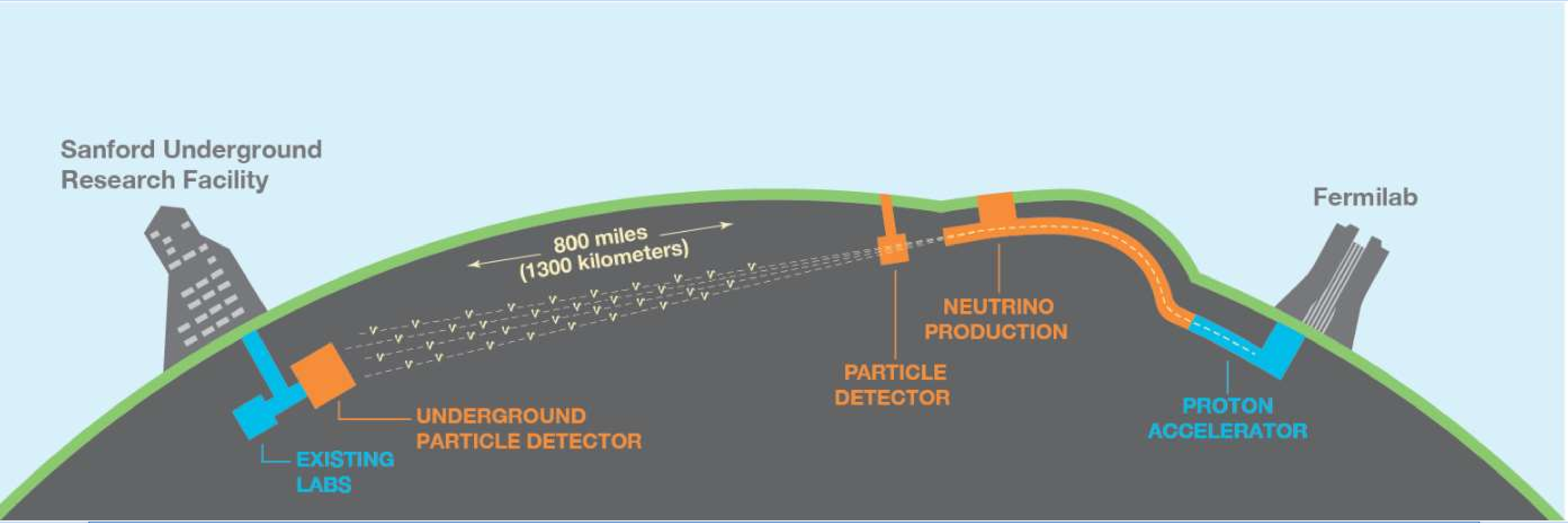


Millicharged Particles in Neutrino Experiments

arXiv:1806.03310

Yu-Dai Tsai, **Cornell University**

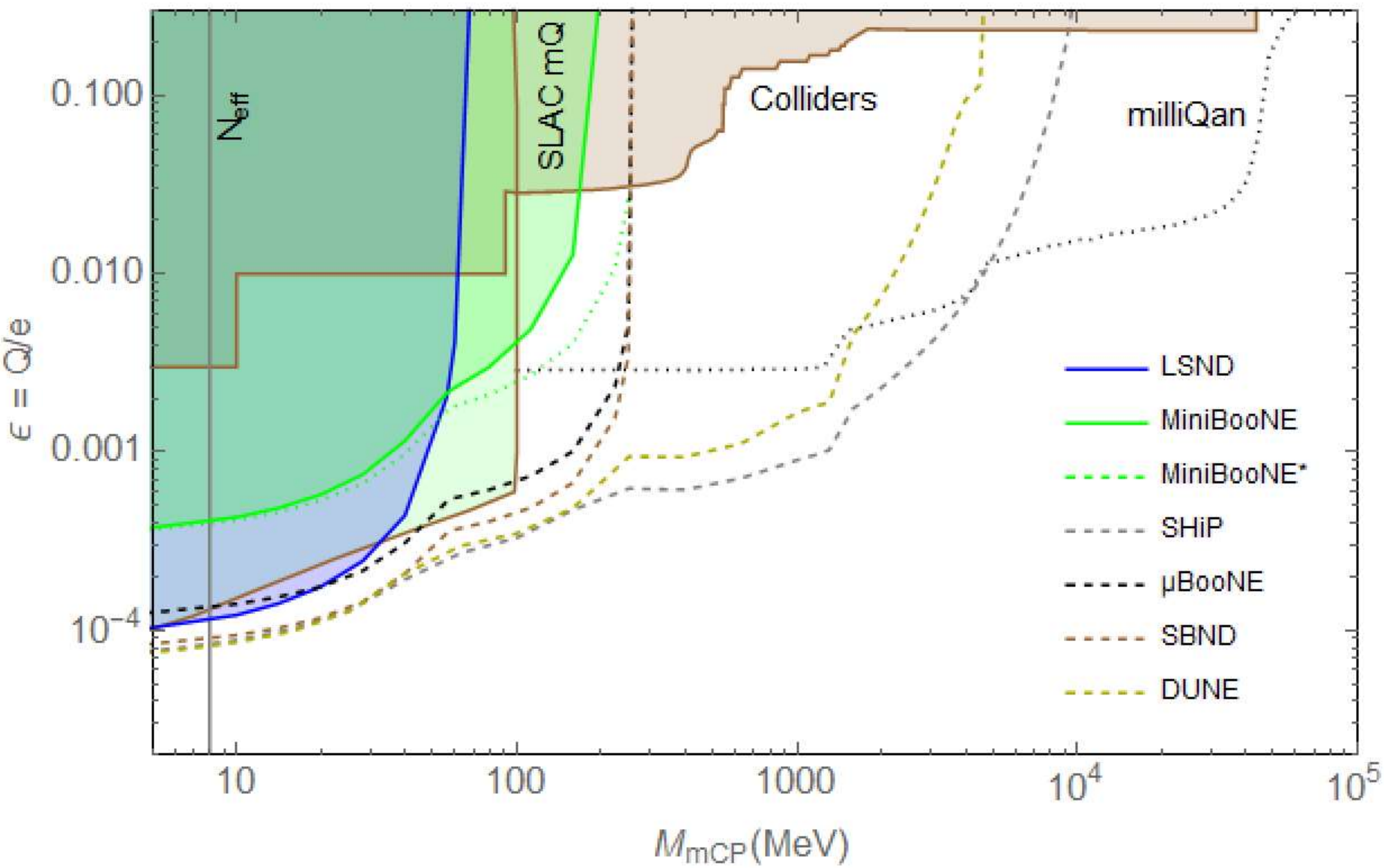
with Gabriel Magill, Ryan Plestid, and Maxim Pospelov

Thanks for the conference!

Outline

- **Motivations**
- **Intro to Millicharged Particle (mCP)**
- **Relevant Neutrino Experiments**
- **Sensitivity Reaches and Discussions**

Preview



Yu-Dai Tsai, CERN 2018

Millicharged Particles

Is electric charge quantized?
Models and implications

Yu-Dai Tsai, CERN 2018

Motivations of mCP Searches

- Testing **charge quantization** (Dirac monopole, Grand Unified Theory (GUT), etc)

- Natural link to **dark sector** (e.g. dark photon)

- Could account for DM (WIMP-like or other scenarios)

- Used to explain the cooling of gas temperature to explain the EDGES result [EDGES collab., Nature, (2018), Barkana, Nature, (2018)]. Only ~ 1% of the DM allowed given other constraints

- Neutrinos are **weakly interacting particles**! Just like **Millicharged particles**

Is charge quantized?

- Empirically, we have only seen quantized electric charge: Unit: e/3
- Theoretically, U(1) allows arbitrary charge
- Dirac quantization:
  - There is magnetic monopoles in simple **Maxwell's equations**: Dirac monopoles (magnetic charge g), with a Dirac string.
  - If we find such monopole (and Dirac string is hidden), this require $\mathbf{e \times g = 2\pi N}$ from the AB effect argument
  - Dirac (1931)
  - Aharonov & Bohm (1959)
  - **no such monopole found!:** charge doesn't have to be quantized

$$\nabla \cdot \mathbf{E} = \frac{\rho_v}{\varepsilon} \qquad \text{(Gauss' Law)}$$

$$\nabla \cdot \mathbf{H} = 0 \qquad \text{(Gauss' Law for Magnetism)}$$

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \qquad \text{(Faraday's Law)}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \qquad \text{(Ampere's Law)}$$

mCP: Models

- Small charged particles under U(1) hypercharge

$$\mathcal{L}_{\mathrm{mCP}} = i\bar{\psi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\mathrm{mCP}})\bar{\psi}$$

- Kinetic Mixing:

  - effectively generate this term in low energy

  - an example that gives rise to dark sector

  - easily compatible with GUT

Kinetic Mixing

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} B^{'}_{\mu\nu} B^{\mu\nu'} - \frac{\kappa}{2} B^{'}_{\mu\nu} B^{\mu\nu}$$

- Introduce an extra U(1), field strength B'
- Consider the low energy effect coupling between B and B'
- Holdom, 1985

Matter Field Charged under U(1)’

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B^{'}_{\mu\nu}B^{\mu\nu'} - \frac{\kappa}{2}B^{'}_{\mu\nu}B^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie'B' + iM_{\rm mCP})\psi$$

