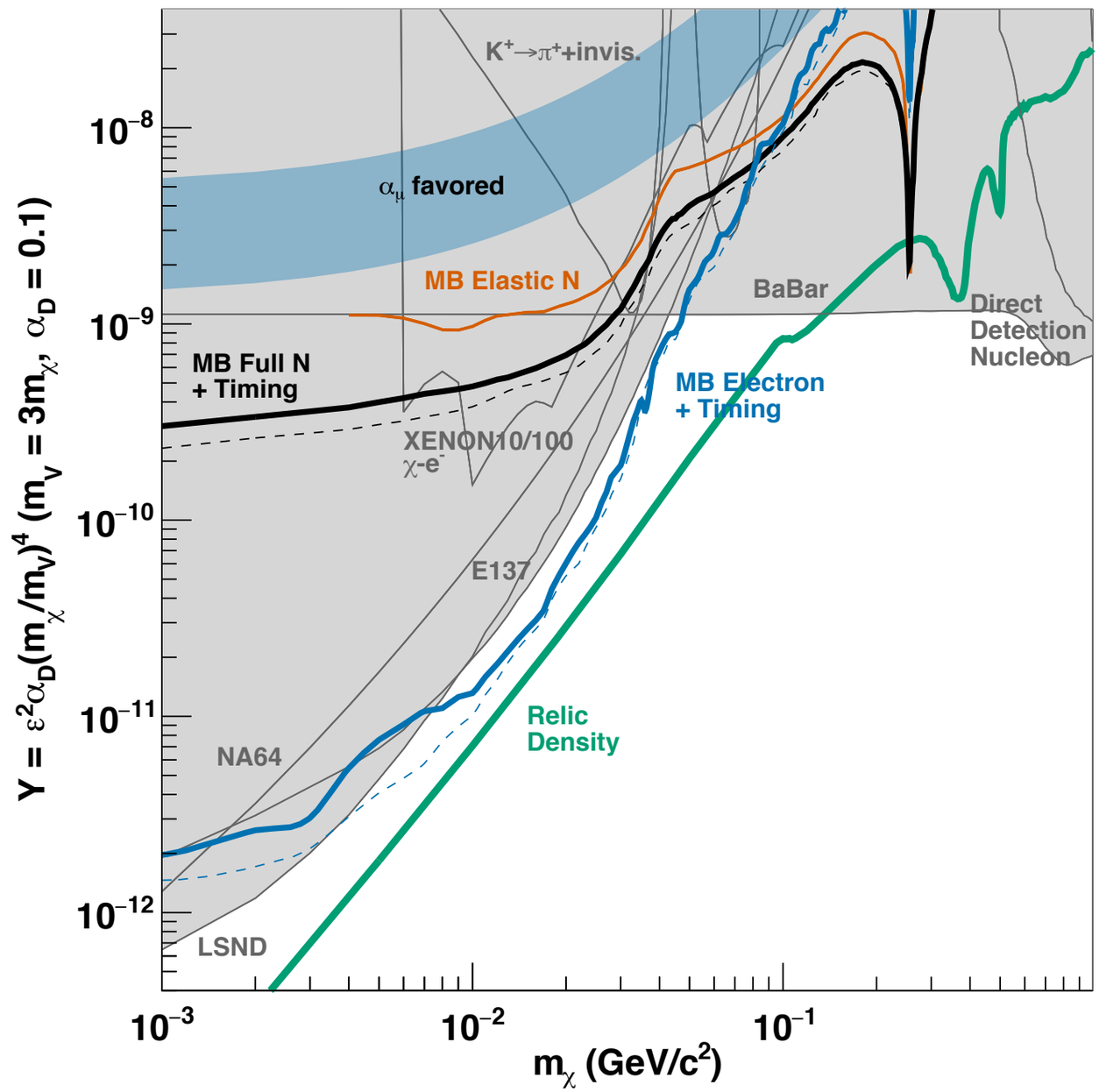
MiniBooNE-DM Collaboration 1807.06137

First ever dedicated accelerator search for light DM scattering

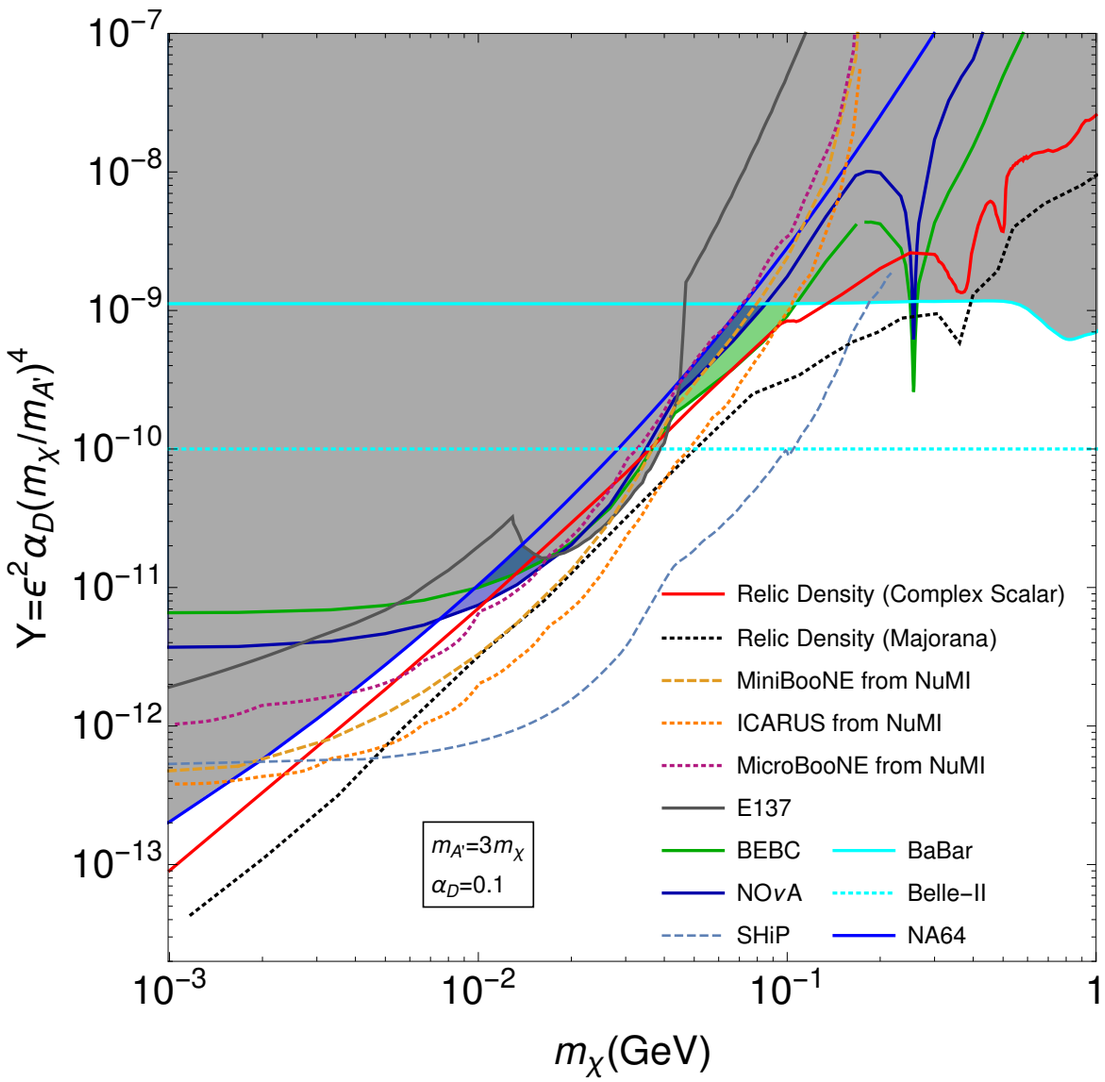
