

# Particle Physics-Astrophysics-Cosmology Webinar

## Journey with Sourced Millicharged Particles and Dark Photons

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University Minnesota

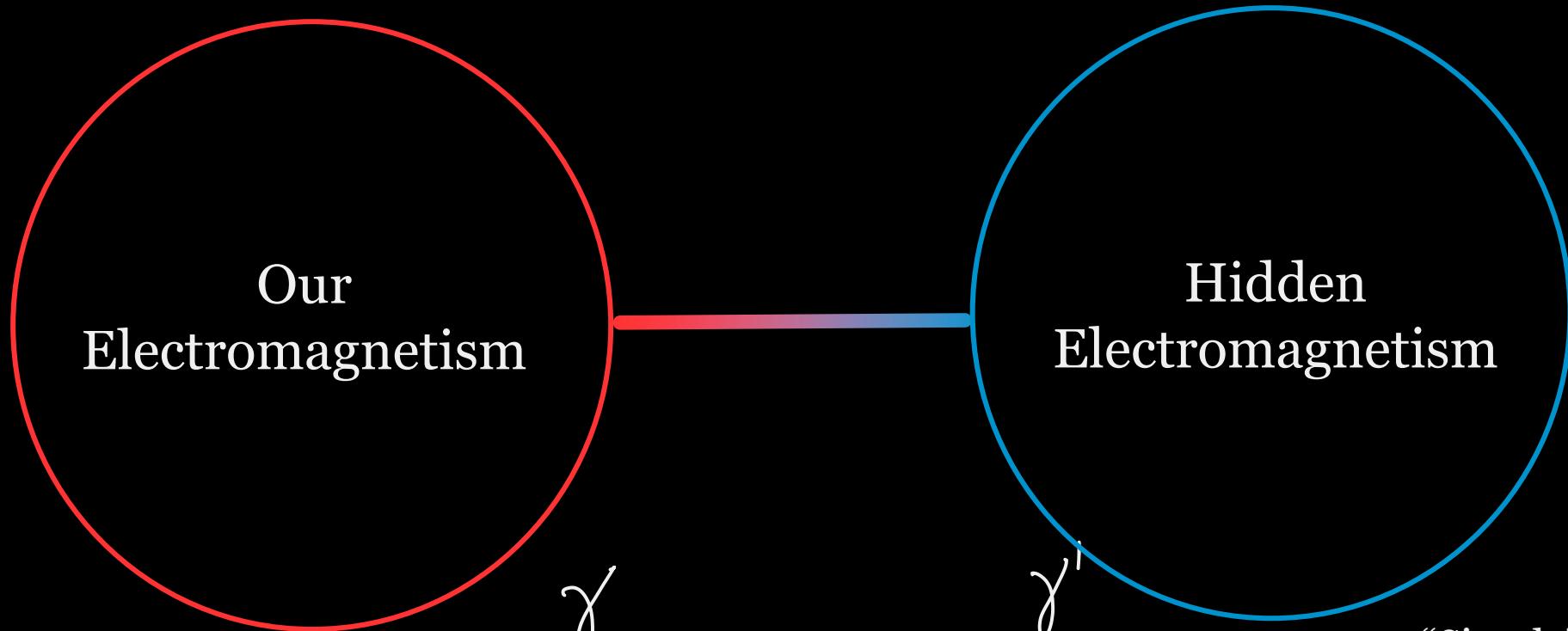
06/07/2023



# Now: Journey to the unknown and seeking opportunities



# A generic light hidden photon



**$\epsilon$**  determined by UV physics  
One can easily generate it via  
high-scale fermions charged  
under both gauge groups.

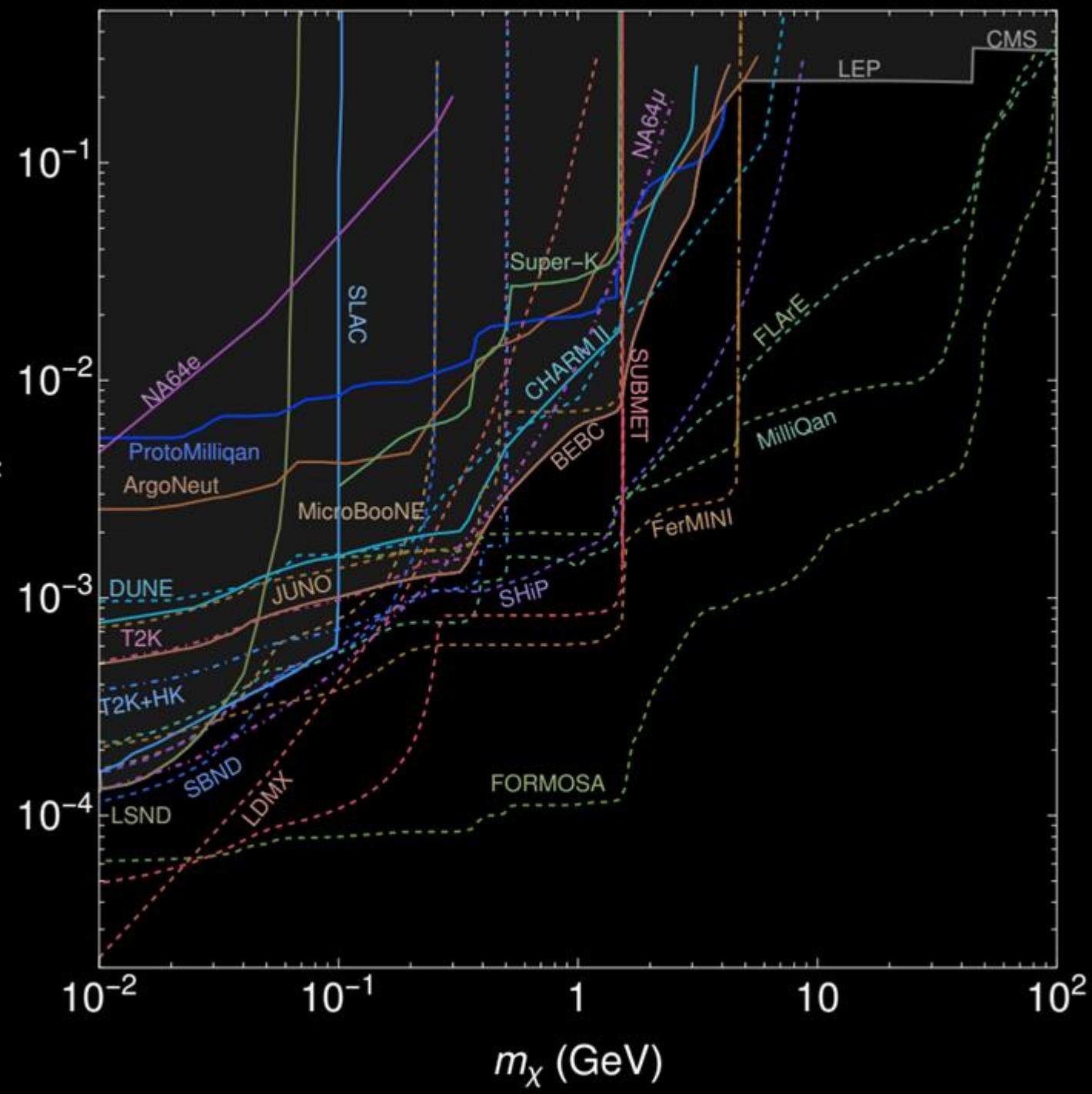
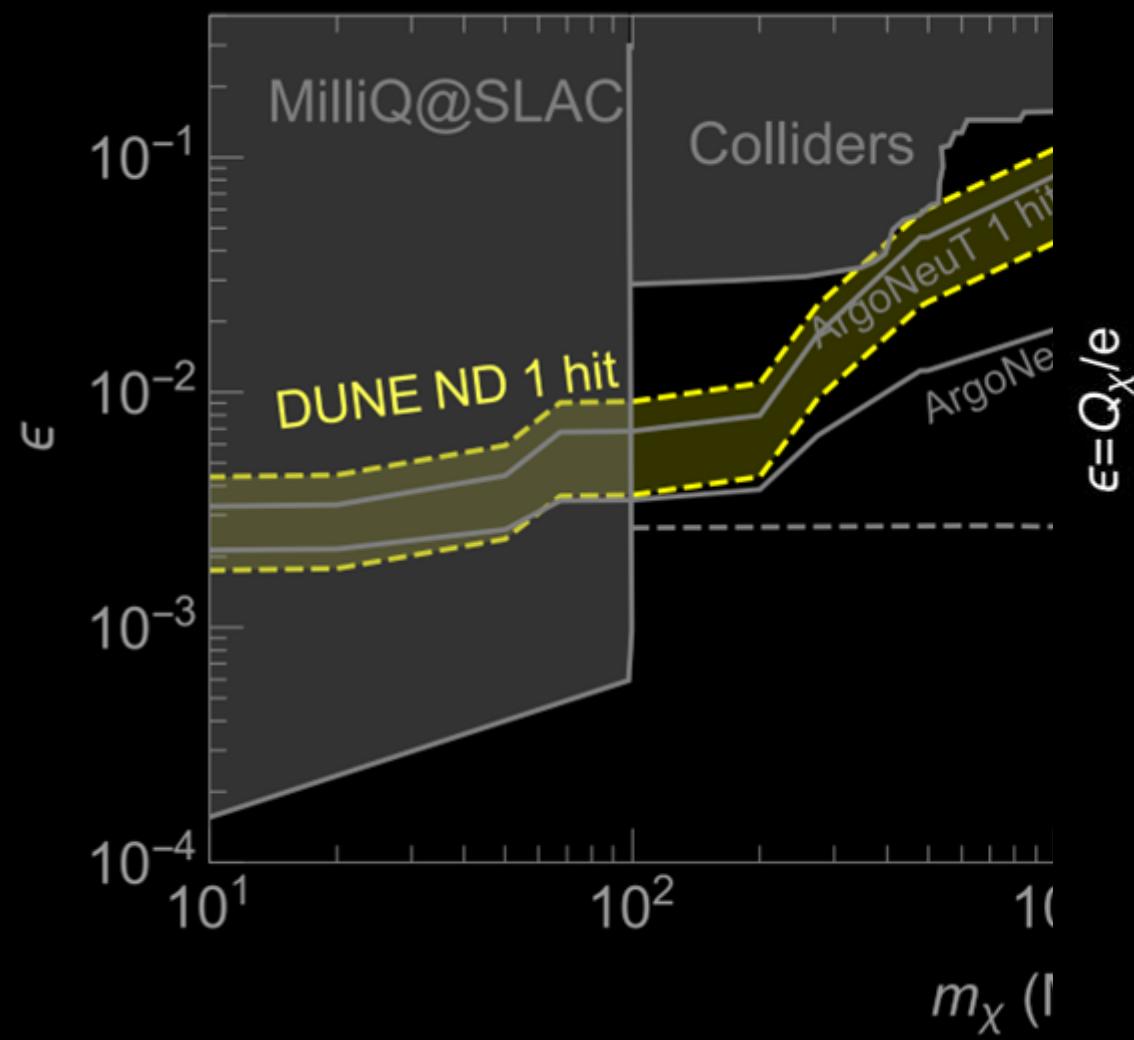
See the discussion on the  $\epsilon$  size, e.g.,  
Gherghetta, Kersten, Olive, Pospelov,  
[1909.00696](#)