- Field redefinition into a more convenient basis

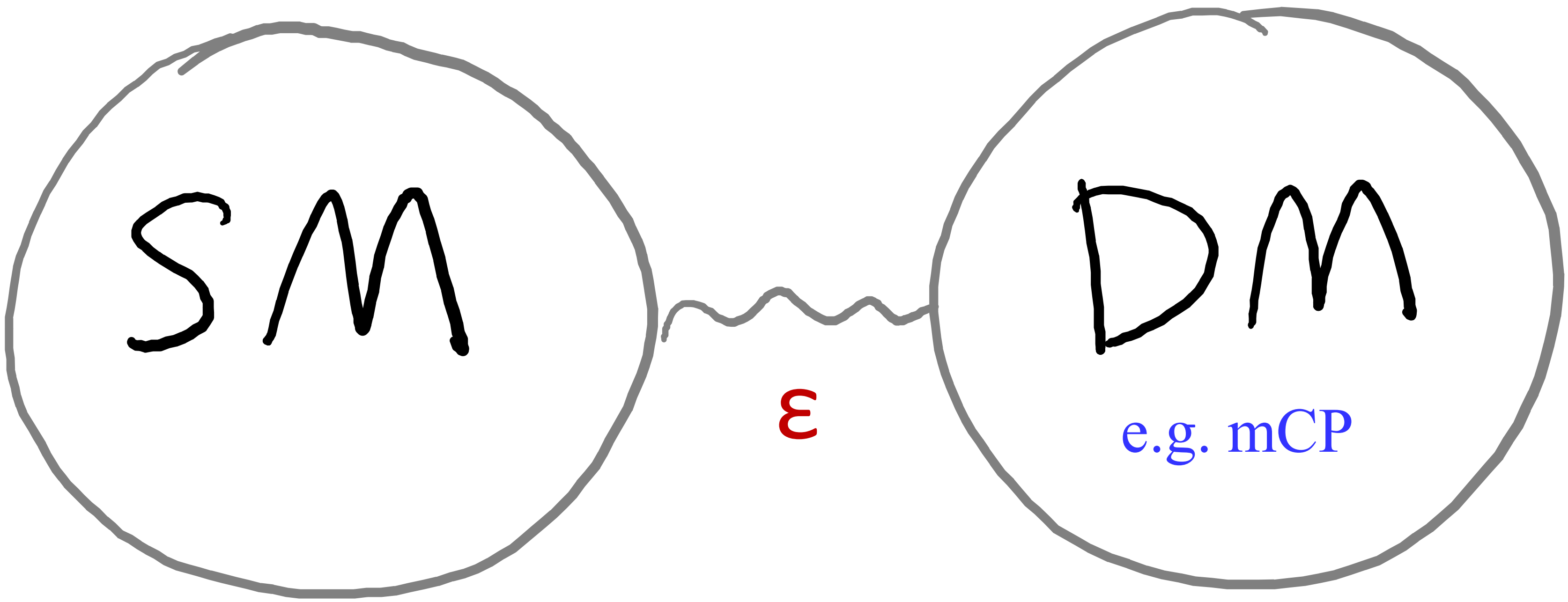
$$B' \to B' + \kappa B$$

- Getting rid of the mixing term

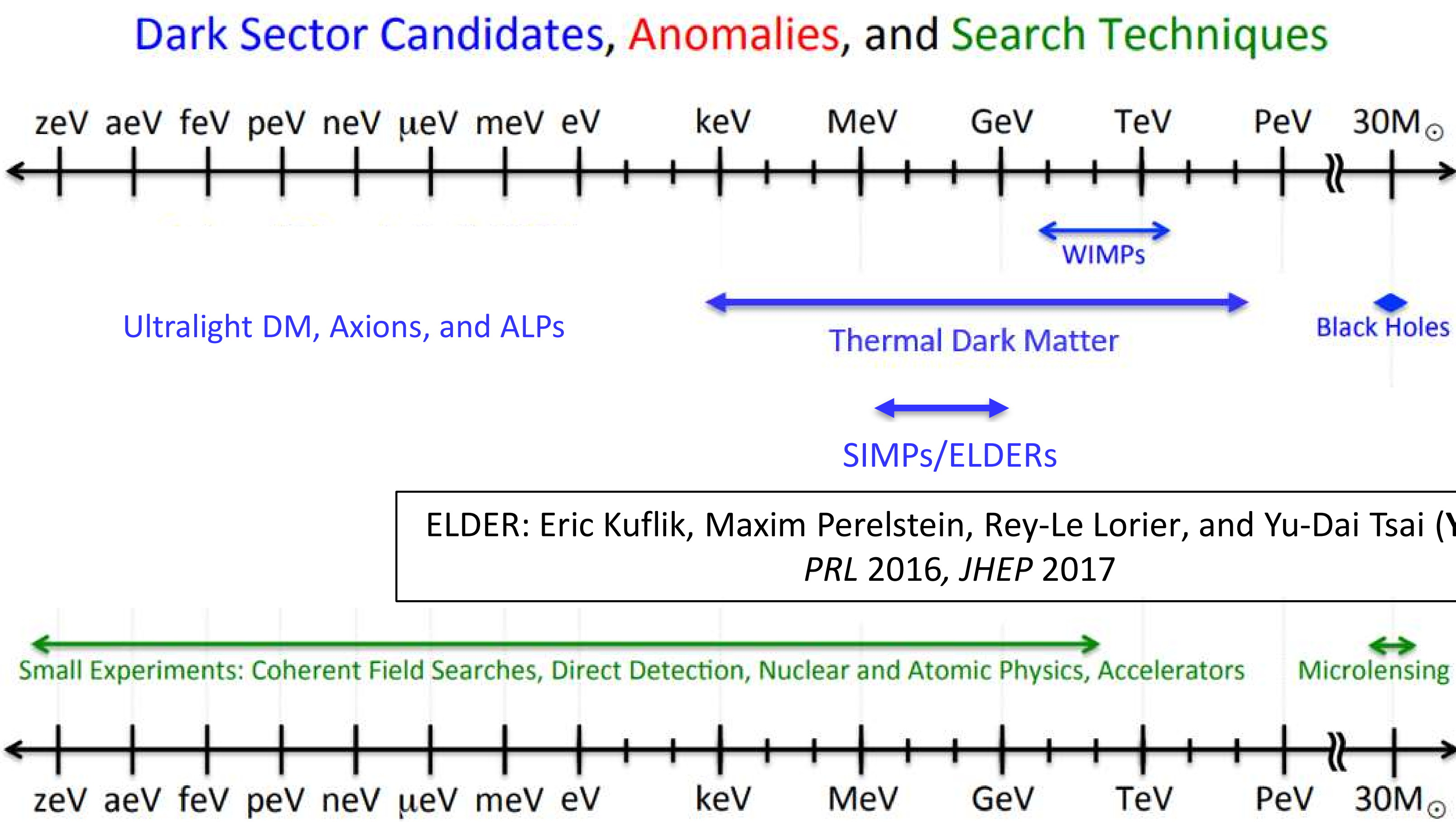
- After EWSB the new fermion acquires an small EM charge Q (the charge of mCP ψ):

$$Q = \kappa e' \cos\theta_W. \quad \epsilon \equiv \kappa e' \cos\theta_W / e.$$

The Rise of Dark Sector



Dark Matter/Hidden Particles Exploration



ELDER: Eric Kuflik, Maxim Perelstein, Rey-Le Lorier, and Yu-Dai Tsai (**YT**)
PRL 2016, *JHEP* 2017

US Cosmic Visions 2017

Yu-Dai Tsai,
CERN 2018

- My Ph.D. study focuses on DM/dark sector model building
- Neutrino experiments are important!

Neutrino Experiments

- Neutrinos are weakly interacting particles
- High statistics (e.g. LSND: 10^{23} POT)
- Low background, well shielded (e.g. solar neutrino programs)
- There are many of them existing and many to come: ***strength in numbers***
- Produce hidden particles without DM assumptions: more direct than cosmology/astrophysics bounds

ν Hopes for New Physics: Personal Trilogy

⋮

- Dark Scalar/Dark Photon at Borexino & LSND

  (1706.00424, Pospelov & **YT**)

- Heavy Neutral Lepton at SHiP & Fermilab

  (1803.03262, Magill, Plestid, Pospelov & **YT**)

- Millicharged Particles in Neutrino Experiments

  (1806.03310, Magill, Plestid, Pospelov & **YT**)

⋮

Not All Bounds Are Created Equal

"Directness" $\longrightarrow$

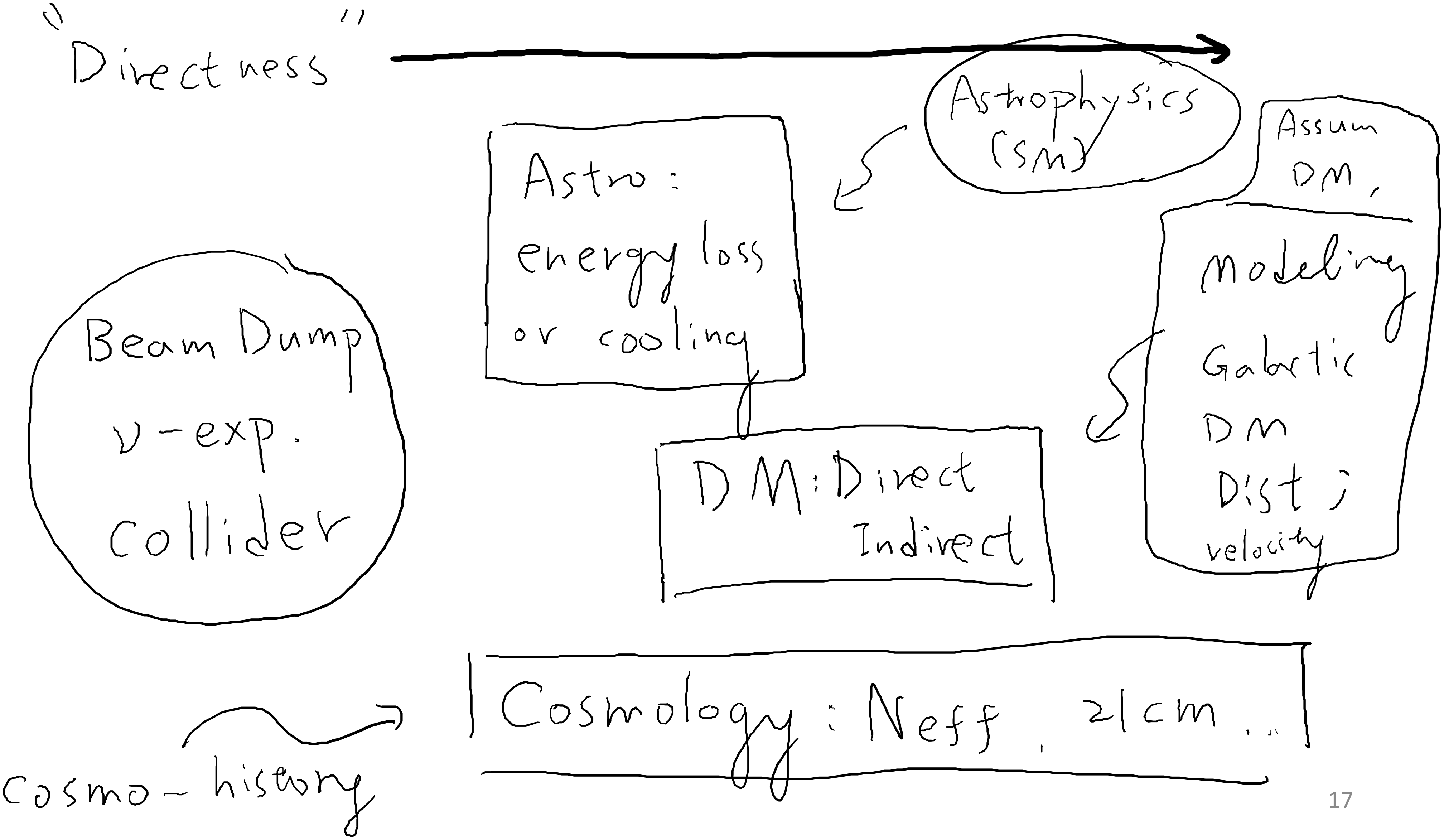
Astro: energy loss or cooling

Beam Dump
ν-exp.
collider

DM: Direct
Indirect

Cosmology: N_{eff}, 21cm ...

Bounds with Different Assumptions



IMPORTANT NOTE

- Our search is **independent of the model I described**
- We simply search for particles (fermions) with {mass, electric charge} = $\{m_\chi, \epsilon e\}$
- **mCPs do not have to be DM in our searches**
- The bounds we derive constrain the DM as well as dark sector scenarios.
- Not considering bounds with dark photon (strong cosmology bound on low mass dark photon)

The mCP we look for

- Our mCP: heavier “electron” with a very small electric charge
- Can be called:

  “Heavy Milli-Electron (HME)”

  or just “ME”

Millicharged Particle Generics

in our consideration

MCP production

- Fixed target neutrino experiments: production of neutrinos from weak decays of charged pions. Similar spectrum of $\boldsymbol{\pi^0}$ is produced (inferred by comparing the production of π^0 and π^+ in pp and pn collisions ([Teis, Cassing, Effenberger, Hombach, Mosel, Wolf, 1996]), or by using counting arguments on the number of production [Norbury & Townsend, NIM B, 2007].
- For large beam energies, other neutral mesons (e.g. **η, Υ, J/ψ**) are also produced.
- Any **significant branching ratios of electromagnetic decays to lepton pairs** implies an corresponding **decay to pairs of mCPs**, resulting in a significant flux of mCPs, even with small charges.

mCP Production

- For η and π^0, Dalitz decays: $\pi^0/\eta \rightarrow \gamma\, \chi\, \bar{\chi}$ dominate
- For J/ψ and Y, direct decays: J/ψ, Y $\rightarrow \chi\, \bar{\chi}$ dominate.
- The branching ratio for a meson, $\mathcal{M}$, to mCPs is given roughly by

$$\mathrm{BR}(\mathcal{M} \rightarrow \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \rightarrow X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right),$$

- M: the mass of the parent meson, X:any additional particles, $f(m_\chi/M)$: phase space factor that decreases slowly as a function of m_χ/M.
- The number of mCPs passing through the detector is a function of both the **branching ratio** and **geometric losses** which can vary significantly between experiments
- Also consider **Drell-Yan production of mCP** from **q q-bar annhilation**.