8 GeV proton beam, 2e20 POT
Uses timing to reduce NC-BG

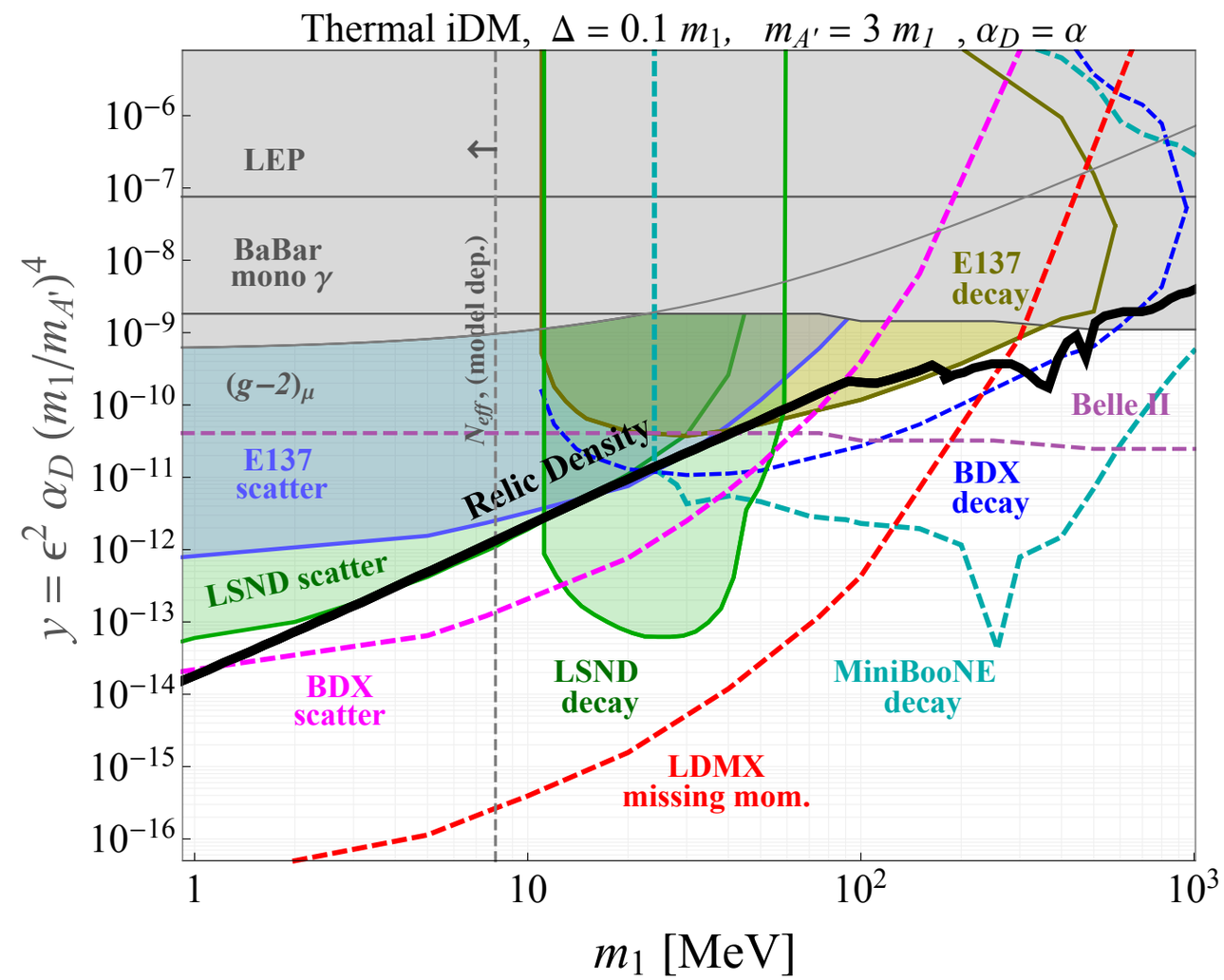
Beats 20+ year limits from theorist Reinterpretations of E137/LSND