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu$$

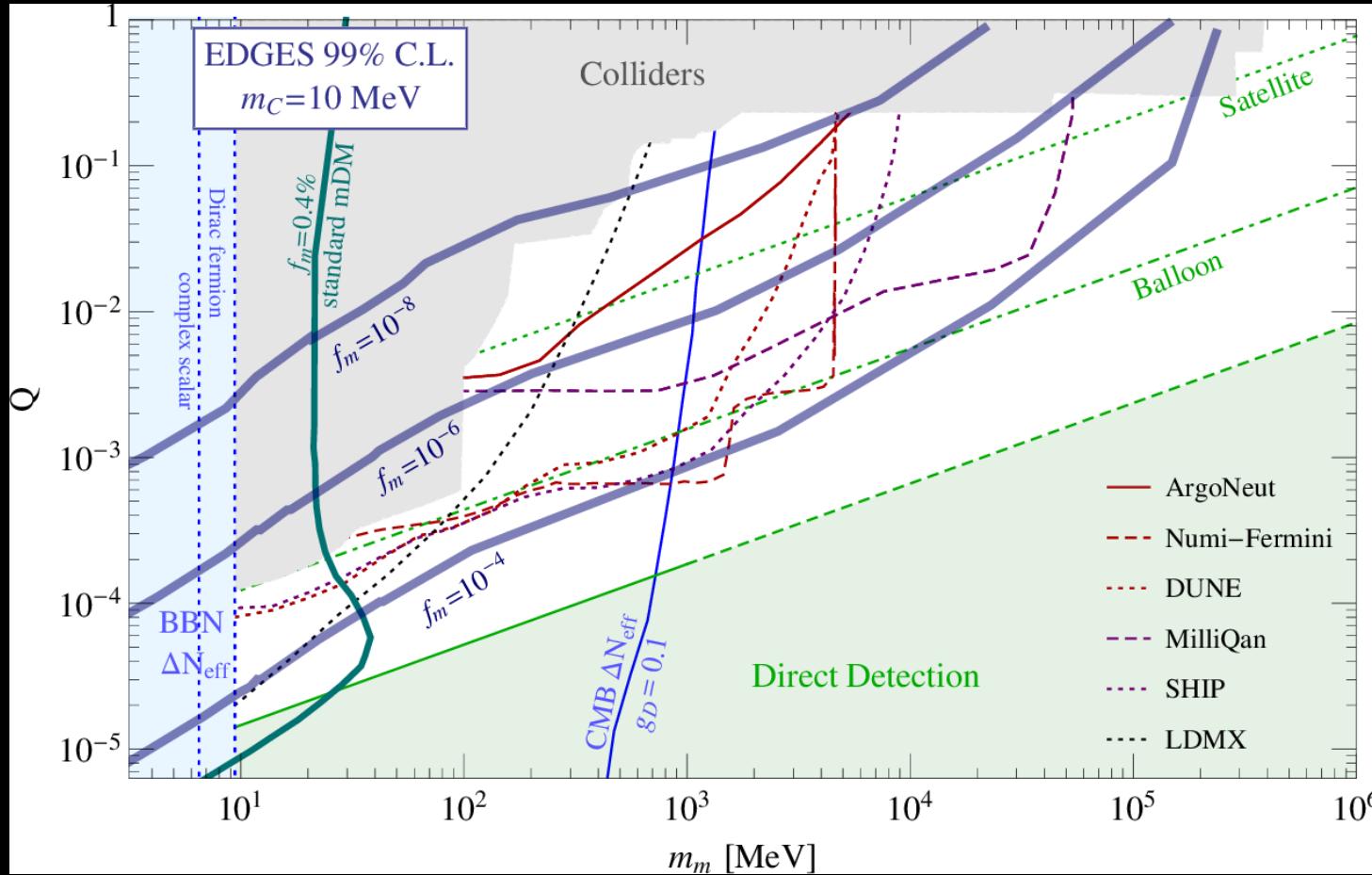
- “Simple” and Heuristic
- Massive dark photon;
  - Millicharged particles;
  - Ultralight dark photon;
  - ...

# Part I: MilliCharged Particles

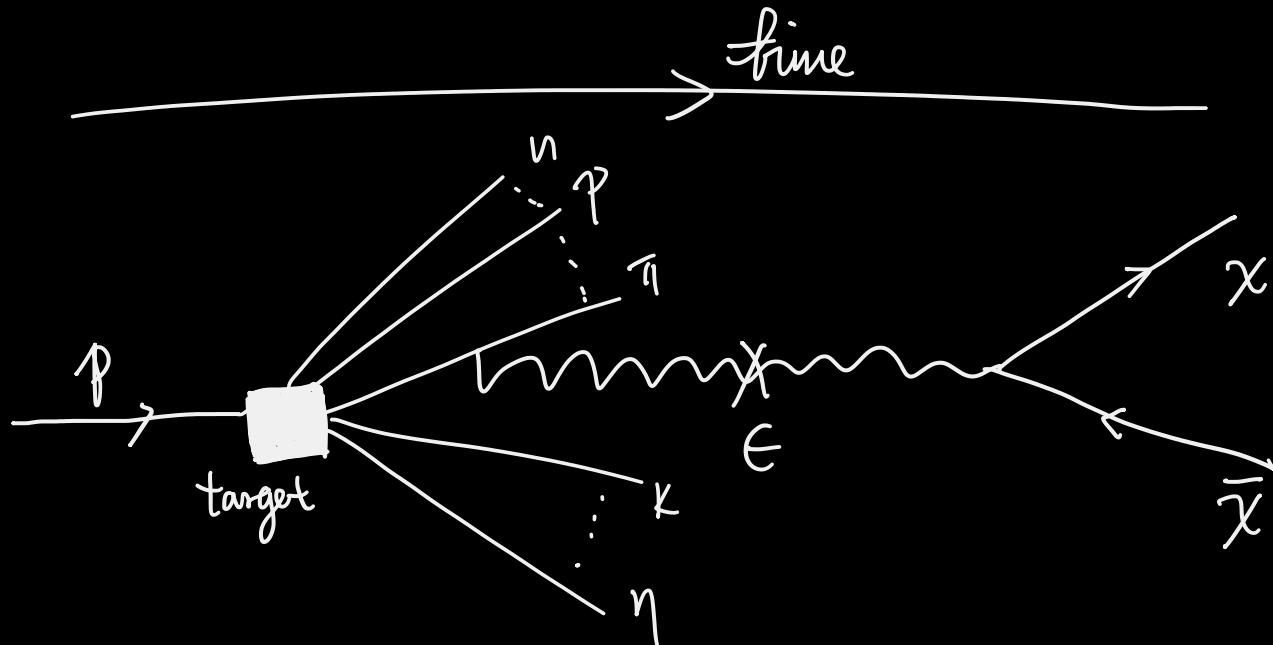
# Current Status & Future



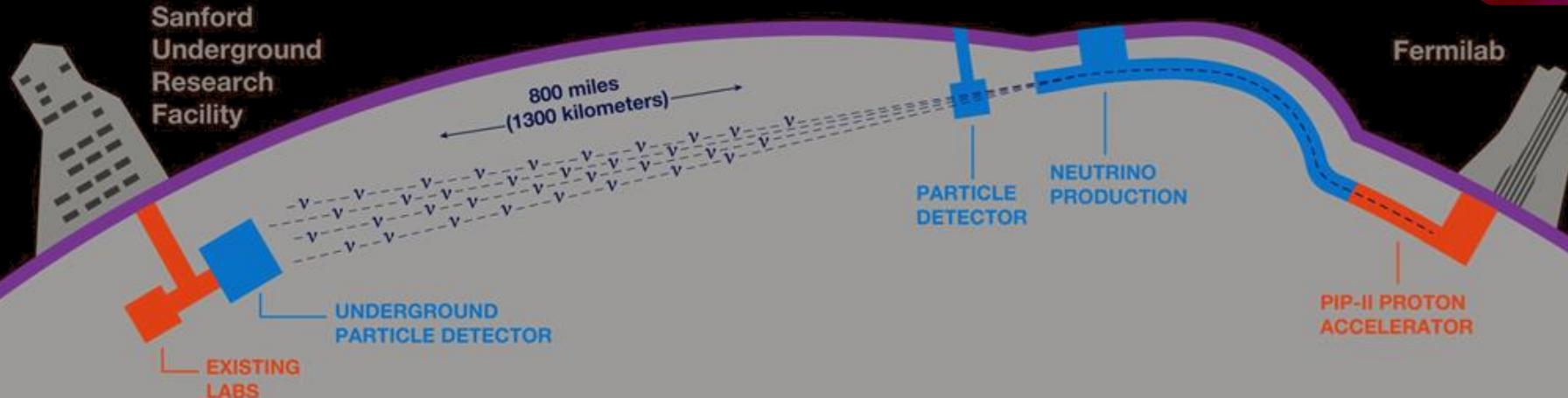
# MCP as partial DM



# Millicharged Particles at Neutrino Experiments



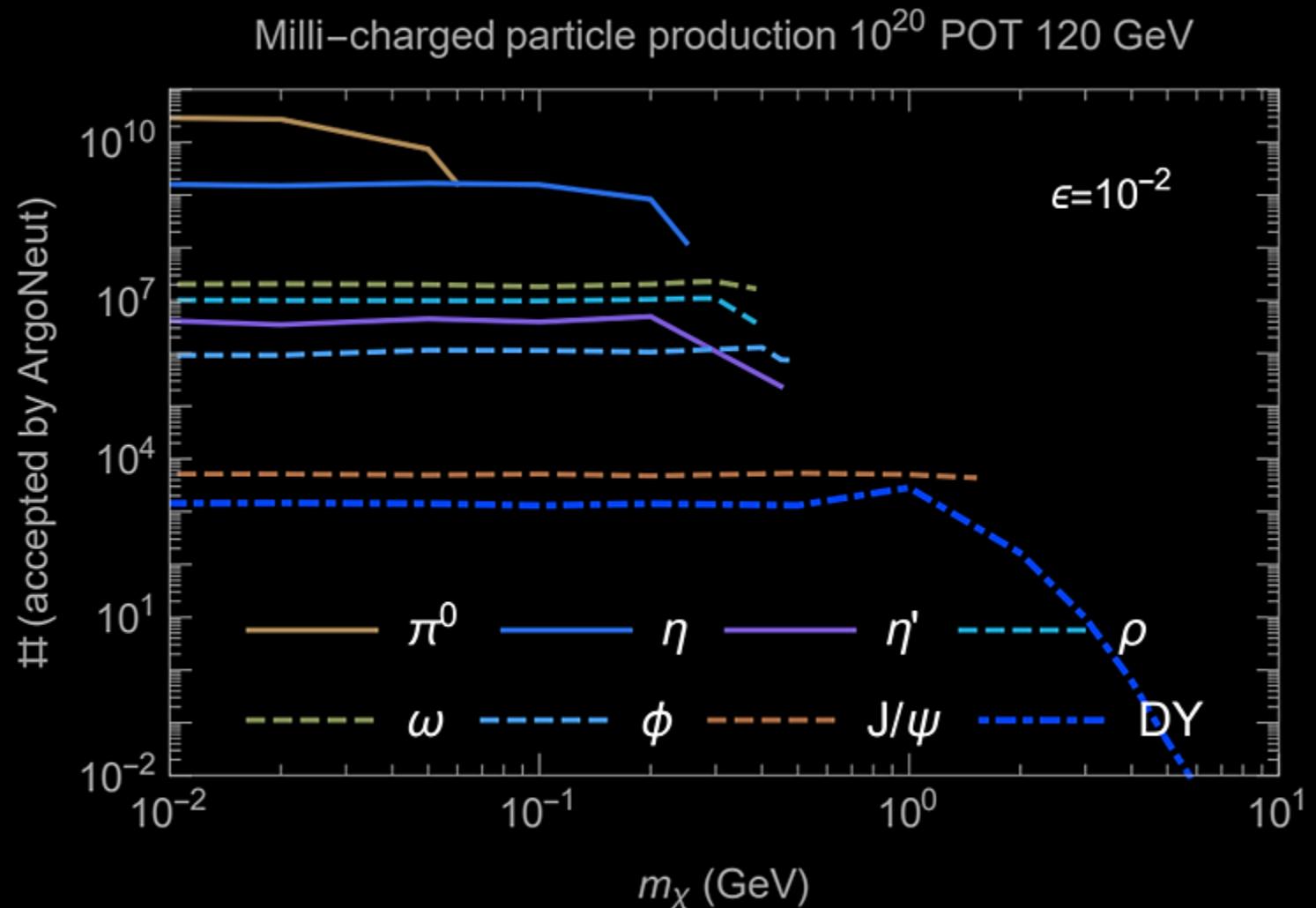
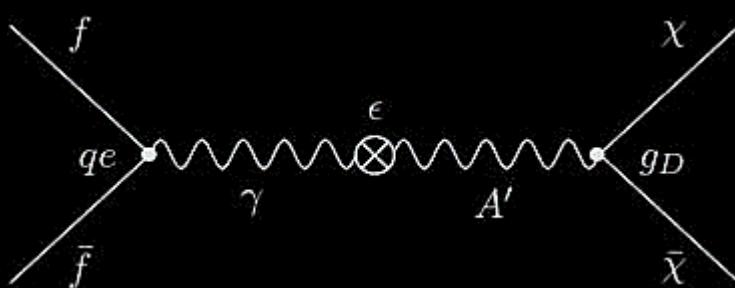
High beam energy  
High beam intensity ( $10^{20} \sim 10^{23}$   
Proton On Target)