MCP Detection

- Detection signature: **elastic scattering with electrons**.
- Look for single-electron events
- **The dominance of electron scattering as a detection signal** is related to the **low- Q^2 sensitivity of the scattering cross section.**
- Explicitly, in the limit of small electron mass, we have

$$\frac{\mathrm{d}\sigma_{e\chi}}{\mathrm{d}Q^2} = 2\pi\alpha^2\epsilon^2 \times \frac{2(s-m_\chi^2)^2 - 2sQ^2 + Q^4}{(s-m_\chi^2)^2 Q^4}.$$

MCP Detection

- Integrate over momentum transfers, the total cross section will be dominated by the small Q^2 contribution
- In this limit, we have $\sigma_{e\chi} \approx 4\pi\, \alpha^2 \varepsilon^2 / {Q_{min}}^2$.
- We can relate Q_{min} in the lab frame to the recoil energy of the electron via $Q^2 = 2m_e\,(E_e - m_e)$.
- An experiment's recoil energy threshold, ${E_e}^{(min)}$, then sets the scale of the detection cross section as

$$\sigma_{e\chi} = 2.6 \times 10^{-25}\text{cm}^2 \times \epsilon^2 \times \frac{1\ \text{MeV}}{E_e^{(\text{min})} - m_e}.$$

MCP Detection

$$\sigma_{e\chi} = 2.6 \times 10^{-25}\text{cm}^2 \times \epsilon^2 \times \frac{1 \text{ MeV}}{E_e^{(\text{min})} - m_e}.$$

- Sensitivity to mCPs can be greatly enhanced by accurately **measuring low energy electron recoils**
- An important feature for **search strategies at future experiments for mCP's**

MCP Signals

- Our sensitivity curves are obtained by performing a standard sensitivity analysis:
- Given a number of background events b and data n, the number of signal events s_{up} . The $(1 - \alpha)$ credibility level is found by solving the equation $\alpha = \Gamma(1 + n, b + sup)/\Gamma(1 + n, b)$, where $\Gamma(x, y)$ is the upper incomplete gamma function [PDG, PLB 2010].
- Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ (~ 2 sigma)

$$s_{\rm up} = \sum_{\rm Energies} N_\chi(E_i) \times \frac{N_e}{\rm Area} \times \sigma_{e\chi}(E_i;\, m_\chi) \times \mathcal{E}.$$

MCP Signals Recap

$$s_{\text{up}} = \sum_{\text{Energies}} N_\chi(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i;\, m_\chi) \times \mathcal{E}.$$

efficiency

- $s_{up} \propto \varepsilon^4$. Roughly, $\varepsilon \propto E_{e,\,R,min}^{1/4}\, B^{1/8}$.
- For most of the mCP parameter space under consideration, **electromagnetic decays of mesons** provide the dominant flux contribution
- **Drell-Yan production (DYP) dominates for the large mCP masses** that are only accessible at **DUNE** and **SHiP**.
- For DYP, we integrate over the full production phase-space using **MSTW parton distribution functions** [Martin, Stirling, Thorne, Watt, 2009]

Background Estimation

- So, how do we estimate the single-electron background for ongoing/future experiments?
- For **MicroBooNE, SBND, DUNE, and SHiP**
- We consider two classes of backgrounds:

  1) Coming from neutrino fluxes (calculable)

     [i.e. **νe** → **νe** and **νn** → **ep**],

  2) Other sources such as

     beam related: **dirt related events**, **mis-identified particles**

     external: **cosmics**, etc

Background Estimation

- We treat neutrino induced backgrounds for each experiment by **summing over the neutrino-flux contributions provided by each collaboration** and accounting for the detection efficiencies.
- A large background reduction is obtained by **imposing the maximum electron recoil cuts E_e(max)**.
- These do not significantly affect the signal (which is dominated by low electron recoils), but significantly reduce charged and neutral current backgrounds.

Background Estimation

- We model the external sources of backgrounds by multiplying the neutrino induced backgrounds by an overall multiplicative factor (these phenomenologist…)
- LAr-TPC detectors can use timing information **as vetoes to reduce backgrounds**; this is **not possible in a nuclear emulsion chamber** (a naïve statement?)
- Therefore, we multiply our neutrino induced backgrounds by a factor of **10 for LArTPC detectors** (MiniBooNE, SBND, and DUNE) and a factor of **25 for nuclear emulsion detectors** (SHiP); this increase in the backgrounds decreases our sensitivity to ε by 20−30%
- Although this procedure could under/overestimates the backgrounds, we emphasize that **our results can be easily revised for different background assumptions**.

Relevant Neutrino Experiments

Experiments Included

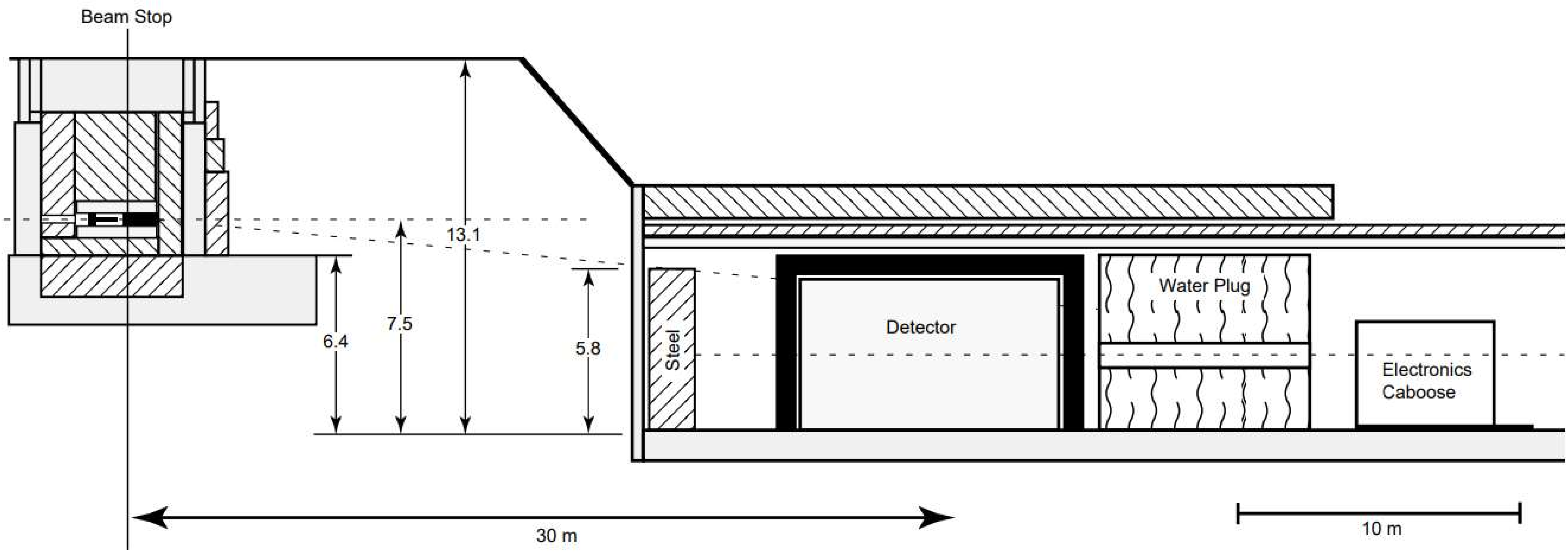
- LSND
- Fermilab SBN Program:

  MiniBooNE, MicroBooNE, and SBND
- DUNE
- SHiP

LSND

The King of POT

LSND



- 800 MeV proton on water target and followed by a copper beam dump.
- LSND still leads many experiments in probing around **MeV hidden particles** because of the total POT ~ 1.7 x10^23

LSND Analysis

- Based on **the LSND measurement of electron-neutrino electron elastic scattering** [LSND, PRD (2011)].
- 2 years of operation on a water target and 3 years of operation on a tungsten target.
- At LSND, the π^0 spectrum is modelled using Burman-Smith distribution [Burman, Smith (1989)], (modeling has close agreement with GEANT simulation from [Kahn, Krnjaic, Thaler, Toups, (2015)])
- Have **single electron background** of ~ 300 events.

	N $[\times 10^{20}]$		$A_{\text{geo}}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
Exp.	π^0	η	1 MeV	100 MeV	E_e^{min}	E_e^{max}	Bkg
LSND	130	—	20	—	18	52	300

Fermilab BooNE:

Booster Neutrino Experiments

Short Baseline Neutrino (SBN) Program

The Fermilab SBN Program

Proton beam

- 8.9 GeV protons on beryllium target. Produced mesons decay in 50 m decay region filled with air.

The Fermilab Short-Baseline Neutrino (SBN) Program

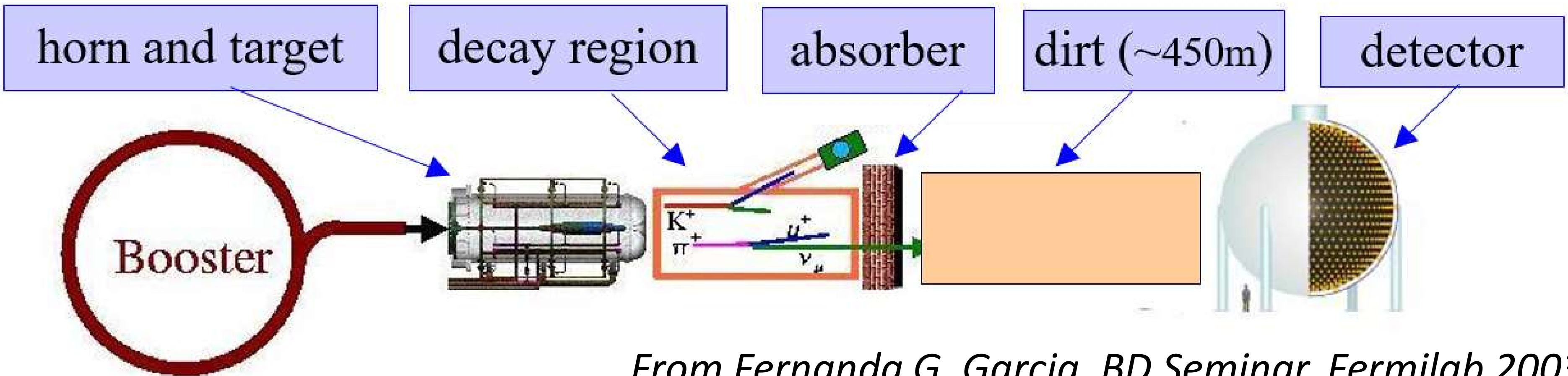
- SBND (Short-Baseline Near Detector): 110m from the target
- MiniBooNE: 490 m
- MicroBooNE: 470 m
- SBN three detector proposal: **arXiv:1503.01520**

mCP Productions in BooNE

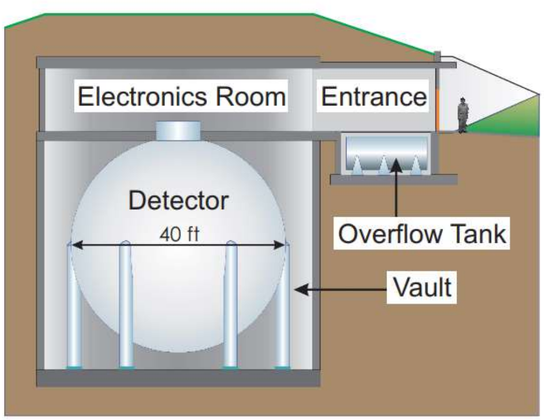
- The **8.9 GeV protons** on target and produce substantial numbers of both π^0 and η mesons.
- π^0's angular and energy spectra are modelled by the Sanford-Wang distribution [Sanford, Wang, BNL report, 1967]
- η mesons modeled by the Feynman scaling hypothesis

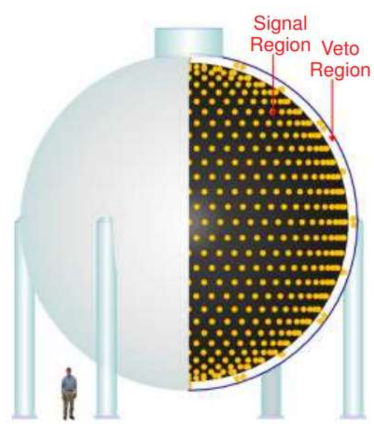
  [Feynman, PRL, 1969].
- These distributions are common across all three of the aforementioned experiments.

Booster Beam and MiniBooNE (skip)



From Fernanda G. Garcia, BD Seminar, Fermilab 2003





Mineral-oil based liquid **Cherenkov detector**.

Mineral oil is a natural scintillator, so charged particles without sufficient energy to produce Cherenkov light still produce scintillation light.