Approaching key thermal DM production milestones



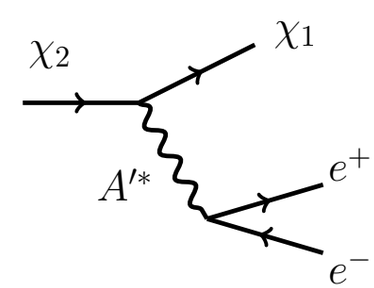
Future DM Reach @ FNAL Neutrino Experiments





Future DM scatter reach for @ FNAL neutrino experiments

Same strategy probes Inelastic DM decays



Buonocore, Frugiuele, deNiverville 1912.09346

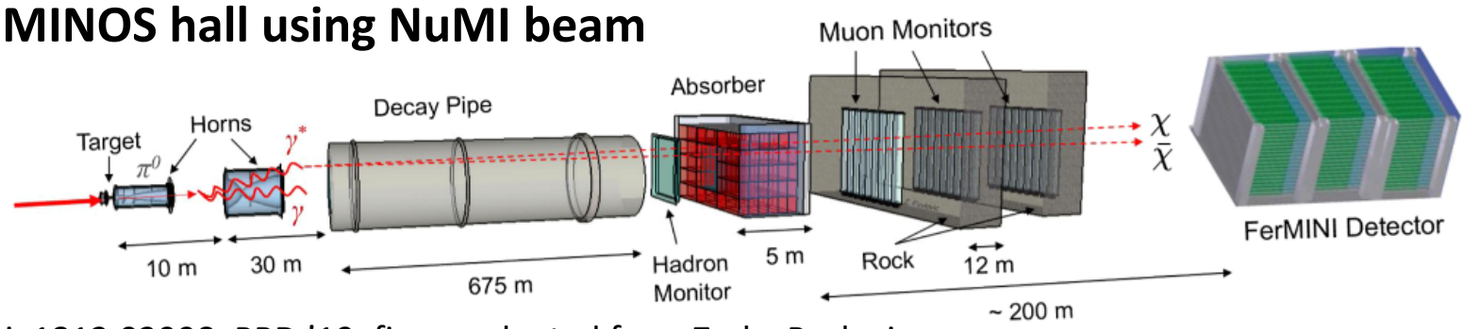
Izaguirre, Kahn, Krnjaic, Moschella 1703.06881

Batell, Berger, Darme, Frugiuele, 2106.04584

FerMINI

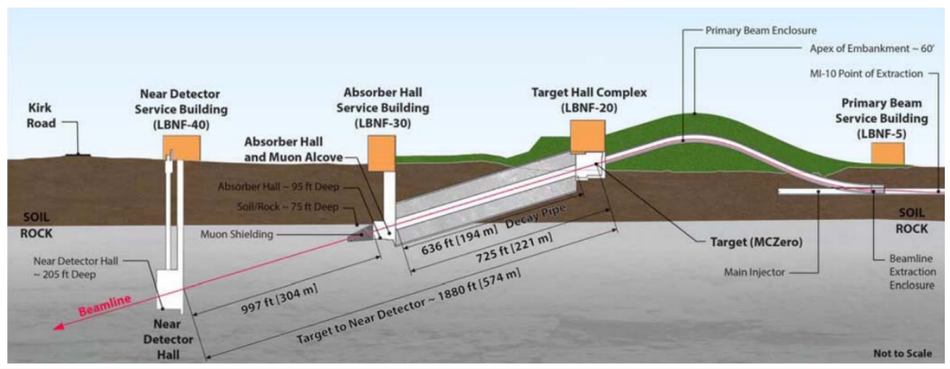
FerMINI: Fermilab Searches for Minicharged Particles