# Strong Beam, strong signal

e.g., NuMI beam: good source  
for Millicharged particles

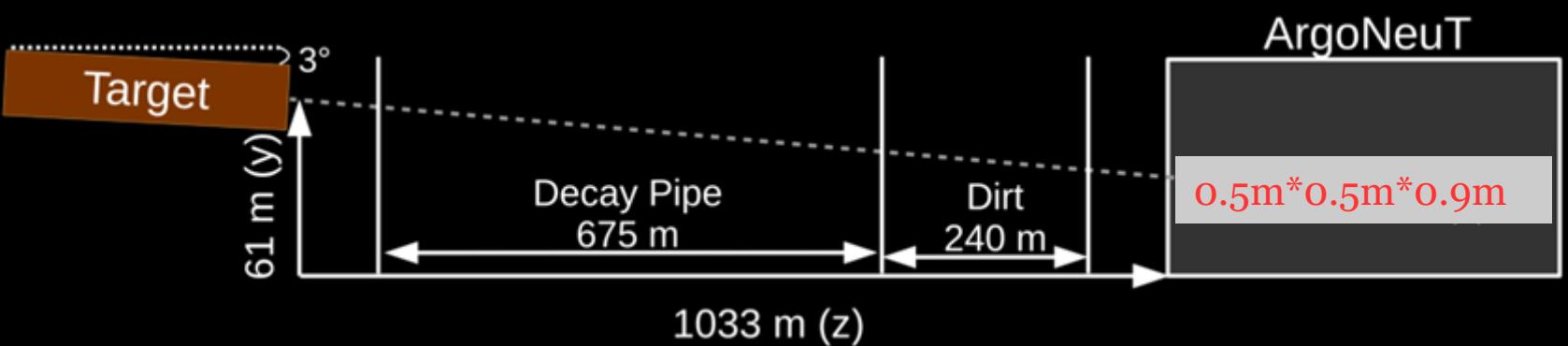
High beam energy  
High POT



# NuMI beam: good source for Millicharged particles

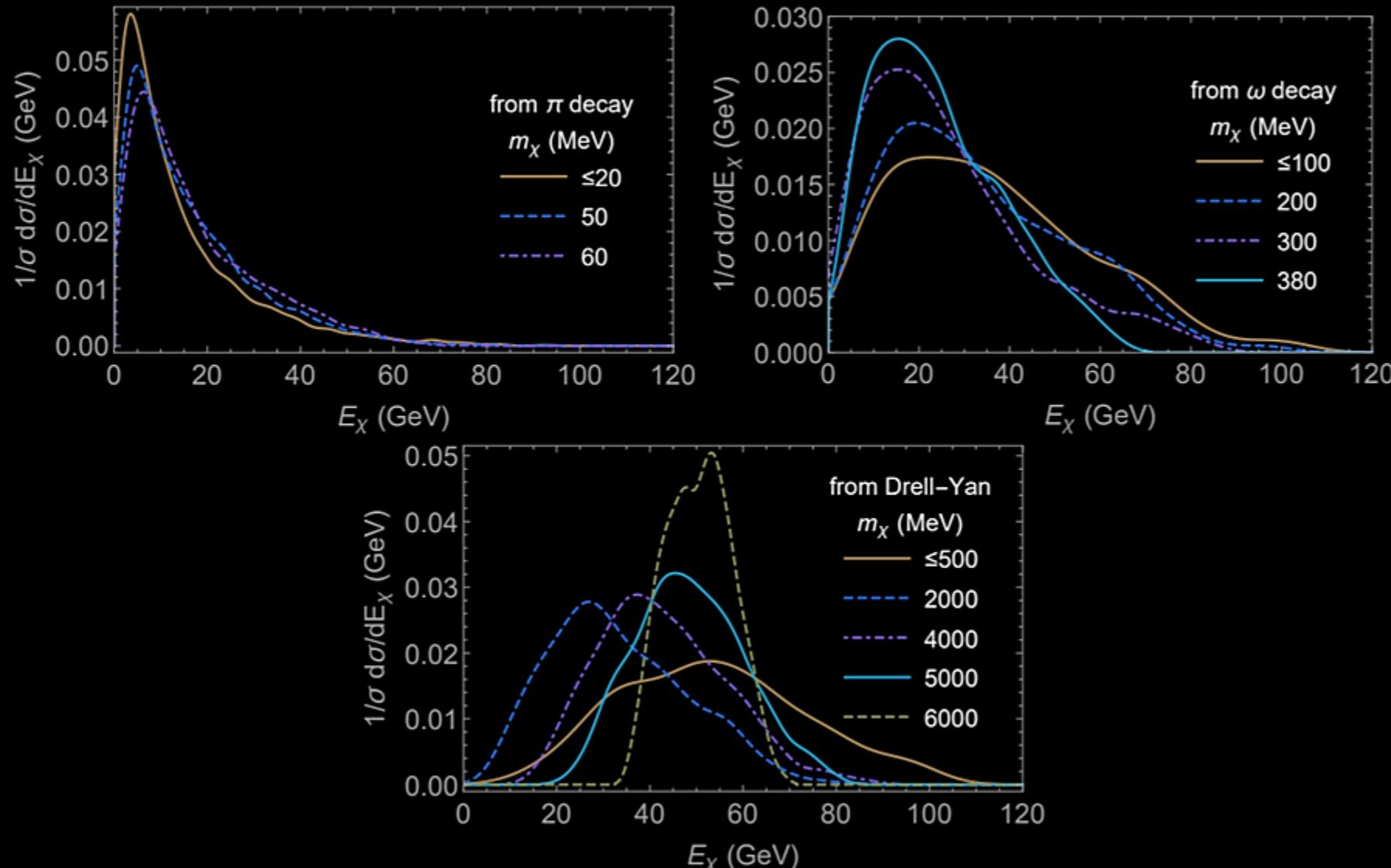
High beam energy  
High POT

Typical geometric  
acceptance:  $10^{-5 \sim 6}$



	$\pi^0$	$\eta$	$\eta'$	$\rho$	$\omega$	$\phi$	$J/\psi$	DY
#/POT	2.9	$3.2 \times 10^{-1}$	$3.4 \times 10^{-2}$	$3.7 \times 10^{-1}$	$3.7 \times 10^{-1}$	$1.1 \times 10^{-2}$	$5.4 \times 10^{-7}$	$4.7 \times 10^{-10} \epsilon^2$
$2 \times \text{Br}_{X \rightarrow \chi\bar{\chi}} (\%)$	$2.3\epsilon^2$	$1.4\epsilon^2$	$0.04\epsilon^2$	$0.009\epsilon^2$	$0.018\epsilon^2$	$0.058\epsilon^2$	$12\epsilon^2$	—
$A_{\text{geo}}^{\text{ArgoNeuT}} (m_\chi = 20 \text{ MeV})$	$3.1 \times 10^{-5}$	$2.1 \times 10^{-5}$	$1.6 \times 10^{-5}$	$1.9 \times 10^{-5}$	$2.0 \times 10^{-5}$	$9.1 \times 10^{-6}$	$5.0 \times 10^{-6}$	$3.2 \times 10^{-6}$
$A_{\text{geo}}^{\text{ArgoNeuT}} (m_\chi = 200 \text{ MeV})$	—	$5.4 \times 10^{-5}$	$3.4 \times 10^{-5}$	$2.3 \times 10^{-5}$	$2.2 \times 10^{-5}$	$1.1 \times 10^{-5}$	$4.6 \times 10^{-6}$	$3.1 \times 10^{-6}$

# Productions: millicharged particles are boosted



# Detection

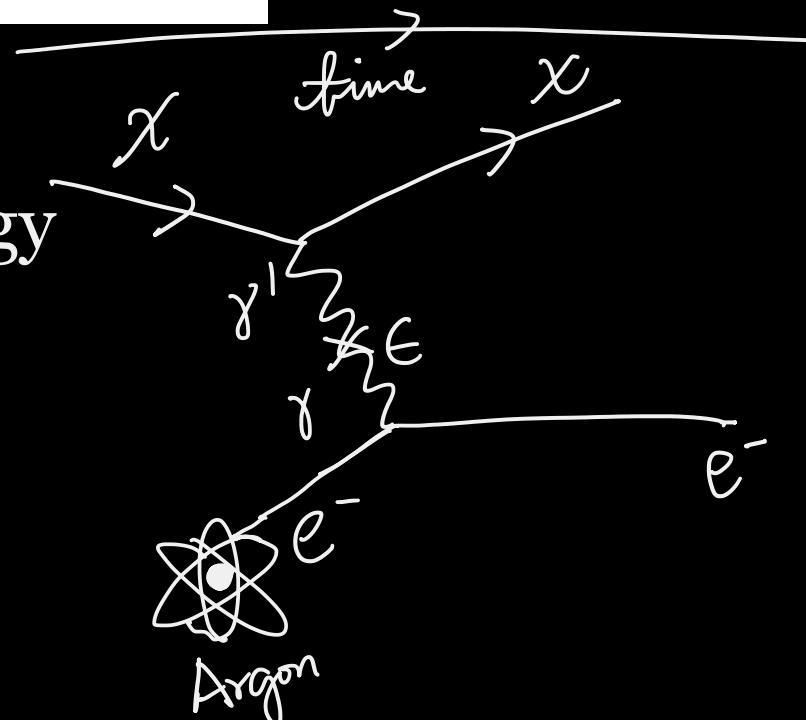
Signal scattering probability and mean free path

$$\frac{d\sigma}{dE_r} = \pi\alpha^2\epsilon^2 \frac{2E_\chi^2 m_e + E_r^2 m_e - E_r (m_\chi^2 + m_e(2E_\chi + m_e))}{E_r^2(E_\chi^2 - m_\chi^2)m_e^2}$$

$$\left. \frac{d\sigma}{dE_r} \right|_{E_\chi \gg m_\chi, m_e, E_r} \simeq \frac{2\pi\alpha^2\epsilon^2}{E_r^2 m_e}.$$

Dominated by  
low recoil energy  
scattering

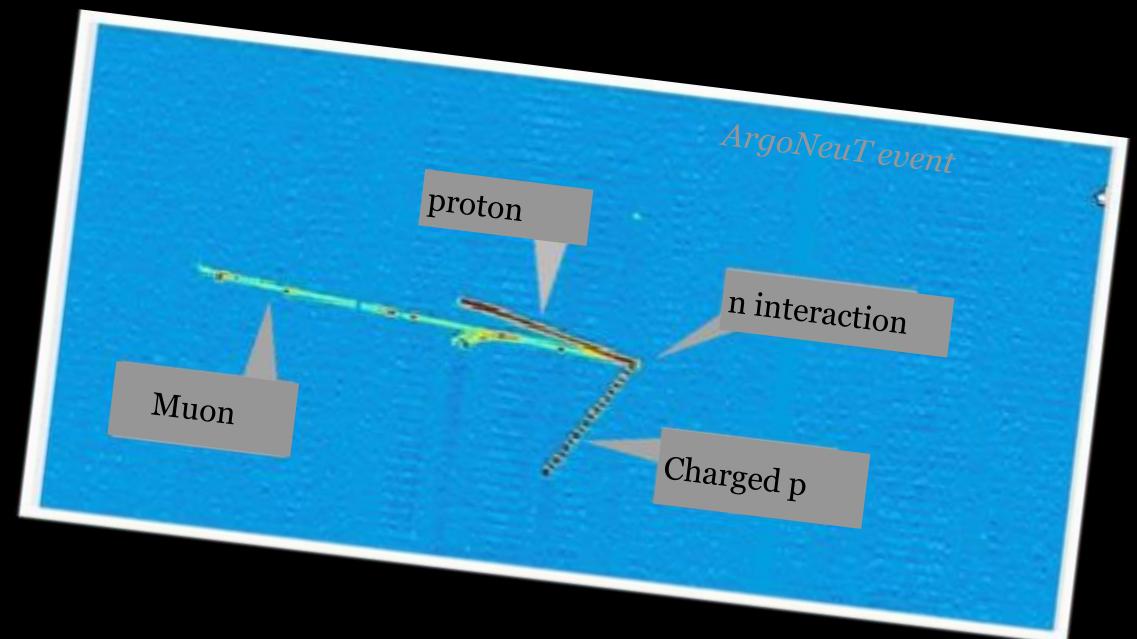
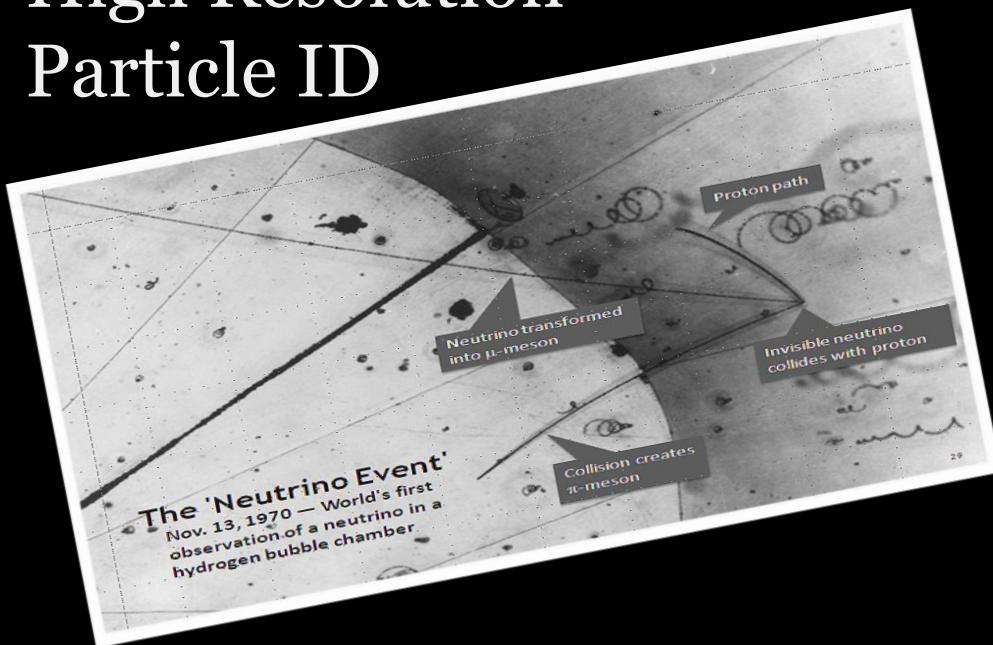
$$\lambda(E_r^{\min}) \simeq \left( \frac{10^{-2}}{\epsilon} \right)^2 \left( \frac{E_r^{\min}}{1 \text{ MeV}} \right) 1 \text{ km}$$