MiniBooNE Analysis

- At MiniBooNE we perform two distinct analyses: First we consider the recently updated neutrino oscillation search [Aguilar-Arevalo et al. (MiniBooNE), (2018)].
- We combine data from both neutrino and anti-neutrino runs and consider a sample of **2.4 × $\mathbf{10^{21}}$ POT** for with the single electron background to be 2.0×10^3 events and the measured data to be 2.4× 10^3.

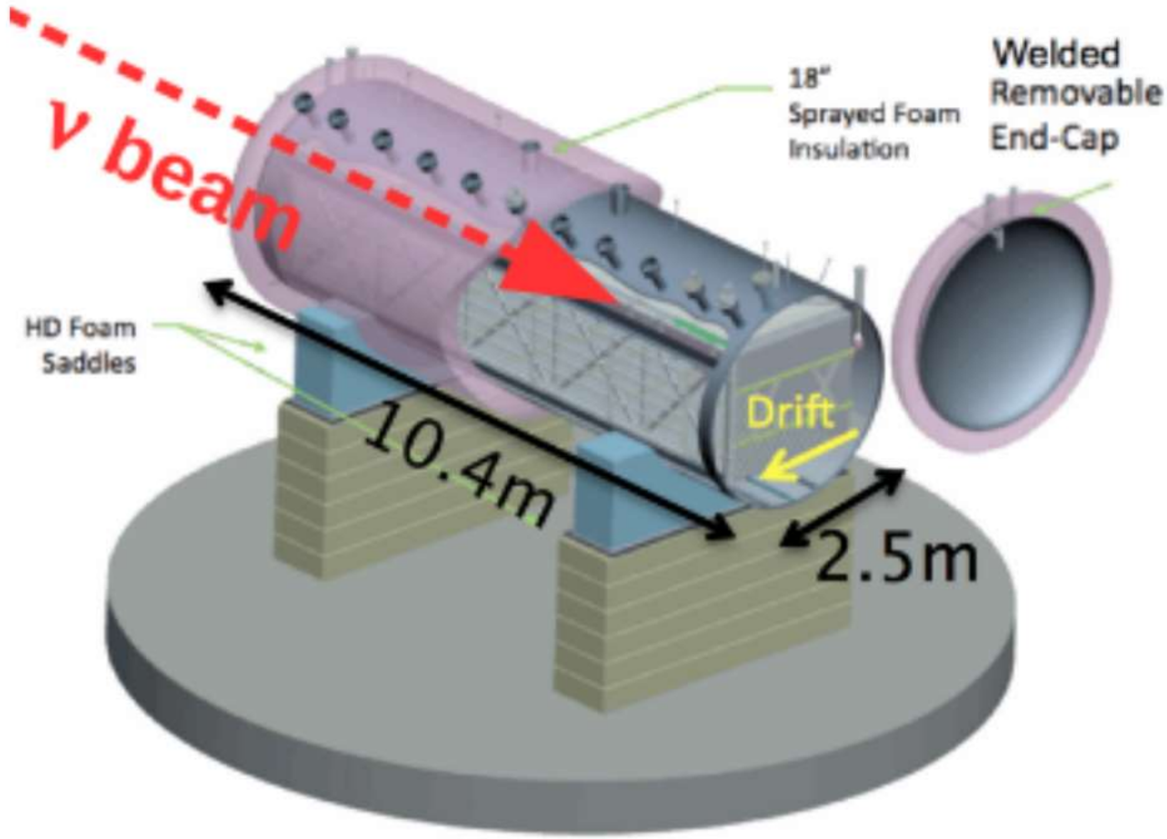
	N $[\times 10^{20}]$		$A_{\mathrm{geo}}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
Exp.	π^0	η	1 MeV	100 MeV	E_e^{min}	E_e^{max}	Bkg
mBooNE	17	0.56	1.2	0.68	130	530	2K

MiniBooNE* Analysis

- Motivated by a **dedicated dark matter search** with 1.9 × 10^20 POT protons beam dump (nucleons elastic scattering) [MiniBooNE, PRL (2017)], we consider an anticipated **parallel analysis** [private communication with MiniBooNE] involving **electron-recoil data**.
- Backgrounds were suppressed by **operating the beamline in an “off-target” mode, (i.e. not collimating charged pions)**, and these can be further suppressed (to zero) by imposing a cut of cos θ > 0.99 on the electron’s recoil angle [Dharmapalan, MiniBooNE, (2012)].
- In both cases electron number density: 3.2 × 10^{26} e^−/cm2.
- Our sensitivity curve assumes that this upcoming analysis reports no signal consistent with mCPs.

MicroBooNE & SBND
at Fermilab BooNE

MicroBooNE Experiment



A Liquid Argon Time Projection Chamber (LArTPC) Neutrino Experiment

MicroBooNE Analysis

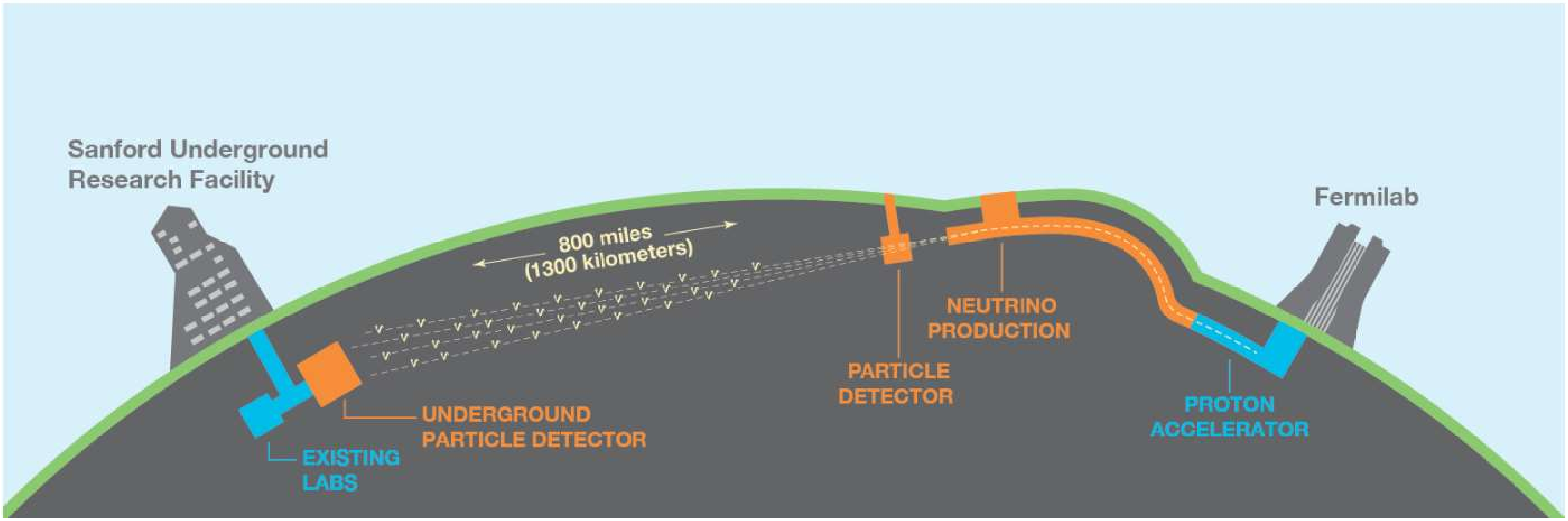
- At **MicroBooNE**, the meson production assume **1.3 × 10^21 POT** and we estimate that the detector has an **electron density of 3.9 × 10^26 e^−/cm2 .**
- The **chosen recoil cuts** are based on the lowest reaches achievable given the **wire spacing in MicroBooNE's liquid argon detector** [MicroBooNE, JINST, 2017]. The wire spacing is 3 mm and the ionization stopping power is approximately 2.5 MeV/cm, so electrons with minimal energy of 1.3 MeV produce tracks long enough to be reconstructed. We use 2 MeV as our electron E_{min} cuts
- Based on this and the requirement for ionization signals that don't shower, we limit ourselves to recoil cuts between **2 MeV and 40 MeV** to stay in the ionization regime

SBND (LAr1ND) Analysis

- A **112 ton liquid argon TPC** neutrino detector located **110m** from the target.
- Because of its **proximity to the target**, the experiment will have very high rates.
- **SBND will be operational in 2020.**
- The treatment of **SBND** is broadly similar to MicroBooNE, but we assume **6.6 × 10^20 POT**, for half the run time of MicroBooNE.

	N $[\times 10^{20}]$		$A_{\rm geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
Exp.	π^0	η	1 MeV	100 MeV	$E_e^{\rm min}$	$E_e^{\rm max}$	Bkg
μBooNE	9.2	0.31	0.09	0.05	2	40	16
SBND	4.6	0.15	4.6	2.6	2	40	240

DUNE


Sanford Underground
Research Facility
800 miles
(1300 kilometers)
Fermilab
NEUTRINO
PRODUCTION
PARTICLE
DETECTOR
PROTON
ACCELERATOR
UNDERGROUND
PARTICLE DETECTOR
EXISTING
LABS

DUNE Near Detector

- The Long Baseline Neutrino Facility (LBNF)
- **80-GeV protons, 1.5 × 10^{21} POT/year**
- Consider the **near detector at 574 m** from the proton beam target (**Carbon)**
- We assume **3 × 10^22 POT** (for all the scientific goals) and a **30 tonne liquid argon detector** which corresponds to **5.4 × 10^25 e −/cm2** .
- LBNF/DUNE Proposal 2015 (arXiv:1512.06148)

DUNE Analysis

- We model **pseudo-scalar meson production** using **the BMPT distribution** [Bonesini, Marchionni, Pietropaolo, Tabarelli de Fatis, EPJ (2001)]
- For production of J/ψ and Upsilon mesons, we use the production energy spectra described by the distributions in [Gale, Jeon, Kapusta, PLB (1999)]
- Our detector treatment and electron recoil cuts are motivated by the capability of MicroBooNE's liquid argon time projection chamber (LAr-TPC) detector. In particular its ability to measure low energy electron recoils.
- We estimate $N_{J/\psi}$ = 3 × 10^16 and N_{Υ} = 5.1 × 10^9

	N $[\times 10^{20}]$		$A_{\rm geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
Exp.	π^0	η	1 MeV	100 MeV	$E_e^{\rm min}$	$E_e^{\rm max}$	Bkg
DUNE	830	16	3.3	5.1	2	40	$19K$

DUNE Analysis

- For large mCP masses, **Drell-Yan production (DYP)** becomes the main production mechanism.
- We calibrate our DYP calculations by reproducing the dimuon invariant mass spectrum from the FNAL-772 experiment [FNAL-772, PRL 1990].

DUNE Detail

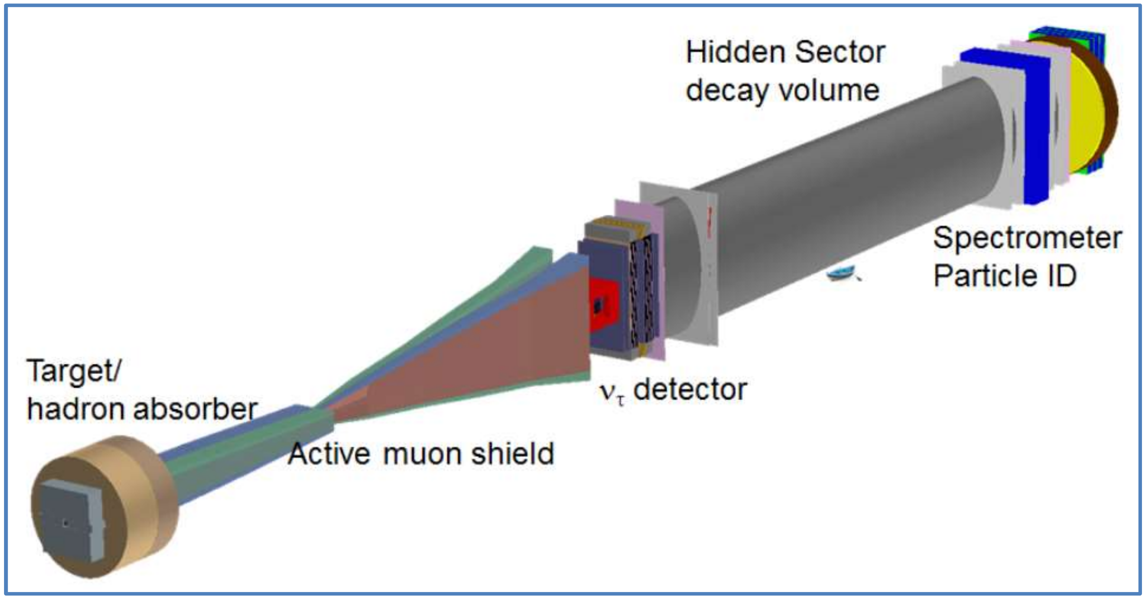
- These distributions rely on production being highly peaked in the forward direction parameterized as dσ/d $x_F \propto (1 - |x_F|)$^5 , where x_F = 2 p_k/ √s is the meson's longitudinal component in the COM frame of the collision.
- We account for geometric losses by using an empirical formulae for the p_T distribution provided in [E672 & E706, PRD (2000)].
- We assume that the production spectrum of Υ mesons are similarly given, and normalize their total cross section to the data in [HERA-B PLB (2006)]. We have reproduced rates in Table 3 of [NA50, EPJ (2006)] for J/Ψ, and for Υ we reproduced the rates in Table 1 of [Herb et al., PRL (1977)].