Site 1: MINOS hall using NuMI beam

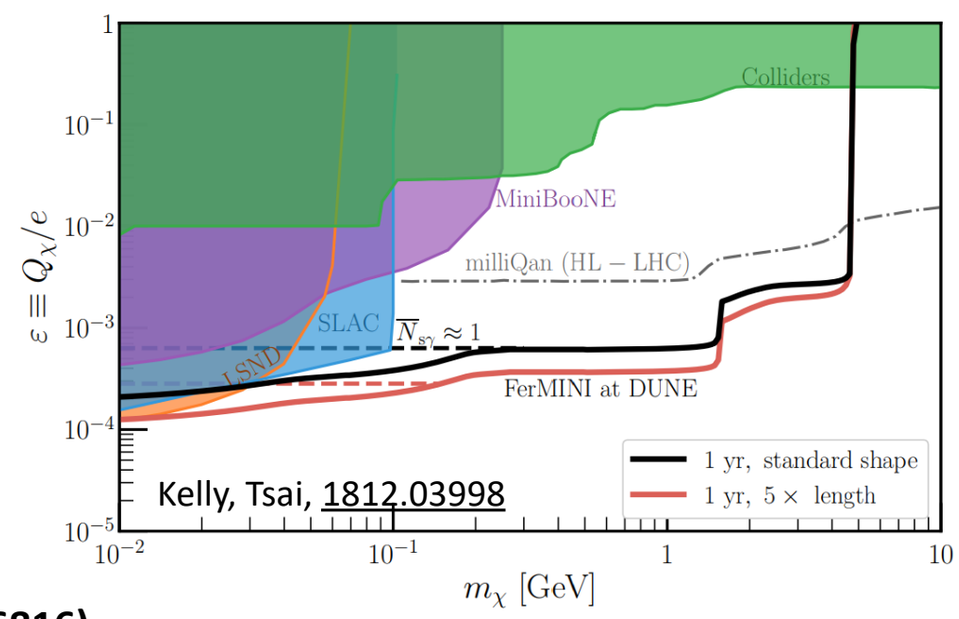


Kelly, Tsai, 1812.03998, PRD '19, figure adapted from Zarko Pavlovic

Site 2: DUNE near detector complex



Jonathan Asaadi – University of Texas Arlington



- Detector based on the **milliQan design (1410.6816)**
- **FerMINI (1812.03998)** inspired proposals: **SUBMET@JPARC (2007.06329)** & **FORMOSA@LHC (2010.07941)**
- mCP research updates: new constraints from **ArgoNeuT (1911.07996)**, **Super-K (2002.11732)**, and **milliQan-prototype (2005.06518)**