# Liquid Argon (LAr) Detectors

- Large (ArgoNeuT, microBooNE, SBND, ICARUS, DUNE)
- Clean
- Tracking
- Calorimetry
- High Resolution
- Particle ID

LAr TPC gives 2-in-1:  
Bubble chamber quality of data with  
added calorimetry





R&D  
1986-2000

**ICARUS**

35 t  
FNAL 2013-16

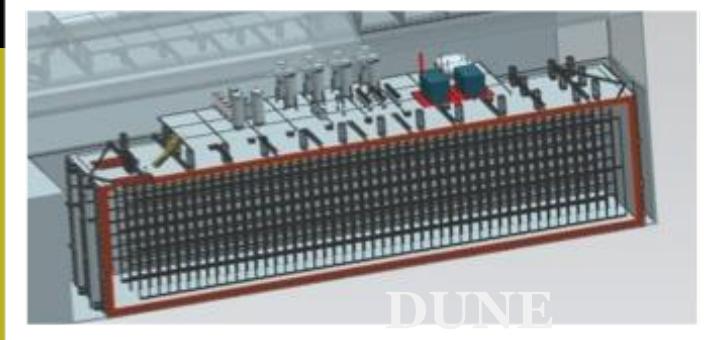
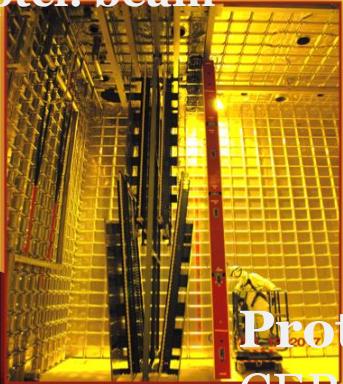
LNGS→FNAL  
2010-13→2018



Yale TPC 2007

NuMI beam  
Dark Journey

CERN NP charged  
ptcl. beam



DUNE

Long Baseline  
 $\nu$   
at SURF-SD

$\mu$ BooNE  
FNAL – 2015-2020



ArgoNeuT  
FNAL  
2009-10



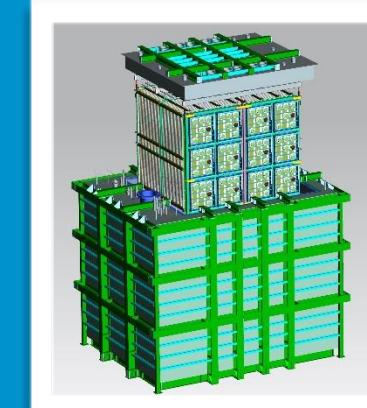
Booster beam

LArIAT FNAL  
2014-2018



PAC Webinar-51

ITBF charged ptcl.  
beam



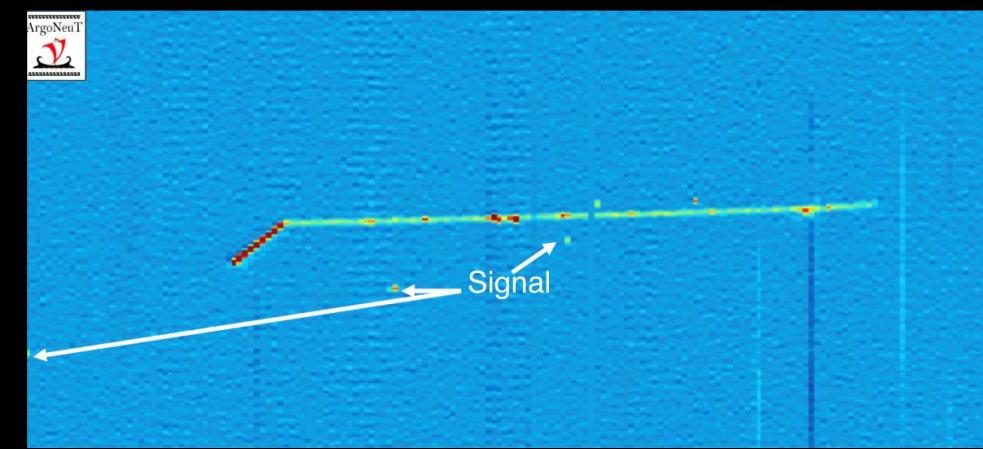
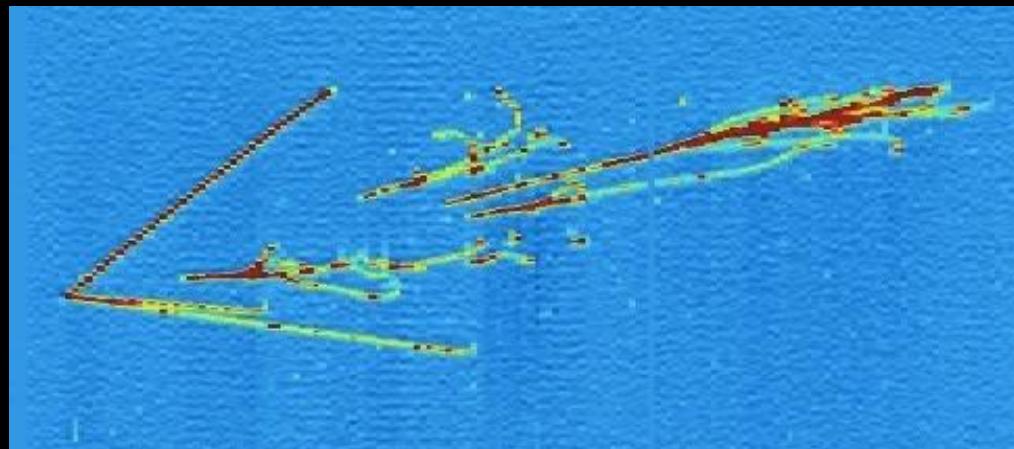
Short Baseline  $\nu$   
at FNAL

Fig. from O. Palamara

# Backgrounds

Soft hits. will be commonplace. Slow neutrons,  $\gamma$ 's, cosmics, electronics, radioactives (Ar39)...

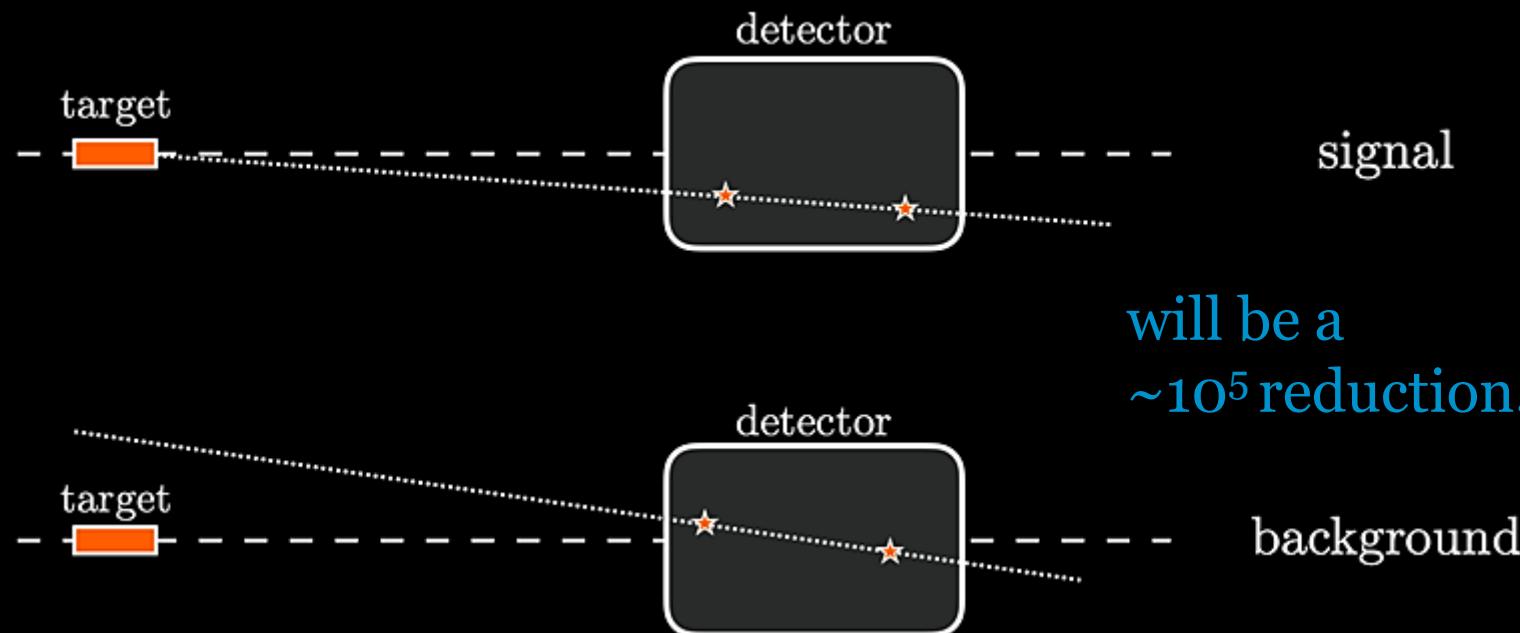
	Bkg Scaling	Bkg reduction	# frames with			# Background events				
			$\geq 0$ hit	$\geq 1$ hits	$\geq 2$ hits	Singlets	Doublets	Aligned doublets	Triplets	Aligned triplets
ArgoNeuT	Reference	Systematic	$3.3 \times 10^6$	$3.9 \times 10^5$	$2.4 \times 10^4$	$4.2 \times 10^5$	$2.7 \times 10^4$	0.24	$1.1 \times 10^3$	$9.1 \times 10^{-8}$



Average occupation number per frame:  
ArgoNeuT: 0.13

# Background Reduction

- Double hit probability  $\sim (P_{\text{hit}})^2$ .
- If we have spatial resolution  $\rightarrow$  2-hit BG can be reduced by requiring alignment with target.