DUNE Detail

- Larger ε may lead to a double scattering of mCPs inside the detectors, which could be used as an additional tool of discriminating their signature against the neutrino background.
- Our results do not include multiple scattering effects through dirt.
- Low velocity mCPs with a moderate charge (i.e. $\varepsilon \geq 0.03$) might get impeded by their long transit through dirt.

  This is relevant for DUNE and could weaken our sensitivity for $m_\chi \geq$ 2 GeV.

SHiP Experiment



- 400 GeV protons
- 2 x 10^{20} POT in 5 years
- We consider the sensitivity in the SHiP near **“tau neutrino” detector** 50 m from the beam stop with an electron density of $2.7 \times 10^{26}\ e^{-}/\ cm^{2}$

SHiP Analysis

- The large beam energies of 400 GeV allow us to include J/ψ and Υ, in addition to π^0 and η.
- At the energies of SHiP, production of π^0 and η can again be described by the BMPT distribution.
- For production of J/ψ, again we assume that their energy production spectra are described by the distributions in [Gale, Jeon, Kapusta, PLB (1999)].
- **DYP** important for SHiP! Dominates above the heaviest meson resonance. Calibrated with FNAL-772 experiment [FNAL-772, PRL 1990]

Summary Table

	N [$\times 10^{20}$]		$A_{\rm geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
Exp.	π^0	η	1 MeV	100 MeV	$E_e^{\rm min}$	$E_e^{\rm max}$	Bkg
LSND	130	—	20	—	18	52	300
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DUNE	830	16	3.3	5.1	2	40	$19K$
SHiP	4.7	0.11	130	220	20	50	25

- A_{geo} (m_χ): the ratio between the number of mCPs that reach the detector and the total number produced.
- We have compared our BooNE geometric acceptances with those generated using [deNiverville, Chen, Pospelov, Ritz, (2017)] and find agreement up to an < O(1) factor

Summary Table

	N $[\times 10^{20}]$		$A_{\rm geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
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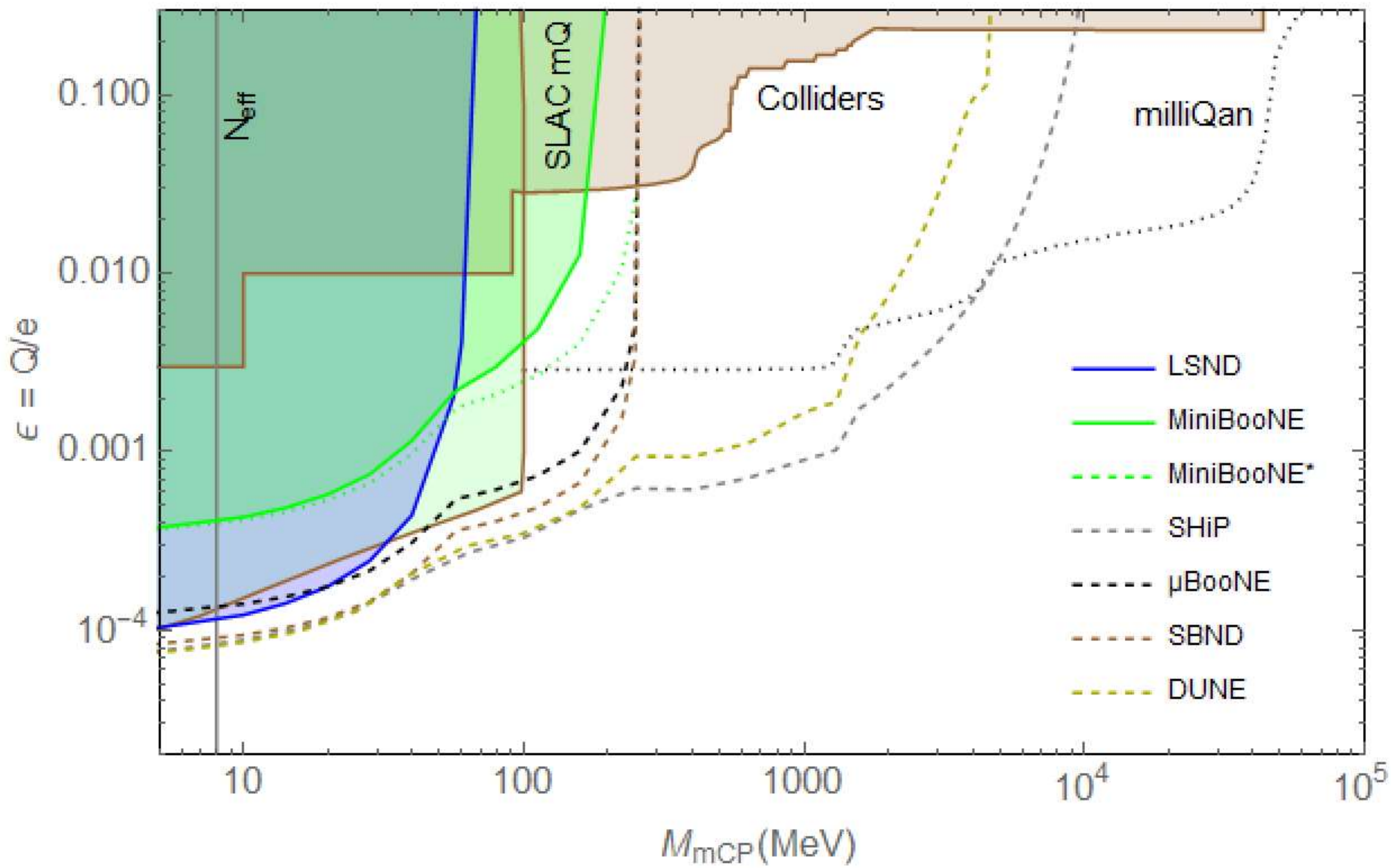
DUNE	830	16	3.3	5.1	2	40	$19K$
SHiP	4.7	0.11	130	220	20	50	25

- cos θ > 0 is imposed (∗except for at MiniBooNE's dark matter run where a cut of cos θ > 0.99 effectively reduces backgrounds to zero [Dharmapalan, MiniBooNE, (2012)]).
- We use an efficiency of 0.2 for Cherenkov detectors, 0.5 for nuclear emulsion detectors, and 0.8 for liquid argon time projection chambers.

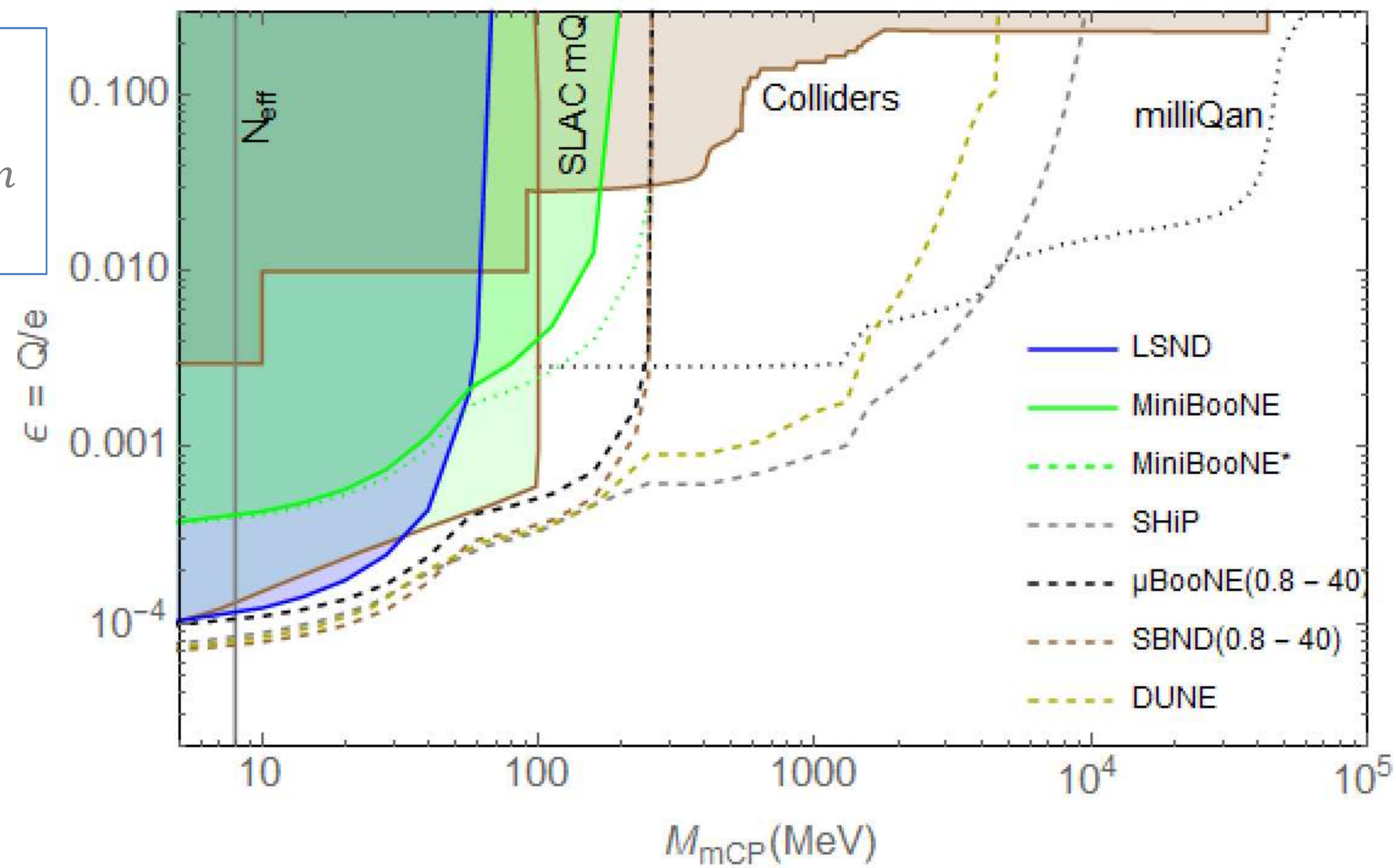
Probes of mCPs



- **MicroBooNE is the most on-shell future probe**
- We are in contact with the experimentalists. Could analyze the real data soon!