Yu-Dai Tsai
Fermilab 2021

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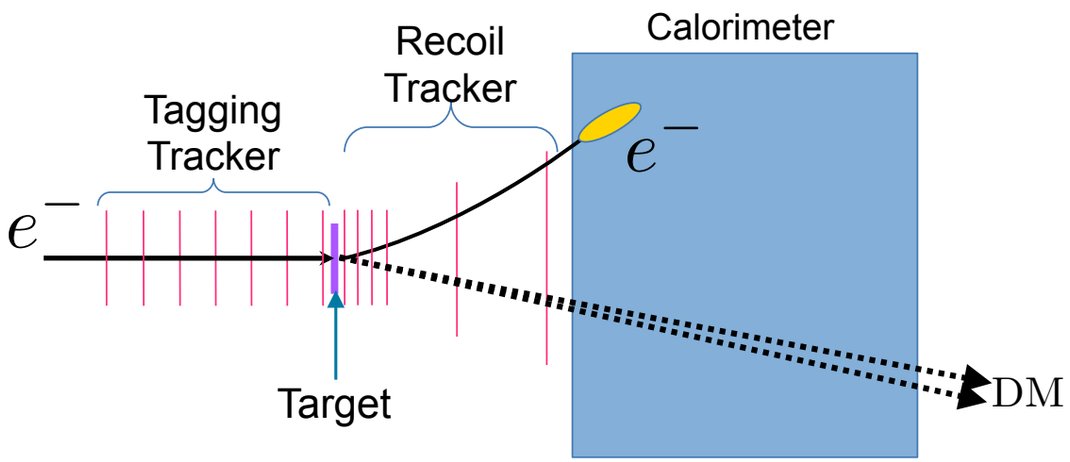
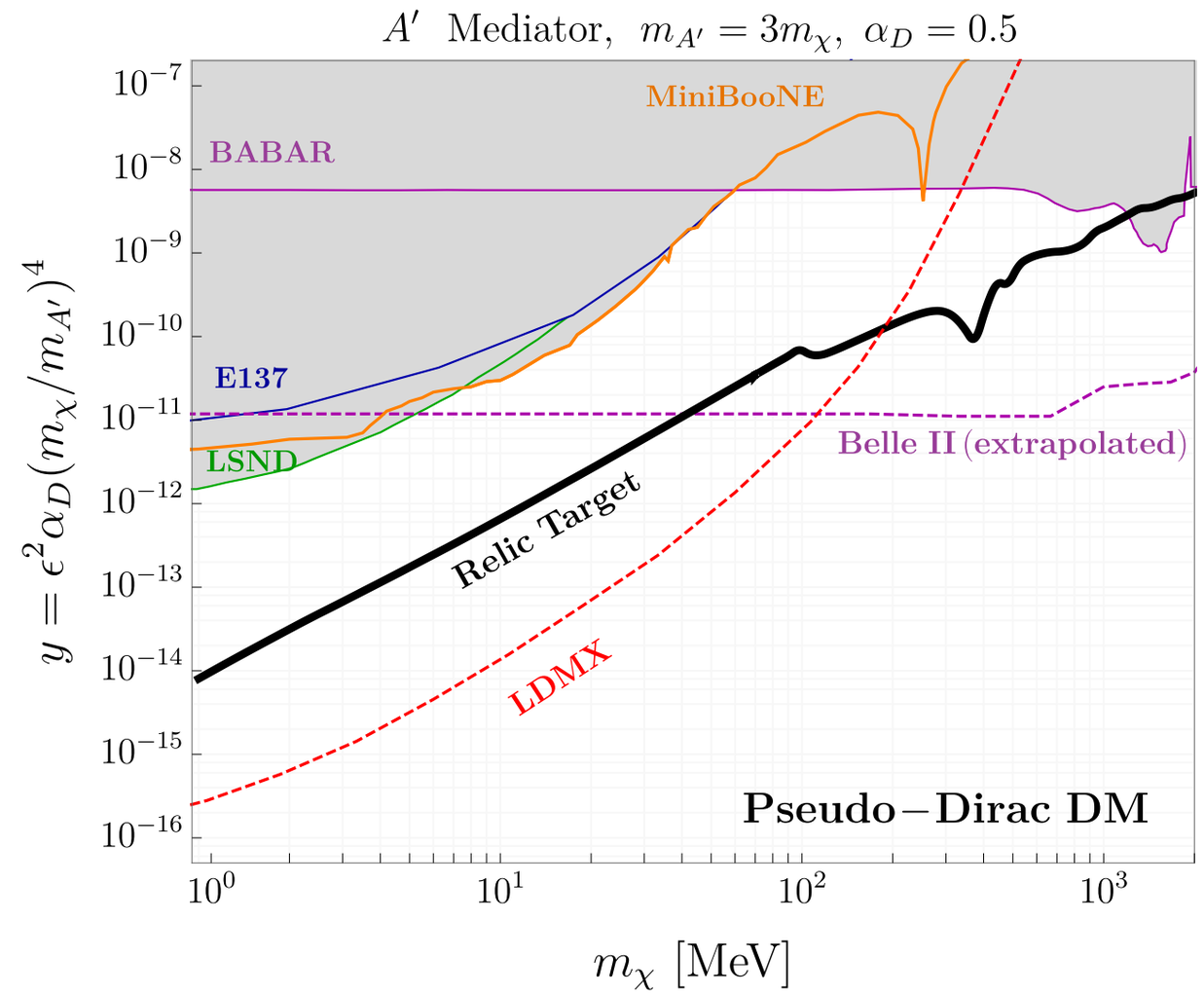
See also Harnik, Liu, Palamara 1902.03246 for ArgoNeuT+NUMI

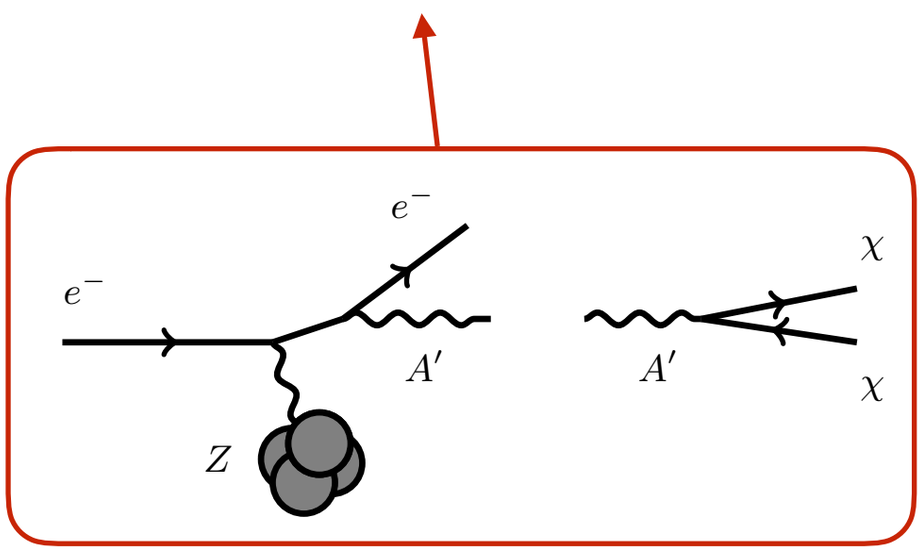
LDRD support
https://arxiv.org/abs/1804.00661
recent Pheno2021 talk