We then recalled a key feature of LAr detectors, and designed a new search:

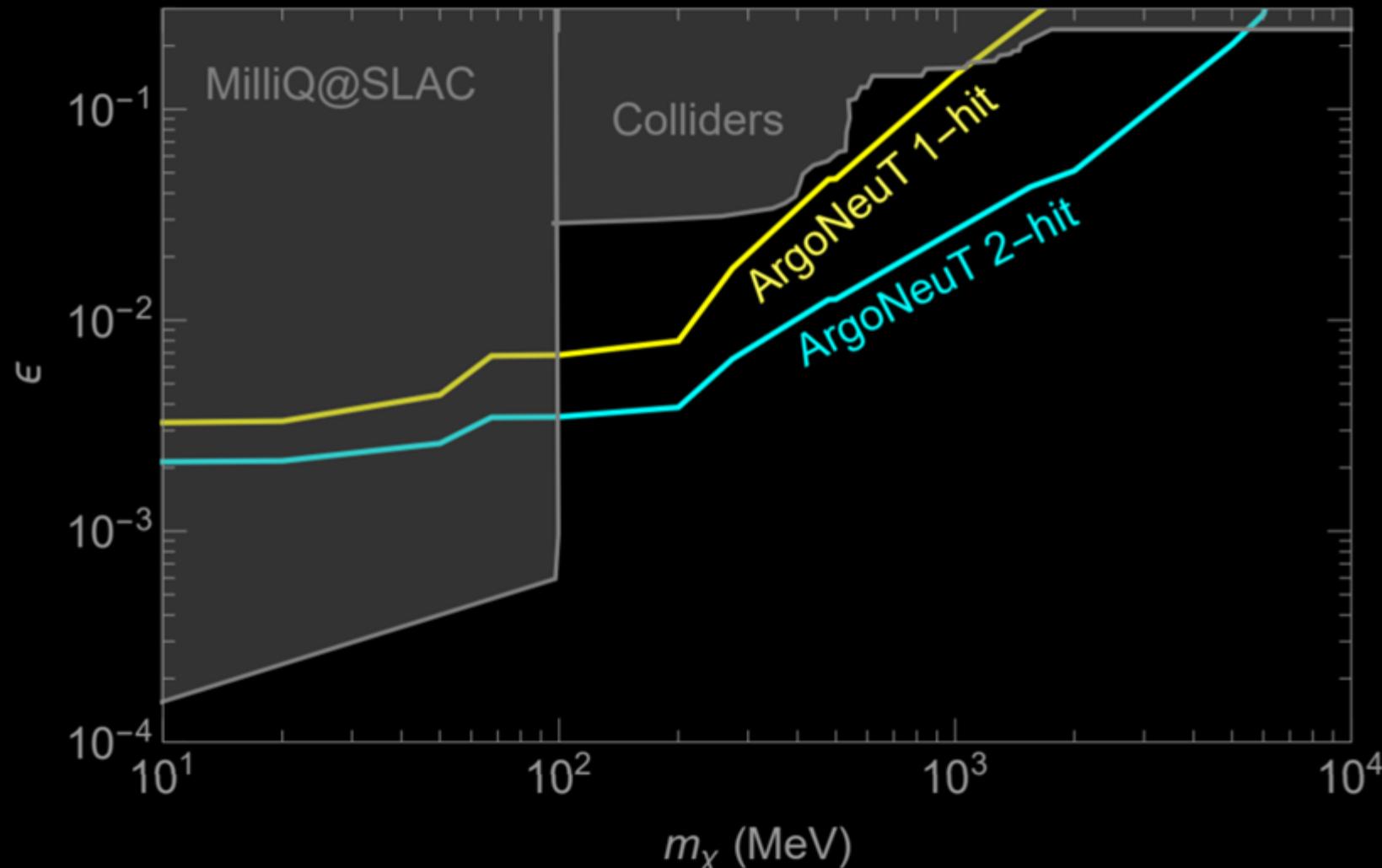
$$\delta y \times \delta x \times \delta z = 5.6 \text{ mm} \times 0.3 \text{ mm} \times 3.2 \text{ mm.}$$

$$N_{\text{2 hit}}^{\text{aligned}} = N_{\text{2 hit}} \times \left( \frac{\delta x}{\Delta x} \frac{\delta y}{\Delta y} \right)$$

will be a  
 $\sim 10^5$  reduction.

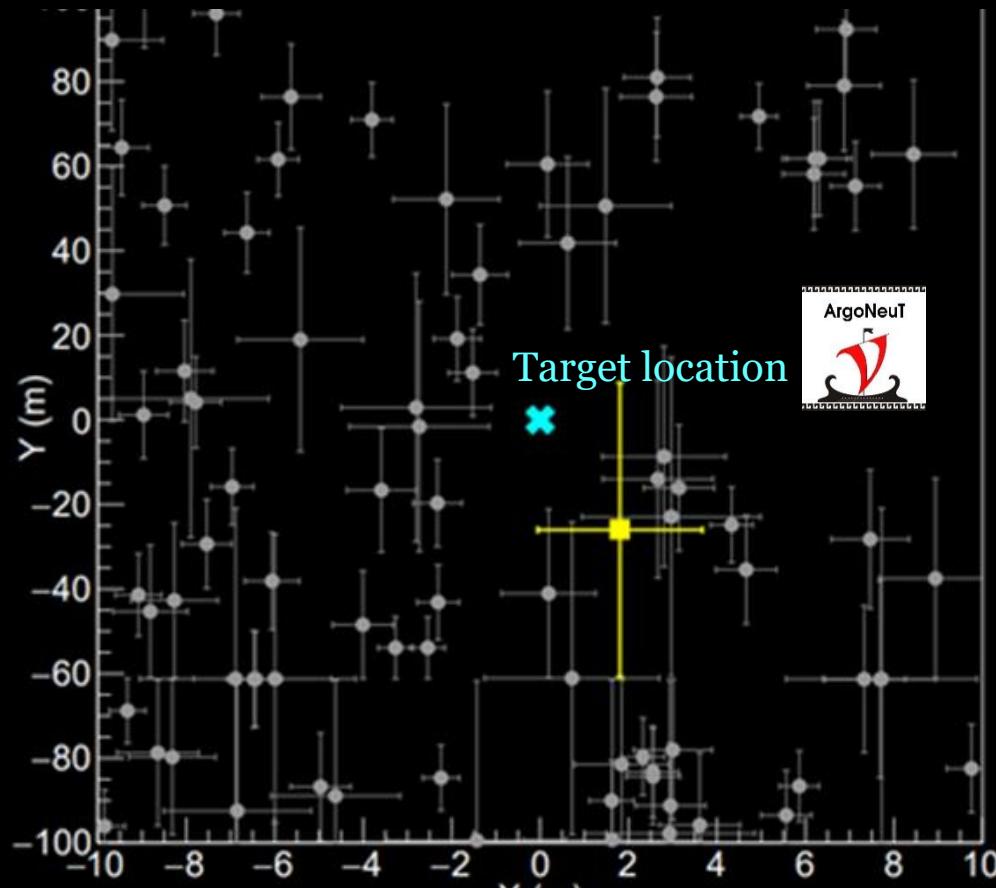
background

# Expected reach



Harnik, ZL, Palamara, [1902.03246](#)

# Search for mCP in ArgoNeuT

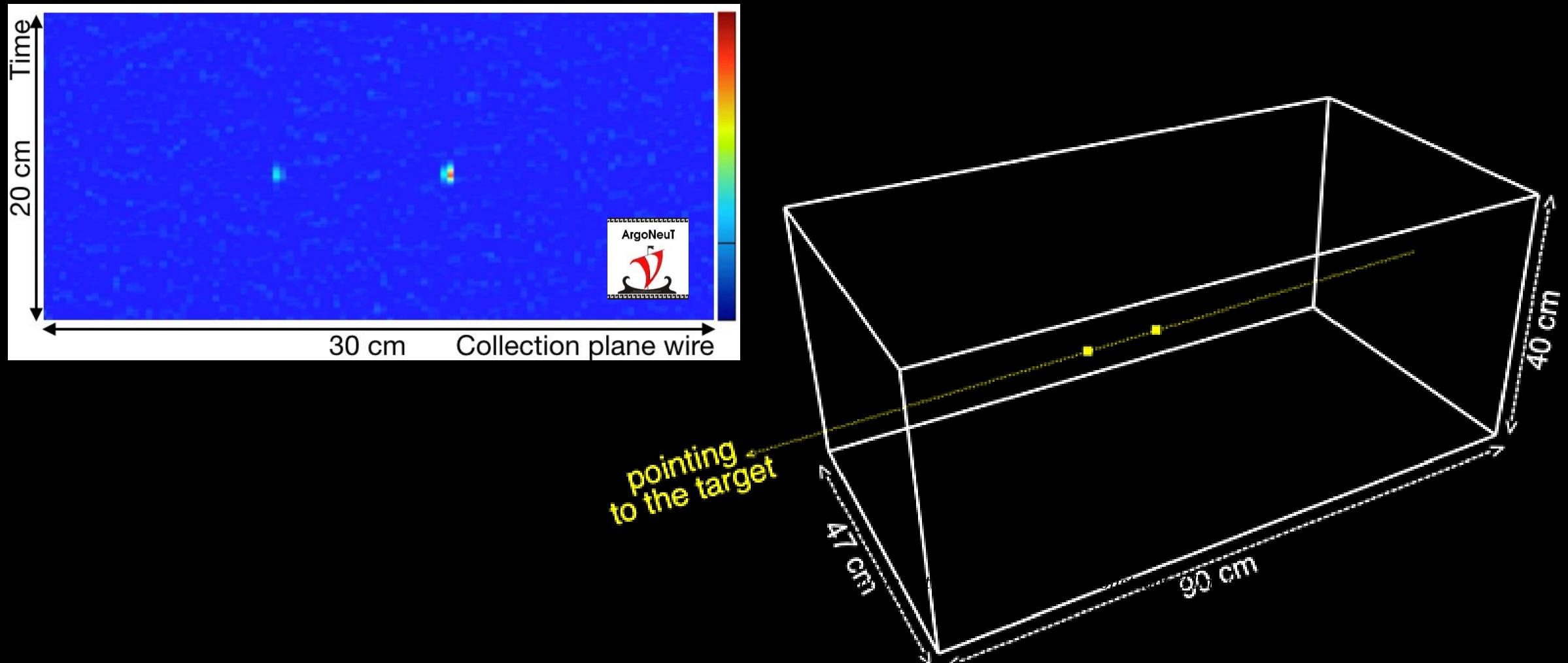


- Uncertainties are determined by
  - the uncertainties in the locations of the clusters inside the detector
    - *0.015 cm in the horizontal drift direction*
    - *0.28 cm in the vertical direction*
    - *0.16 cm along the beam direction*
  - while small compared to the size of the detector, uncertainties become quite large when extrapolated to the location of the target (1033 m upstream)

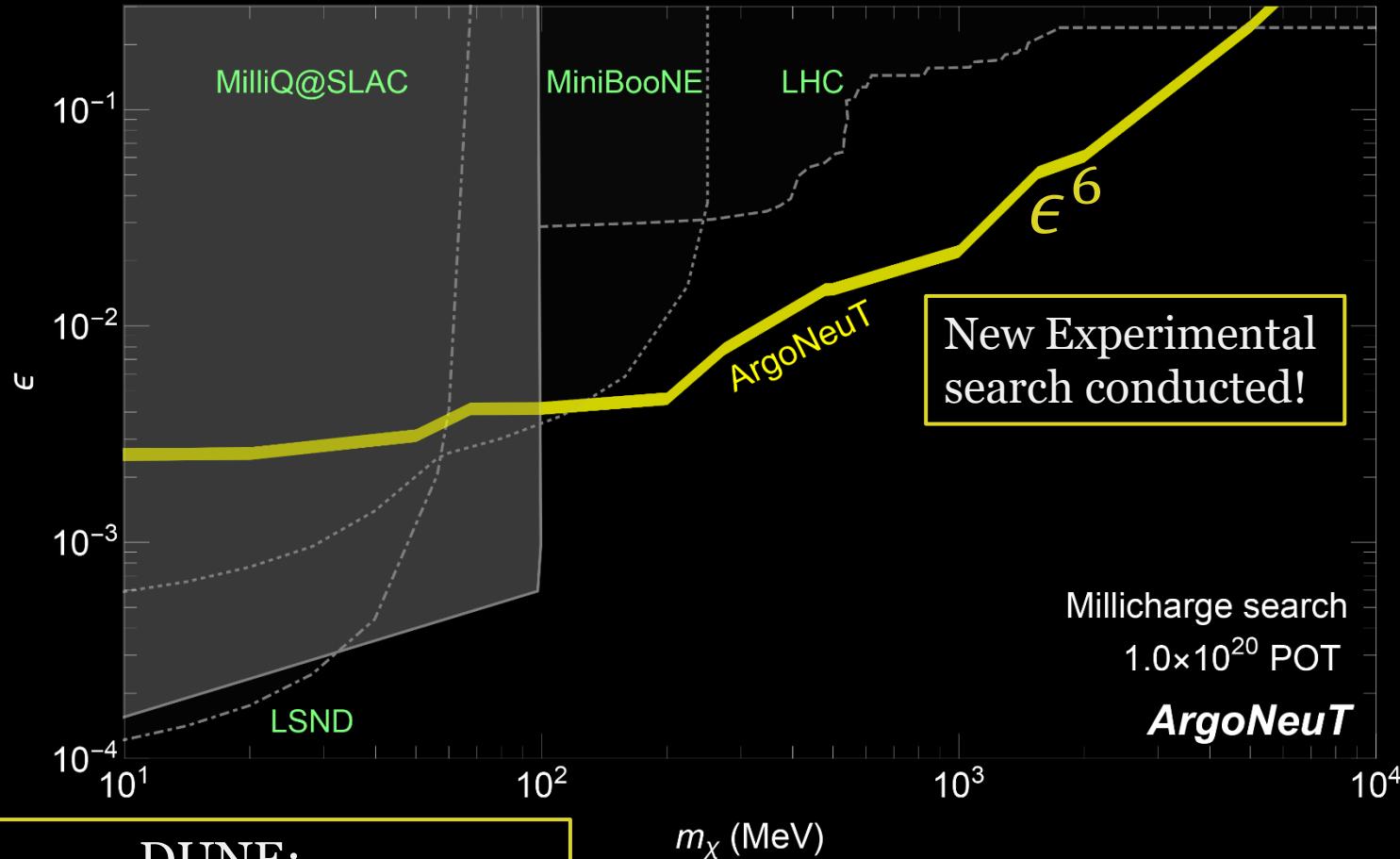
*Locations of the points of intersections of lines defined by two clusters with a plane perpendicular to the beam at the downstream target's edge*

one mCP Signal Candidate Event observed,  
Compatible with the expected background