(Unrealistically?) Optimistic Probe

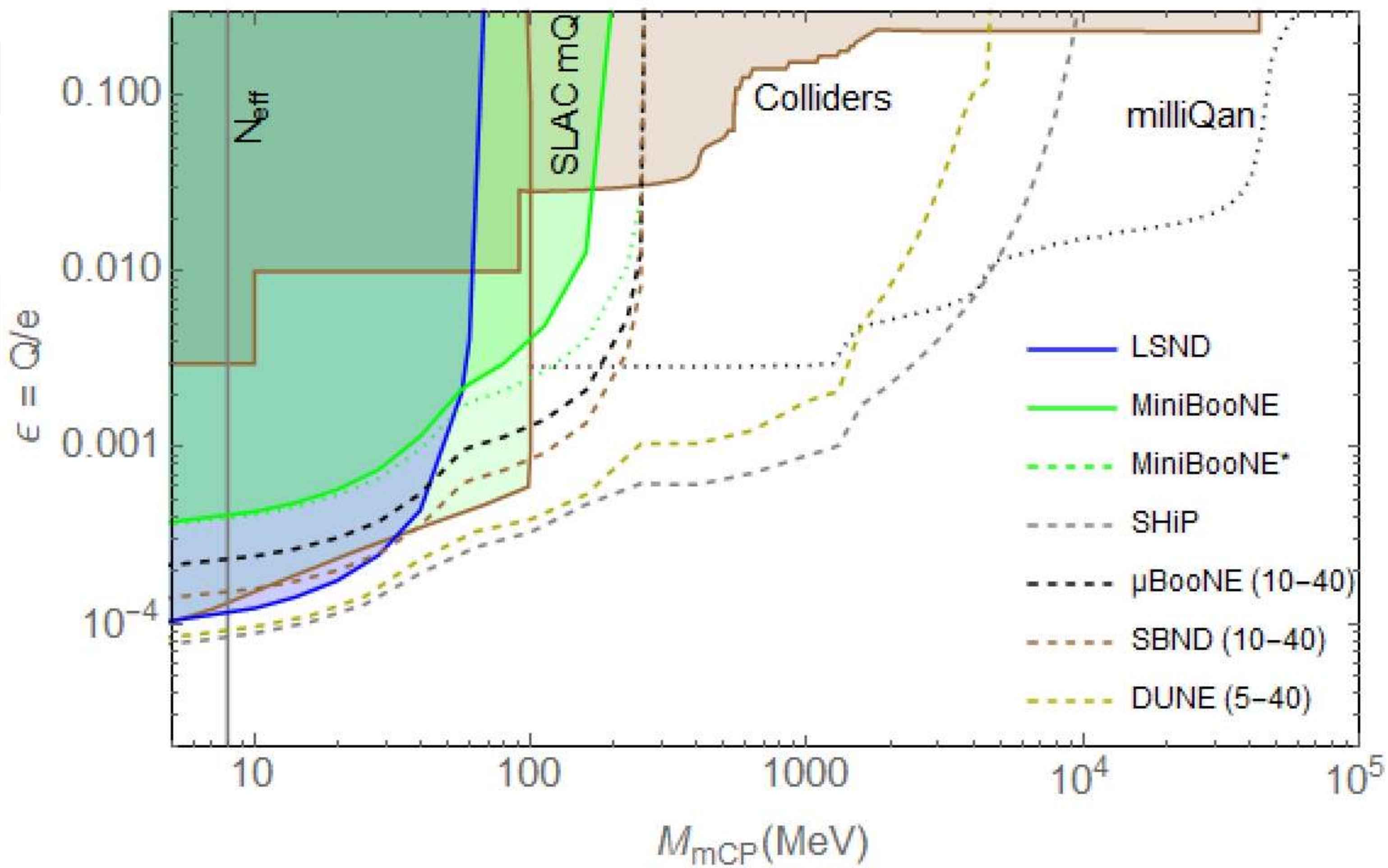
Roughly,
$\varepsilon \propto E_{e,r,min}^{1/4}$
$\varepsilon \propto B^{1/8}$



- **MicroBooNE communication:** "In principle you can reach a electron recoil threshold of about 300-500 KeV"

(Comparably) Conservative Probe

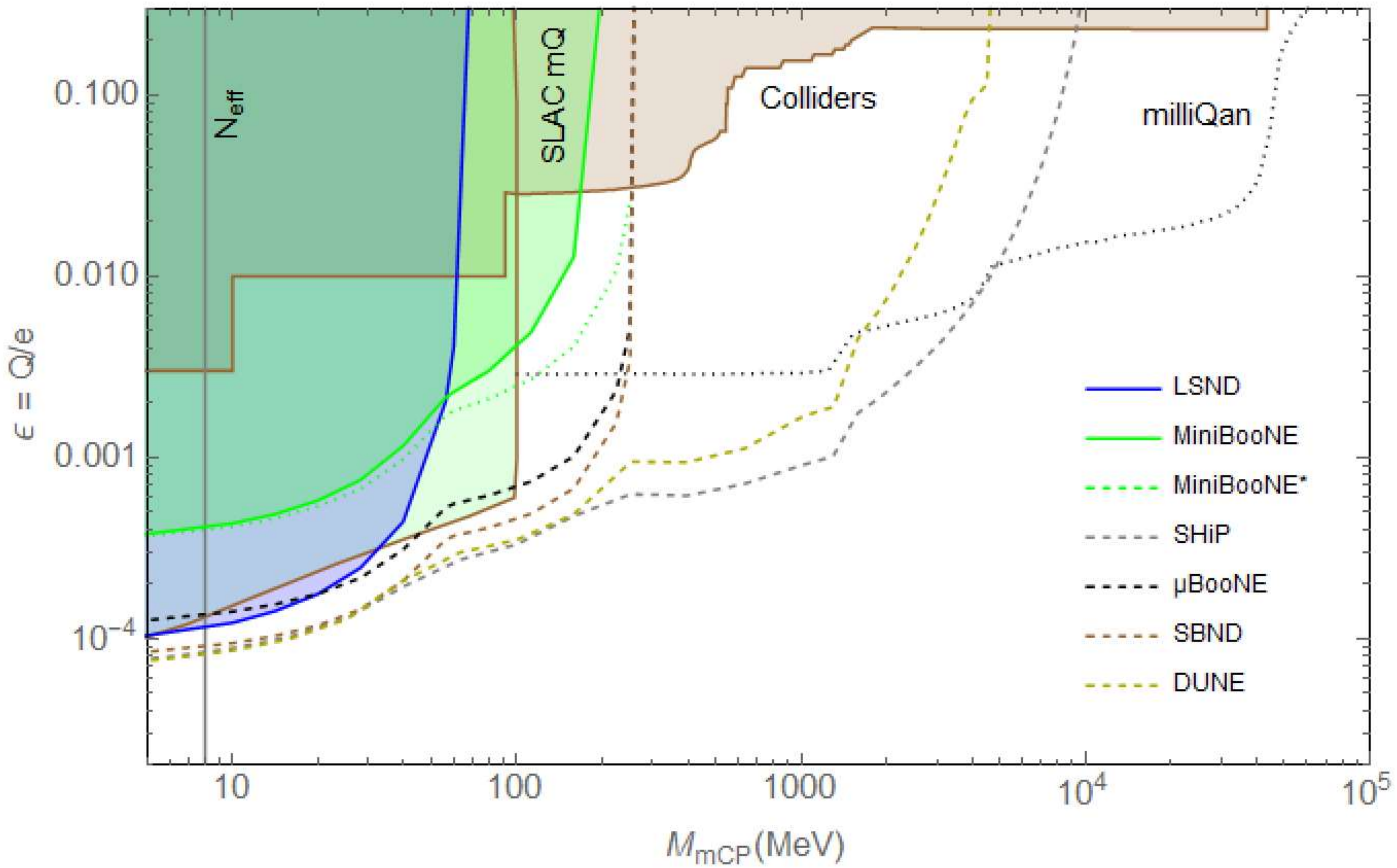
Mesons	Mass
π^0	135 MeV
η	547 MeV
J/ψ	3.1 GeV
Υ	9.5 GeV



- **Features correspond to the neutral meson productions / correlate to the neutral meson masses**

Existing Bounds

mCP Bounds

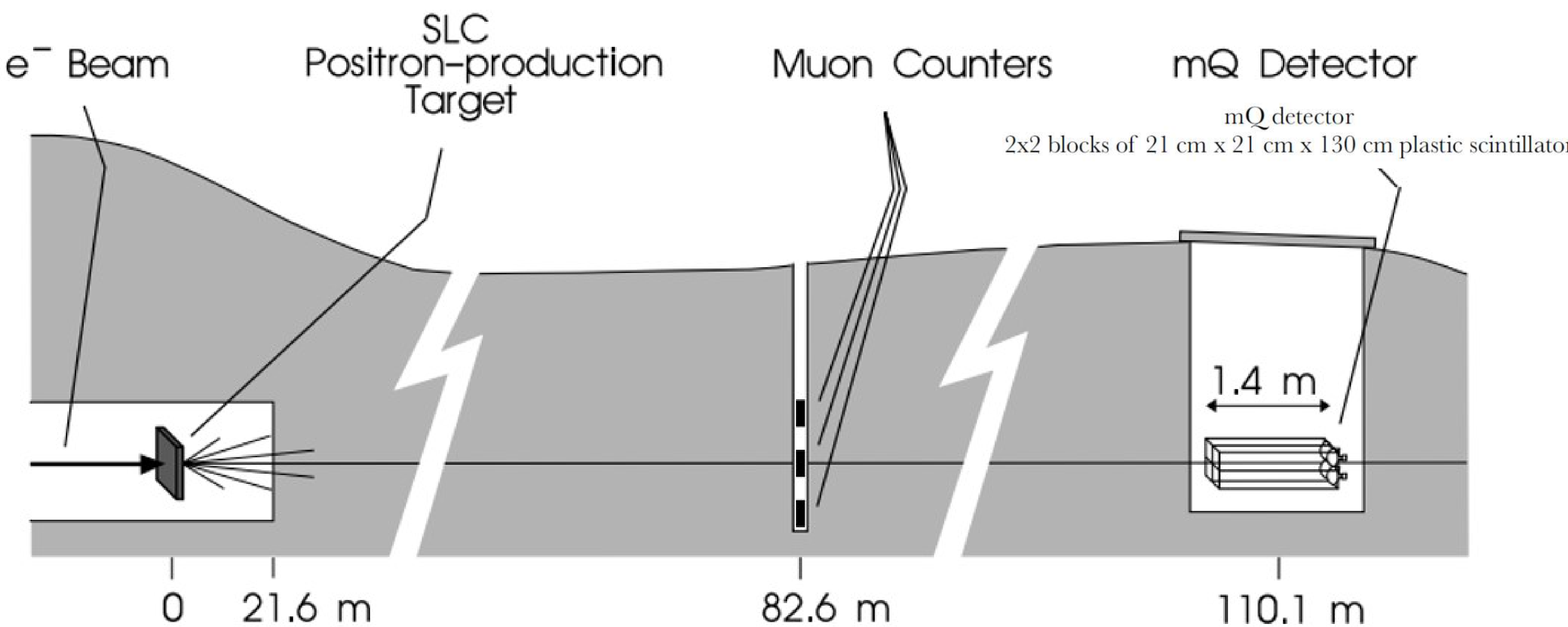


- Below MeV, there are very strong lab/astrophysical bounds, that I will not talk about today (see e.g. Haas, Fermilab, 2017)

SLAC mQ Experiment

- 29.5 GeV pulsed electron beam
- Total of 10^{19} Electrons on Target (EOT)
- Sets mCP constraint from 100 keV to 100 MeV