Lepton Beams

LDMX







1) Measure **each** e- energy in/out
2) Trigger on missing momentum
3) Veto additional SM activity

Only measure electron beam — don't require DM to scatter

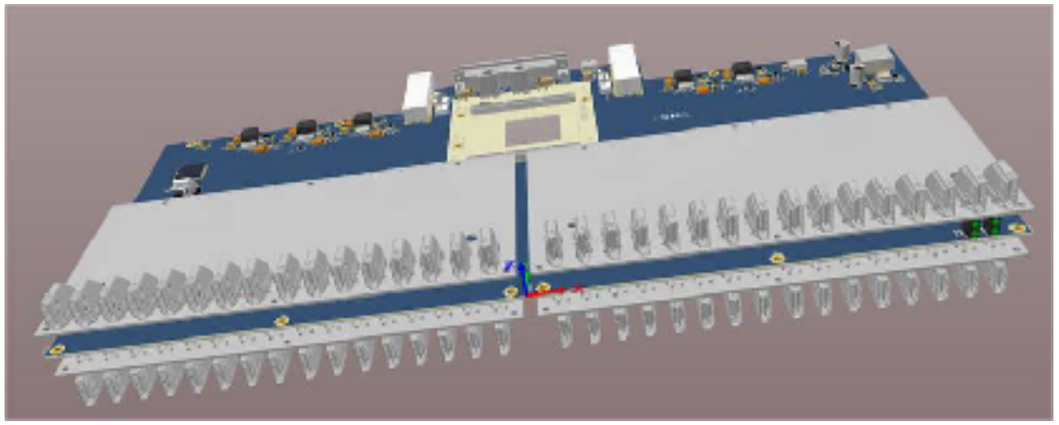
Izaguirre, Krnjaic, Schuster, Toro 1411.1404

LDMX

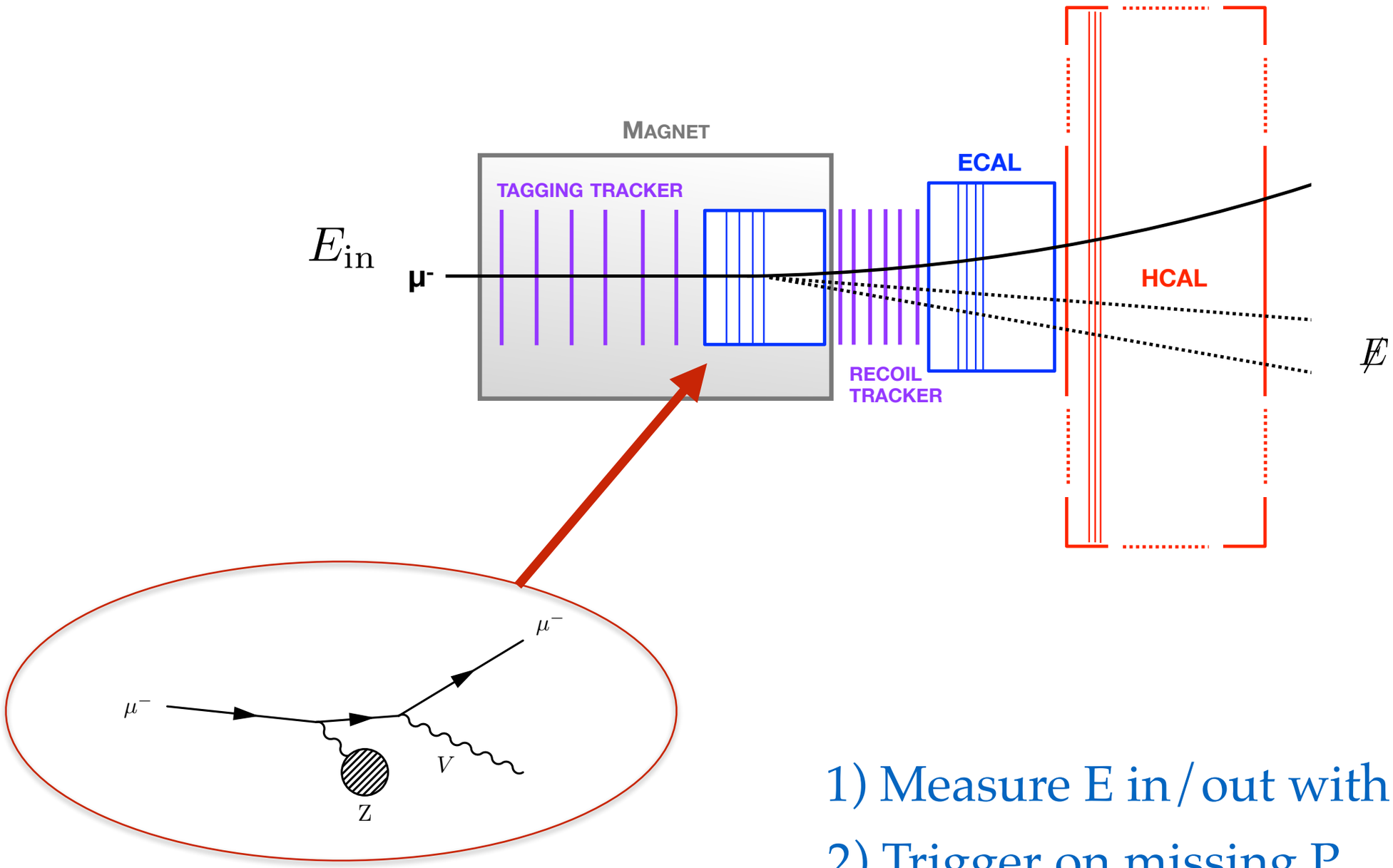
LDRD support
https://arxiv.org/abs/1808.05219
https://arxiv.org/abs/1912.05535
https://arxiv.org/abs/1912.06140