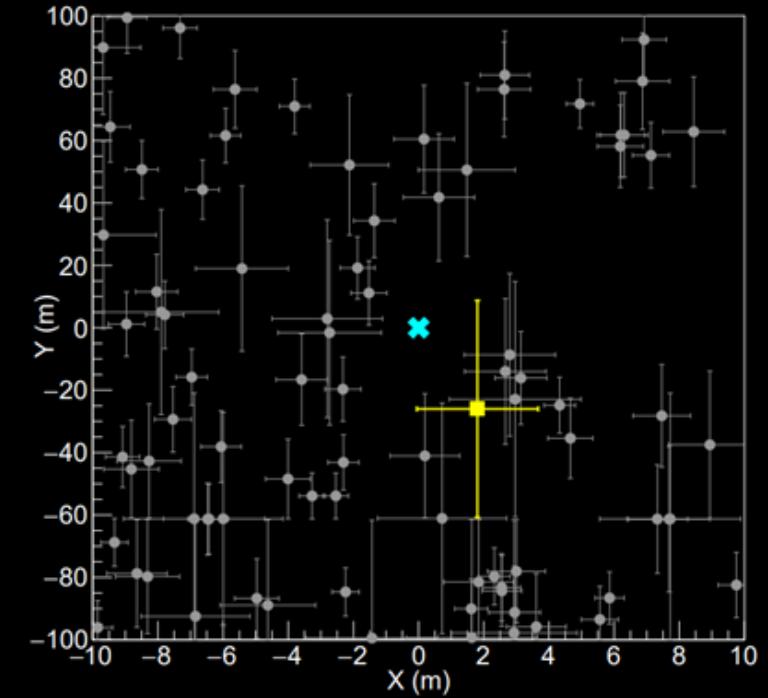
# The Candidate Signal Event



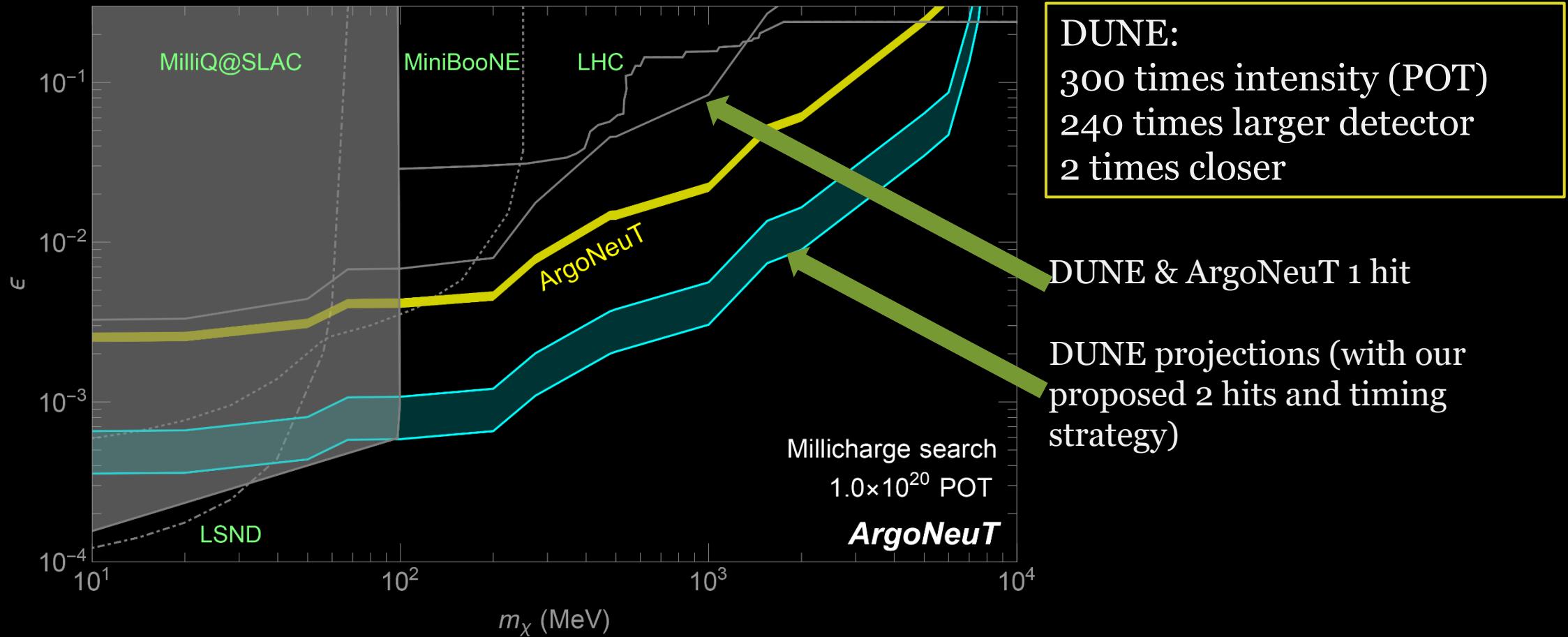
# New exciting coverage



DUNE:  
300 times intensity (POT)  
240 times larger detector  
2 times closer



# Looking into the future



# How to see Millicharged Particles (Again)?

Signal scattering probability and mean free path

$$\frac{d\sigma}{dE_r} \Big|_{E_\chi \gg m_\chi, m_e, E_r} \simeq \frac{2\pi\alpha^2\epsilon^2}{E_r^2 m_e}.$$

Dominated by low recoil energy scattering

What if we lower the threshold?

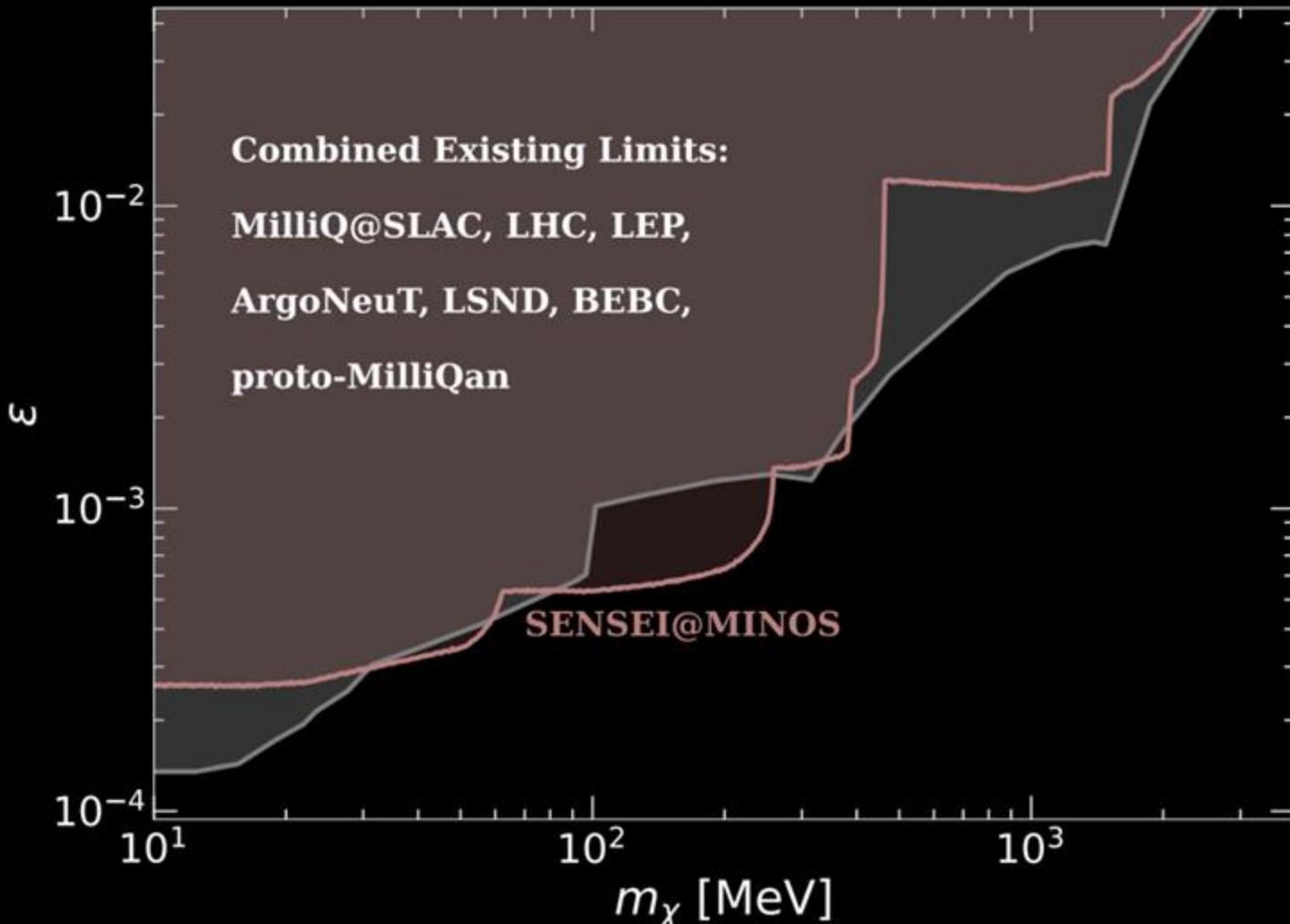
$$\lambda(E_r^{\min}) \simeq \left(\frac{10^{-2}}{\epsilon}\right)^2 \left(\frac{E_r^{\min}}{1 \text{ MeV}}\right) 1 \text{ km}$$

Compared to LAr, Skipper CCD increases signal efficiency by  $10^5$  (1 MeV v.s. 10 eV)

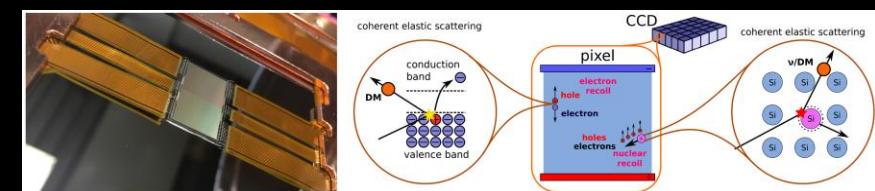
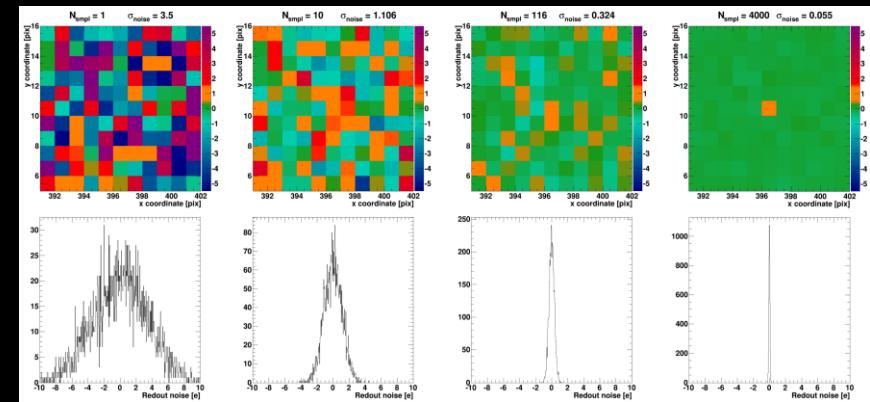
## **Single Scatter Detection Parametric:**

- Detection Rate proportional to Volume
  - SENSEI 3gram is small in volume, about  $1/10^5$  compared to ArgoNeuT
- Detection Rate proportional to effective POT