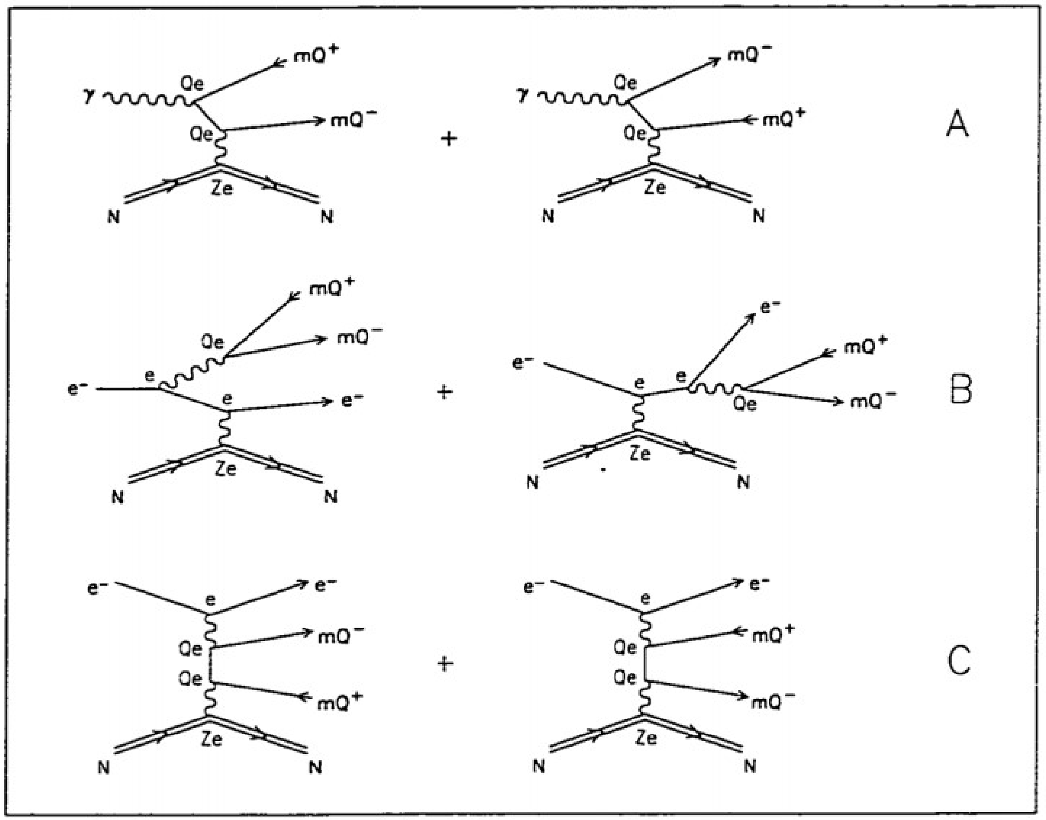
Phys.Rev.Lett.81:1175-1178,1998



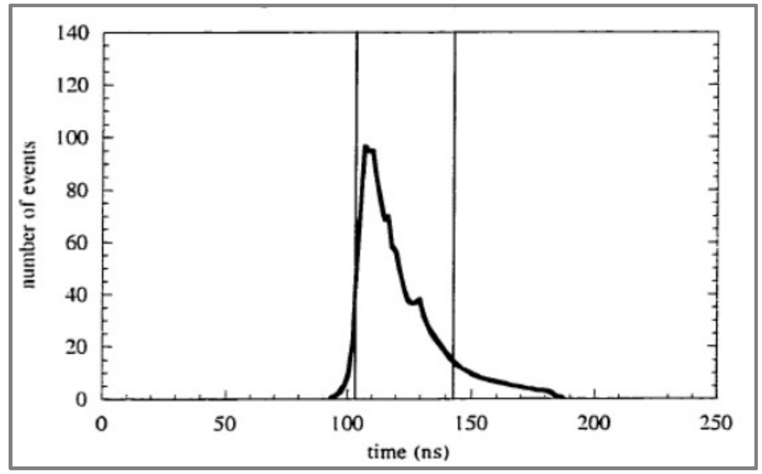
The SLAC mQ experiment is sensitive to the **infrequent excitation** and **ionization of matter** expected from the passage of a **millicharged particle**.

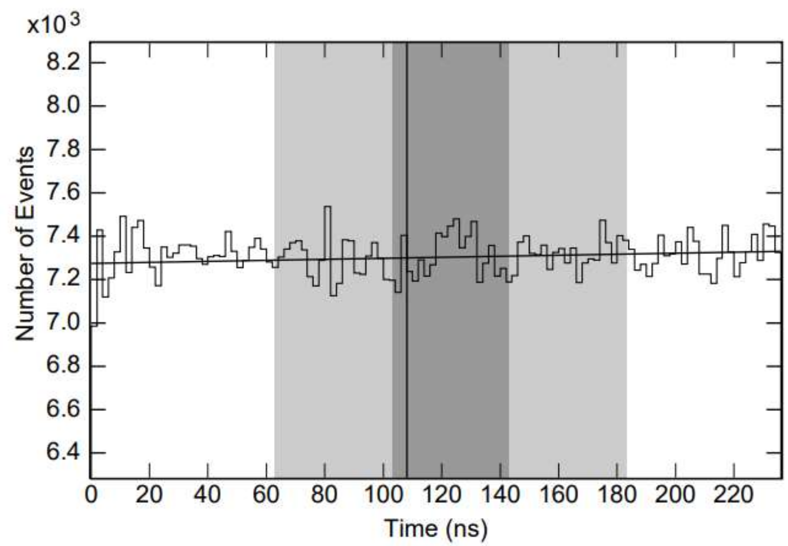
SLAC mQ: Productions/Detections

Prinz, SLAC Report (thesis), 2001/ Prinz et al., PRL,1998



Feynman diagrams for mQ production. A. Photoproduction. B. Electroproduction, "Bremsstrahlung" mechanism. C. Electroproduction, "multiperipheral" mechanism.





Collider/Accelerator Bound

- Results from 2000
- Anomalous Single Photon (ASP)
- SLAC Beam Dump Experiment
- Free Quark Search:

> - The most stringent/relevant limit on mCP comes from **SLAC PEP (Positron Electron Project)**, which constrains $M_{\mathrm{mCP}} > 14$ GeV for $0.2 \leq \varepsilon$ [Marini et al., PRL 1982]

ASP Constraint

- Anomalous Single Photon (**ASP**) experiment, **Hearty et al., PRL 1987**:
- The ASP detector was designed to look for events of the form $e^+e^- \rightarrow \gamma + $ **weakly interacting particles** (including 3 neutrinos and other hidden particles) @ SLAC storage ring PEP.
- Subtracting the neutrinos, the limit on the cross section for the production of other weakly interacting particles is smaller than 0.049 pb, which one can set the constraint:

TABLE I. Values of the paraton mass μ excluded by the ASP experiment.

Mass (GeV)	Charge
$\mu < 1$	$\epsilon = 0.08$
$\mu < 5$	$\epsilon = 0.08$
$\mu < 10$	$\epsilon = 0.09$
$\mu < 13$	$\epsilon = 0.20$

Collider/Accelerator Bound

- **SLAC Beam Dump Experiment:**
- Rothenberg, SLAC Report No. 147 1982
- Same productions as in mQ experiments

Mass (GeV)	Charge
$\mu < 0.2$	$\epsilon = 0.0003$
$\mu < 1$	$\epsilon = 0.0006$
$\mu < 2$	$\epsilon = 0.001$
$\mu < 10$	$\epsilon = 0.003$
$\mu < 100$	$\epsilon = 0.01$
$\mu < 10^3$	$\epsilon = 0.03$

- Davidson, Campbell, Bailey, 1991

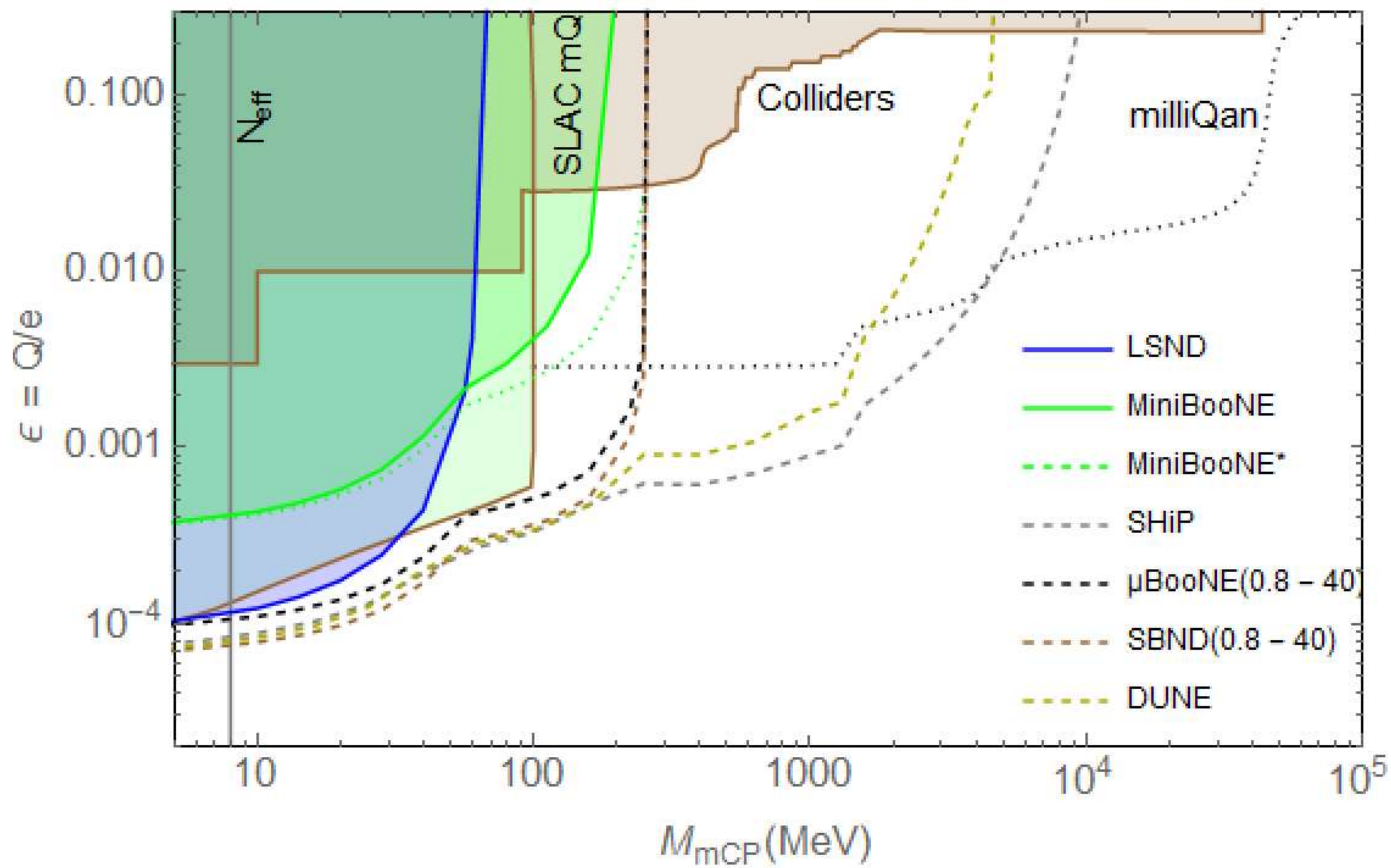
Cosmology Bound: N_{eff}

- Once thermally populated mCP thermalized with electron and photon
- Bœhm, Dolan, and McCabe, 2013

$$N_{\text{eff}} = N_\nu \left(\frac{4}{11}\right)^{-4/3} \left(\frac{T_\nu}{T_\gamma}\right)^4 .$$

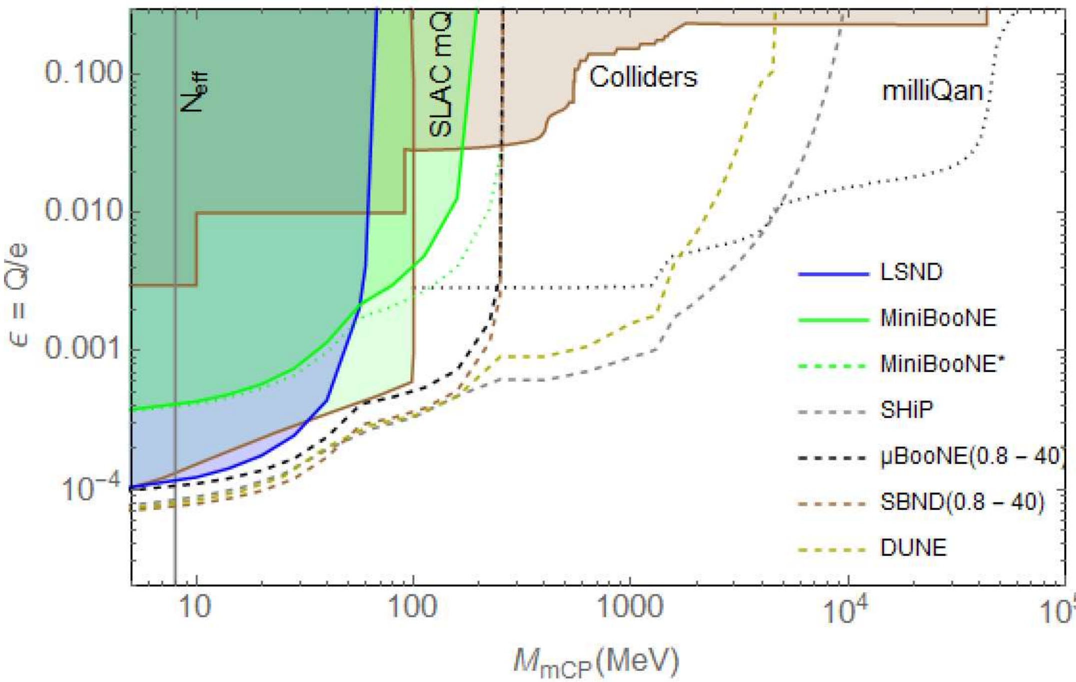
- After neutrino decoupling at TD ≈ 2.3 MeV, the entropy of the ‘neutrino plasma’ and ‘electromagnetic plasma’ are separately conserved, without new physics.
- mCP in thermal equilibrium with electron/gamma would affect the $T\gamma$
- Constraining mCP (Dirac fermion) below ~ 8 MeV
- N_{eff} = 3.046 (SM) now, should be updated/revisited (~ 10 MeV)!
- **Can modify the thermal history to alleviate this bound**.