- **Motivation**
  - Search for sub-GeV dark matter in the **invisible** (DM) final state using **electron missing momentum technique**
    - Push current bounds by orders of magnitude to definitively cover thermal DM milestones
  - **Electron-nucleon scattering measurements** provide valuable input for DUNE
- **Status**
  - Funded as a part of DOE dark matter new initiatives (DMNI)
    - June review of DMNI projects just completed
  - Plan to run at End Station A at SLAC
- **Fermilab role**
  - Key contributor to Trigger and DAQ and HCal electronics
    - N.Tran leads TDAQ group
    - W. Ketchum, C. Herwig (PD), C. Mantilla Suarez (PD), G. Krnjaic (theory), N. Blinov (PD, theory), S. Li (PD, theory) involved in detector design and physics studies

FNAL HCal readout electronics design



M³: Muon Missing Momentum



1) Measure E in/out with B field

2) Trigger on missing P

3) Veto additional SM activity

Kahn, Krnjaic, Tran, Whitbeck 1804.03144, LDRD supported

M^3: Muon Missing Momentum

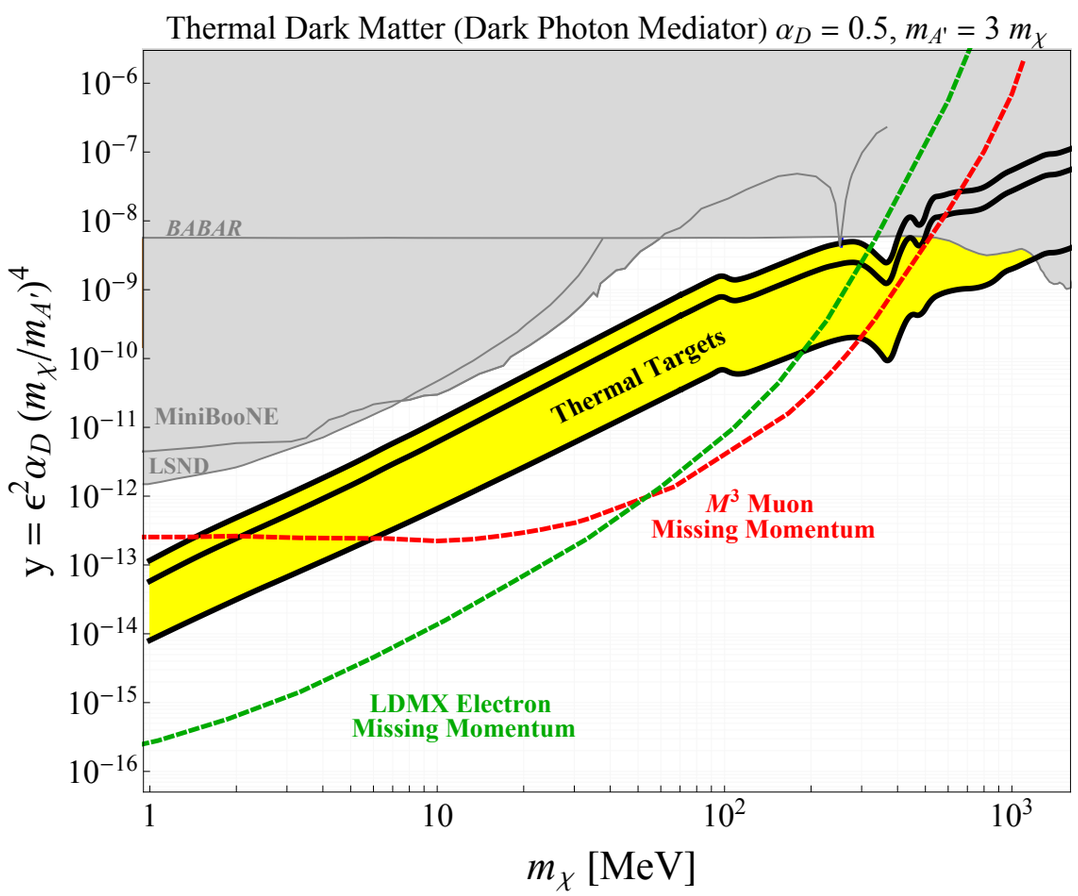
- **Motivation**
  - **Covers all light new physics related to g-2 for any invisibly decaying particle < m_μ**
  - Search for sub-GeV dark matter in the **invisible** (DM) final state using **muon missing momentum technique**
- **Status**
  - **With recent g-2 result, renewed enthusiasm** in exploring options
    - Cost, collaborations, beam options
    - Snowmass studies planned and ongoing
- **Fermilab role**
  - Fermilab has unique muon beam capabilities
  - Collaboration with UIUC and TTU
    - FNAL: G. Krjnaic (theory), N. Tran (PD), C. Herwig (PD), C. Mantilla Suarez (PD), involved in detector design and physics studies
  - Mini-workshop June 22 to discuss light new physics related to g-2 at Fermilab
    - https://indico.fnal.gov/event/48936