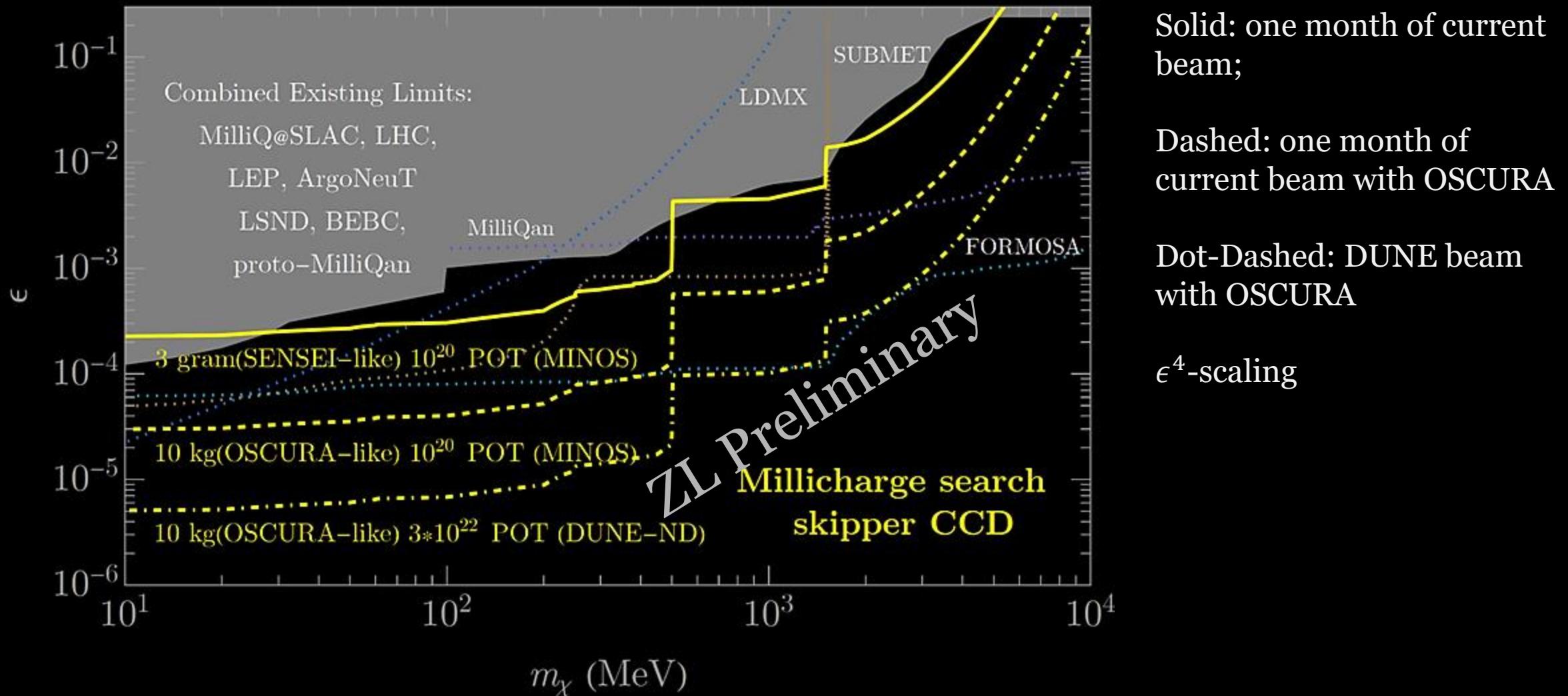
# New Results with SENSEI Collaboration ([2305.04964](#))



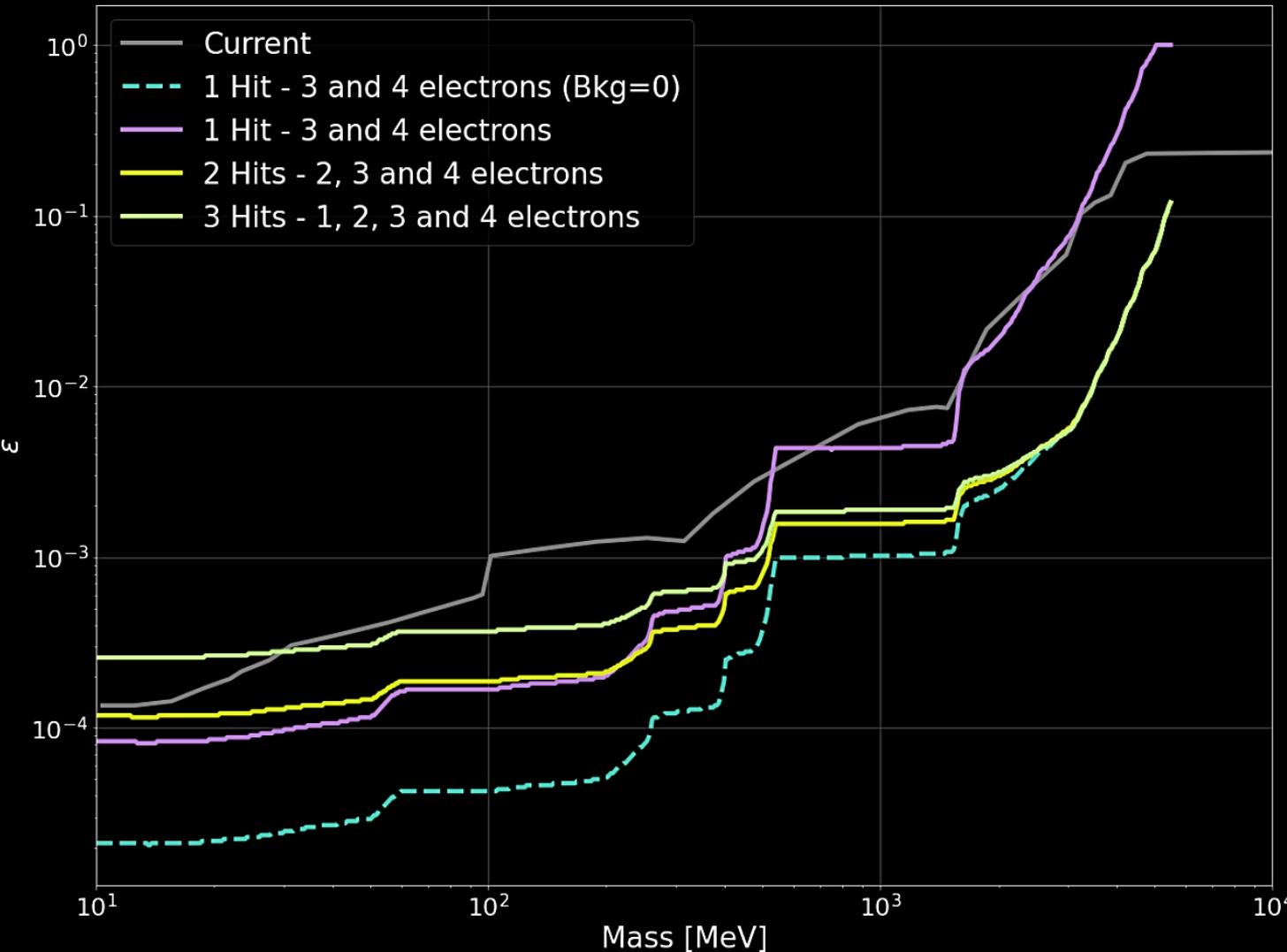
3 gram of detectors with 3 days equivalent of data already achieving new results.



# There are many already “under construction”



# with the OSCURA collaboration ([2304.08625](#))



Assuming 1kg skipper CCD for “early science” of OSCURA experiment.

Different background level assumptions:

- Very conservatively assuming a large number of backgrounds;
- Adapting our multi-hit strategy;
- Also shown in dashed the zero-background projections (consistent with my earlier calculation in the previous slide).

# Good at Excluding. Are we good discovering?

I think so:

One can test if the excess events follow (this requires a reasonable modeling of backgrounds) the expected behavior:

$$\frac{d\sigma}{dE_r} = \pi\alpha^2\epsilon^2 \frac{2E_\chi^2 m_e + E_r^2 m_e - E_r (m_\chi^2 + m_e(2E_\chi + m_e))}{E_r^2(E_\chi^2 - m_\chi^2)m_e^2}$$

$$\left. \frac{d\sigma}{dE_r} \right|_{E_\chi \gg m_\chi, m_e, E_r} \simeq \frac{2\pi\alpha^2\epsilon^2}{E_r^2 m_e}.$$

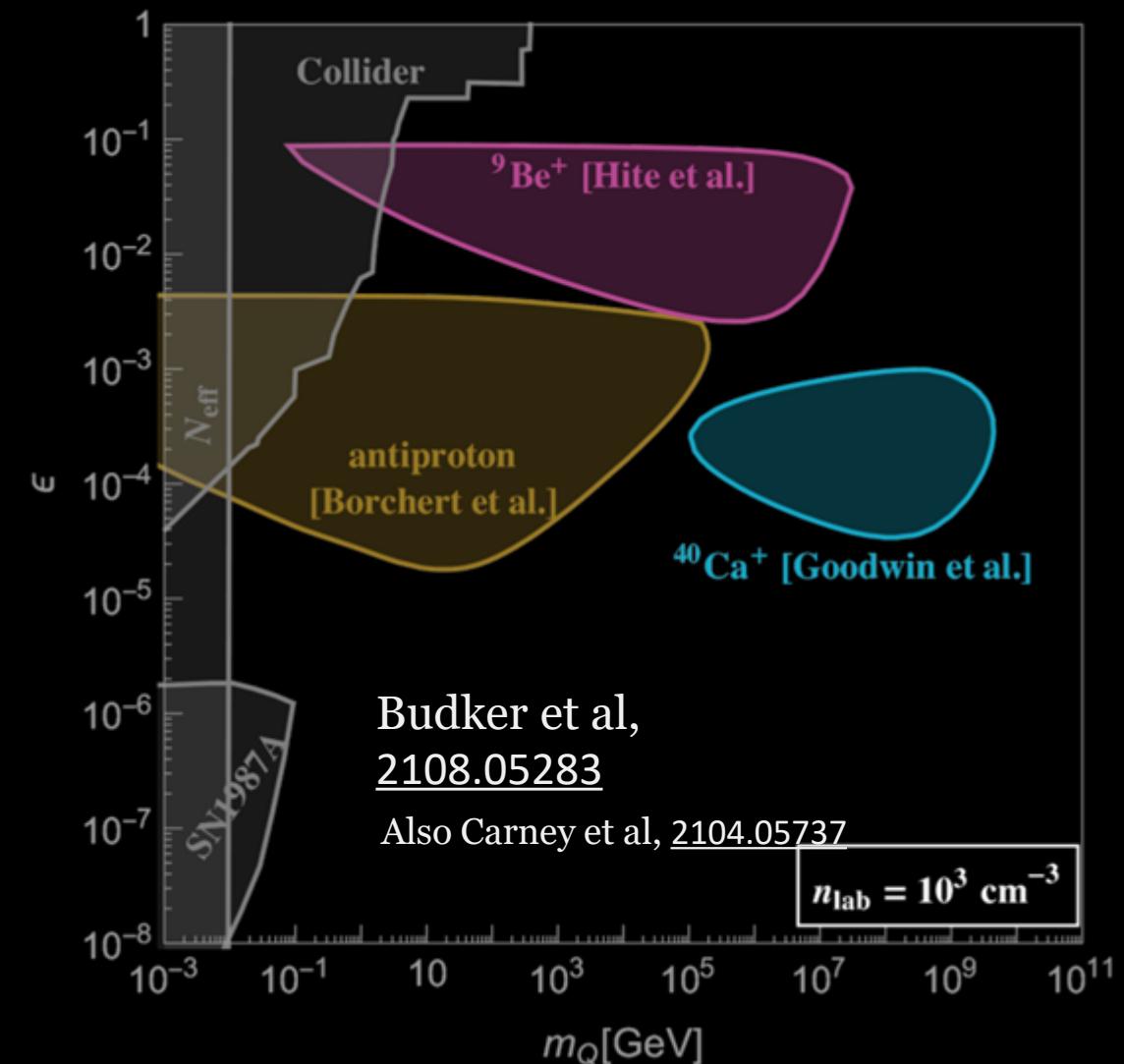
# Fast developing frontier:

Beyond beam production, we can have:

- Atmospheric production of MCPs (e.g., Plestid et al, [2002.11732](#); Du, Fang, Liu [2211.11469](#))
- Local (and collected) abundance of MCP (a fraction of) DM, enabling new searches such as using ion-trap heating or cavity-like experiment

On the theory side, a few aspects to improve:

- Signal efficiency calculation (dark ELF);
- MCP production prediction improvement.



# Part II: Dark Photons @ Dark SRF



Mainly based upon A. Romanenko et al, [2301.11512](https://arxiv.org/abs/2301.11512)

# Intro

There are many past, ongoing, and future searches.