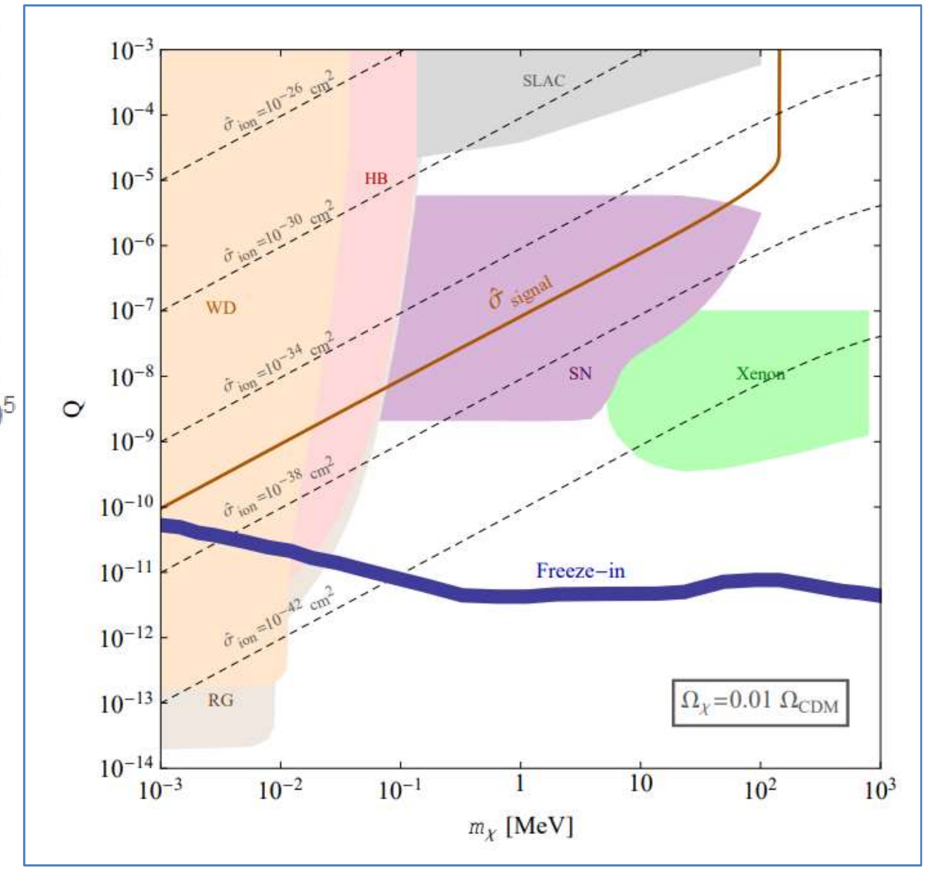
Existing Bounds for mCPs: Recap



- Colliders/Accelerator: Davidson, Hannestad, Raffelt 2000 + refs within.
- SLAC mQ: Prinz el al, PRL (1998); Prinz, Thesis, (2001).
- N_{eff}: Bœhm, Dolan, and McCabe, (2013).

mCP DM: Explaining EDGES Results





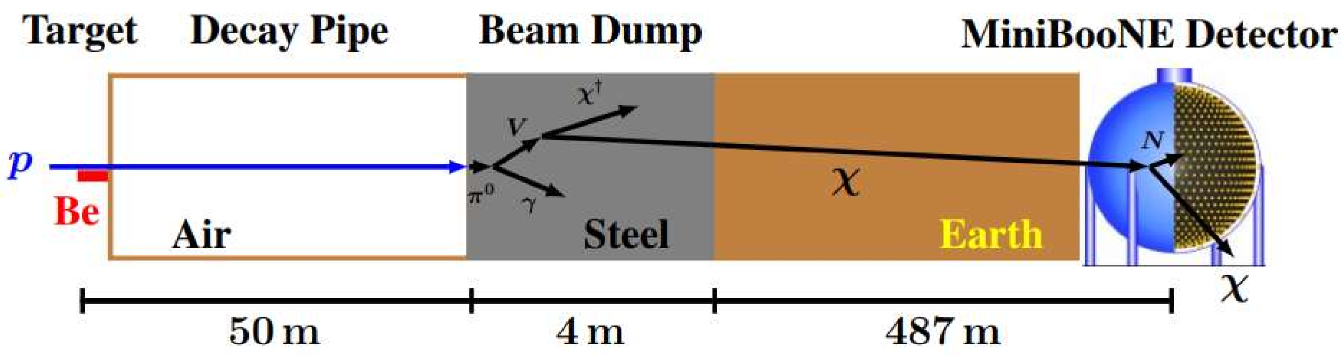
Barkana, Outmezguine, Redigolo, Volansky, 2018

Conclusions

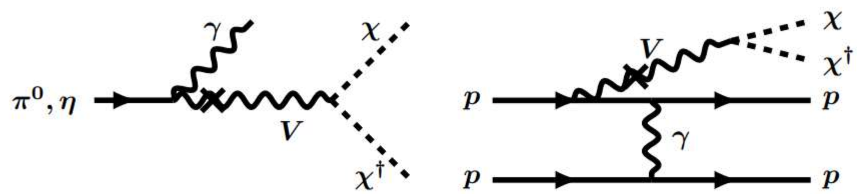
- **It is interesting for various experiments to look for mCP's, with realistic cuts and setups**
- **MicroBooNE potentially have data to set leading constraints.**
- **SBND, SHiP, and DUNE provides exciting prospective**

Thank You!

MiniBooNE Beam Dump DM Run

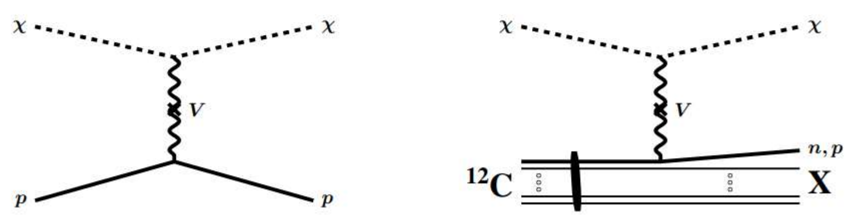


MiniBooNE-DM, PRL (2017)



(a) π^0, η Decay (b) Proton Bremsstrahlung

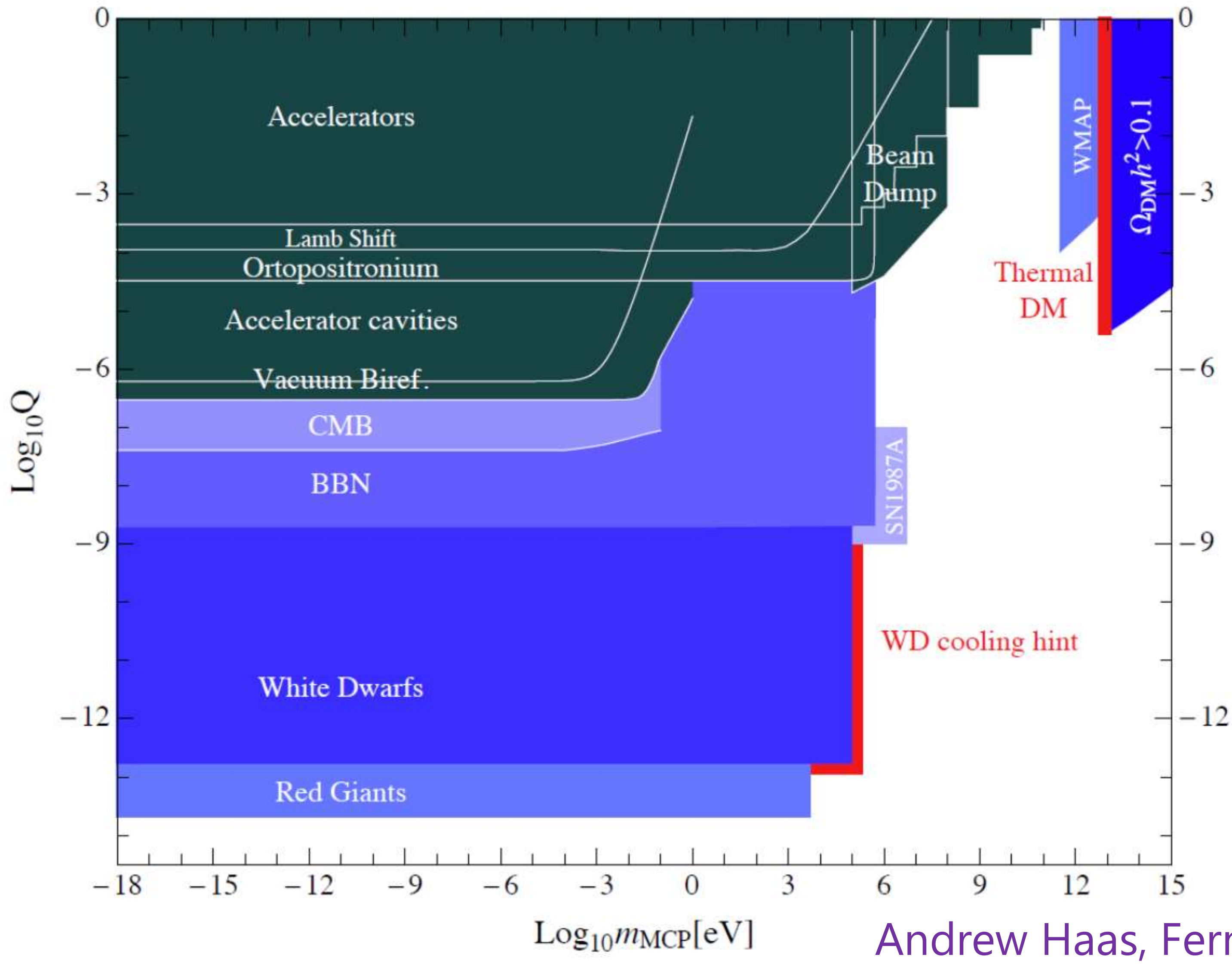
FIG. 2. DM production channels relevant for this search with an 8 GeV proton beam incident on a steel target.



(a) Free protons (b) Bound nucleons in ^{12}C.

FIG. 3. DM interactions with nucleons in the detector.

More bounds



Andrew Haas, Fermilab (2017)

$Br(o-Ps \to \text{invisible}) < 4.2 \times 10^{-7}$ (90% C.L.) Badertscher et al, PRD (2007)

$\delta E = E(2S_{1/2}) - E(2P_{1/2}) \quad \delta E_{\mathrm{VP}} \simeq -\frac{\alpha^5 m_e}{30\pi}\left(\frac{m_e}{\mu}\right)^2 \varepsilon^2.$ Gl¨uck, Rakshit, Reya PRD (2007)