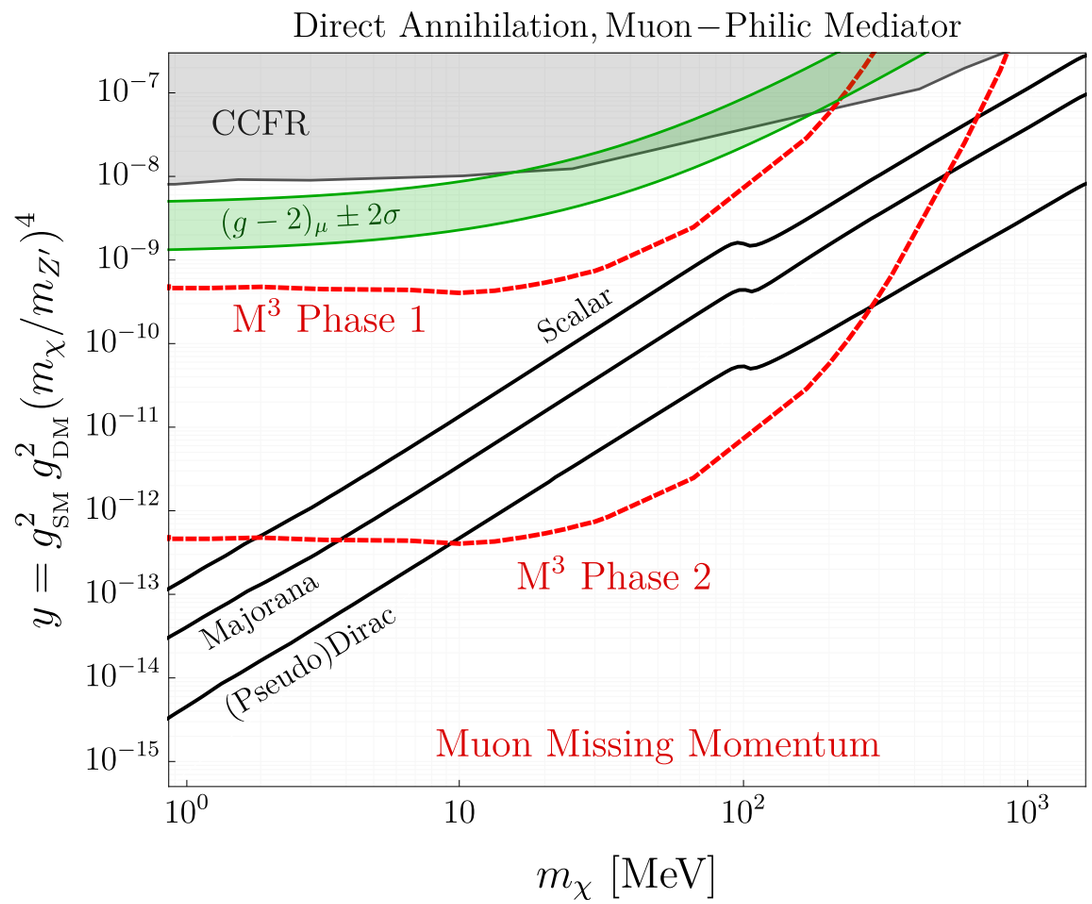
M³: Muon Missing Momentum

Time sensitive idea to follow up g-2 result
We would be happy to give a dedicated PAC talk about M³

For thermal DM milestones (lepton flavor universal), Muon Missing Momentum (M³) experiments have sensitivity to higher dark matter masses (> ~100 MeV)

Muon beams provide model-independent probe of light new physics contributing to $(g\text{-}2)_\mu$ anomaly





Kahn, Krnjaic, Tran, Whitbeck 1804.03144

Conclusion

Dark sector research @ FNAL covering full spectrum of strategies

Resonant cavities: << eV axions/ALPs/dark-photons, millicharged partilces
ADMX (DMNI funding), Dark SRF, dual cavity light shining through walls

Direct detection: MeV-GeV particle DM w/ low threshold (<< keV) detectors
Super-CDMS SNOLAB (HVeV), SENSEI/OSCURA (DMNI funding)

Accelerator production: MeV-GeV particle DM, light new forces (visible decays), millicharged particles, heavy sterile neturinos

Proton beams: Mini/MicroBooNE/SBN/ICARUS/DUNE/DarkQuest

Lepton beams: LDMX (electron), Muon Missing Momentum (muon @FNAL)

Lots of other cool things…

MAGIS-100 atom interferometry to probe gravitational waves and << eV DM
SRF cavities to probe dark photons, photon-photon scattering (axion mediated)
Muon beam dump experiments to probe long lived particles
Neutrino tridents to produce DM in NC scattering