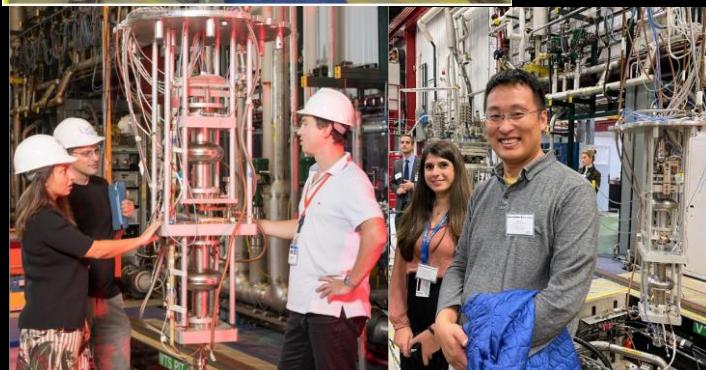
Today, I share the pathfinder journey and results of one such effort and discuss its future.



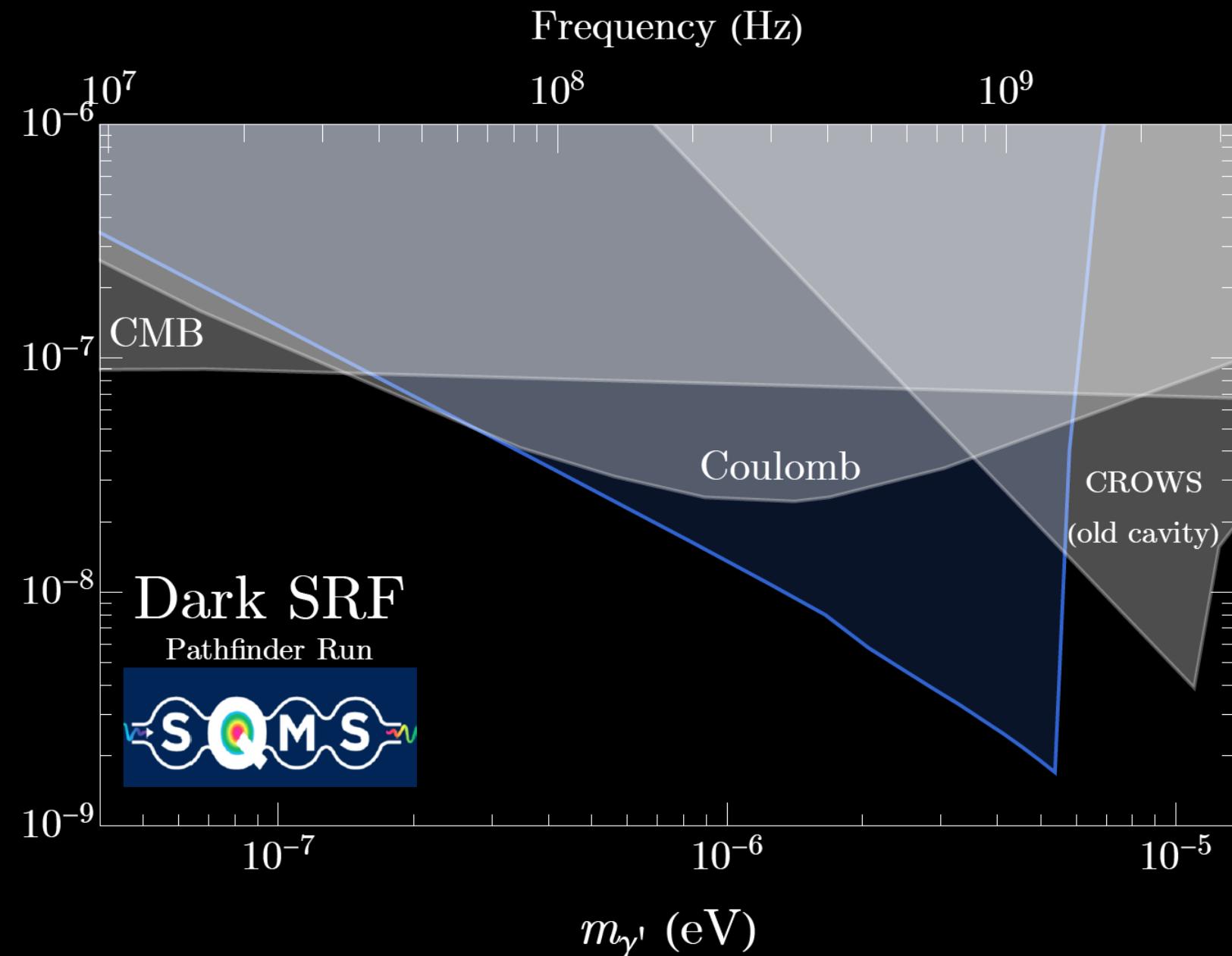
Graham et al, Phys.Rev. D90 (2014) no.7, 075017  
S. R. Parker et al, Phys. Rev. D 88, 112004 (2013)  
J. Hartnett et al, Phys. Lett. B 698 (2011) 346  
J. Jaeckel and A. Ringwald, Phys. Lett. B 659, 509 (2008)

# Pathfinder result

Our pathfinder run results  
already explore new territory!

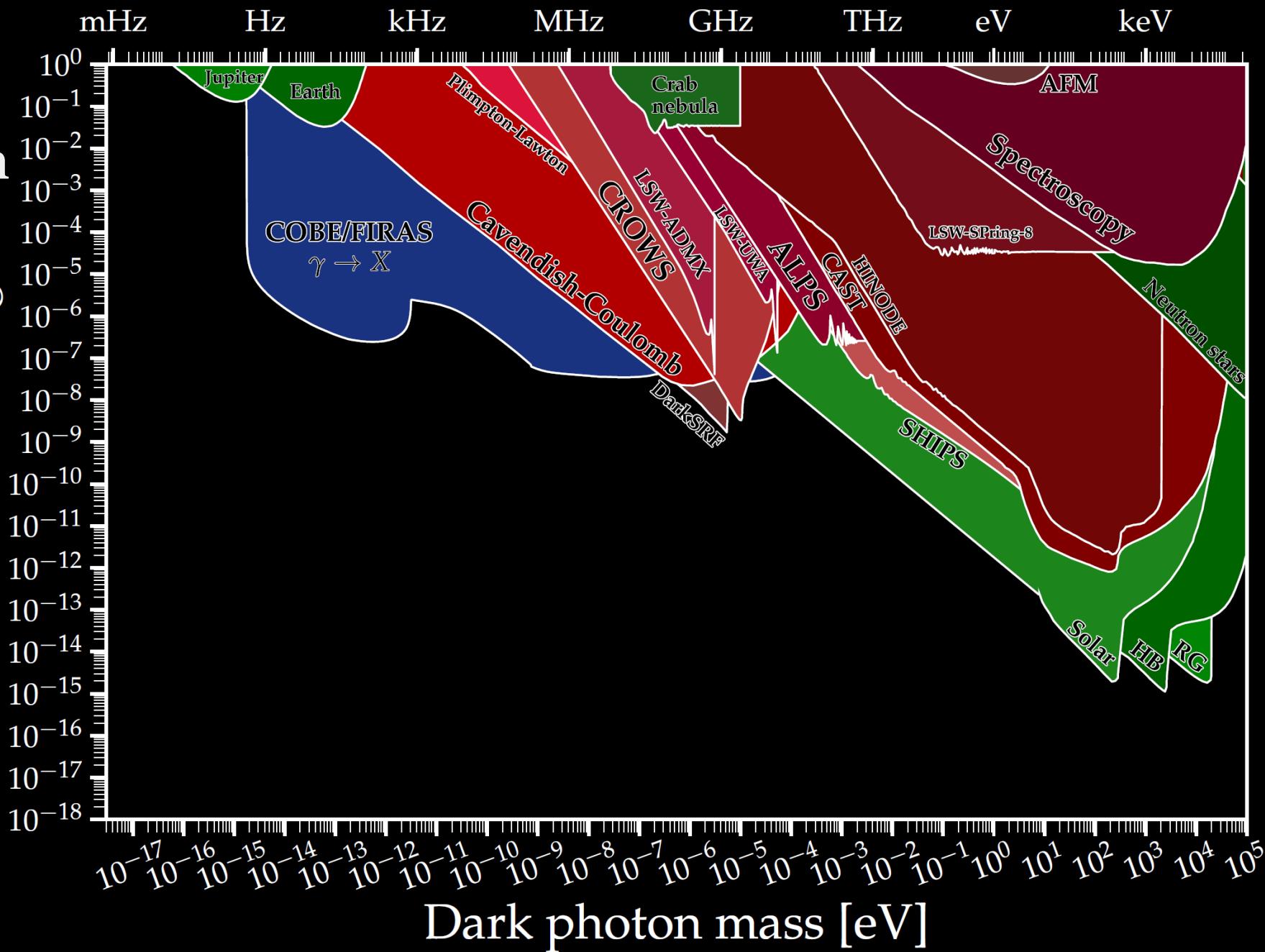


Work was performed at Fermilab and University of Minnesota



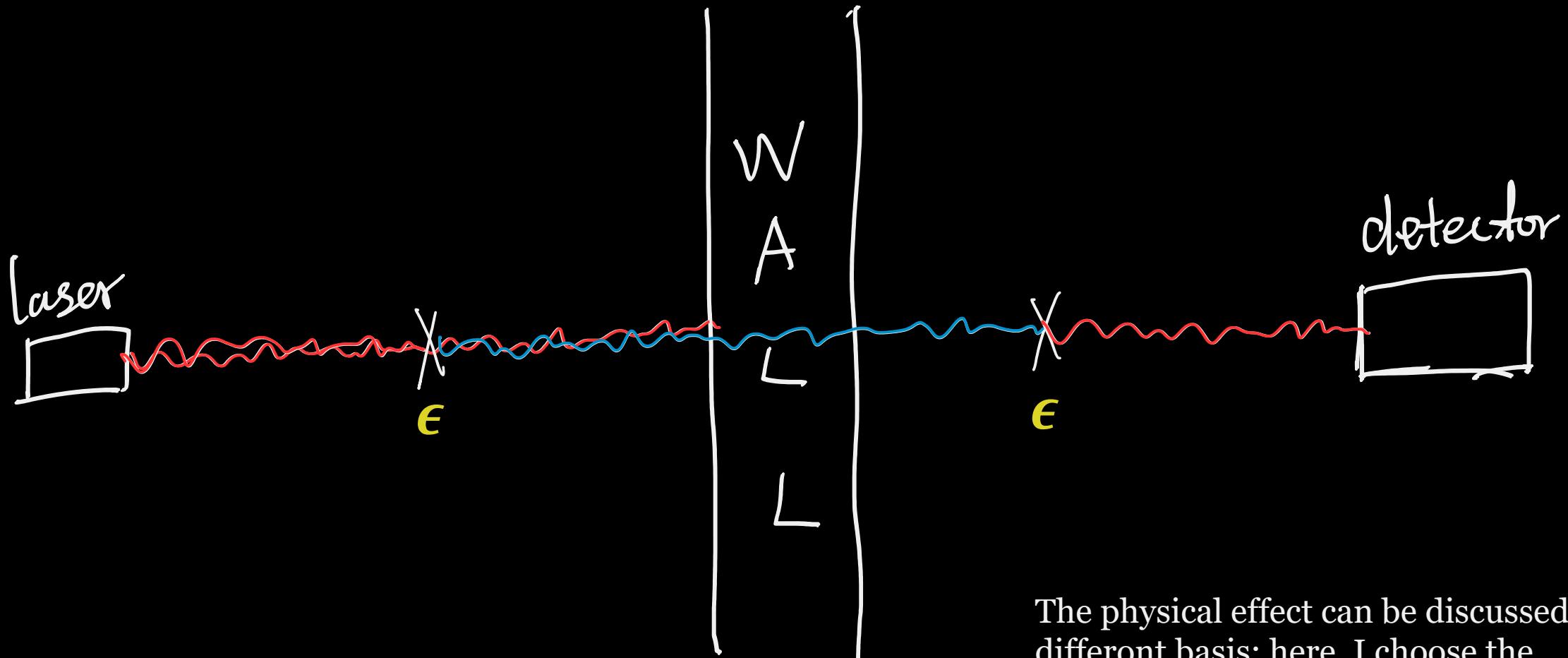
# An active program: much less known when not dark matter

Kinetic mixing



# **What is Dark SRF?**

# Light Shining through Wall (LSW)



The physical effect can be discussed in different basis; here, I choose the interaction basis that contains two different propagation modes.

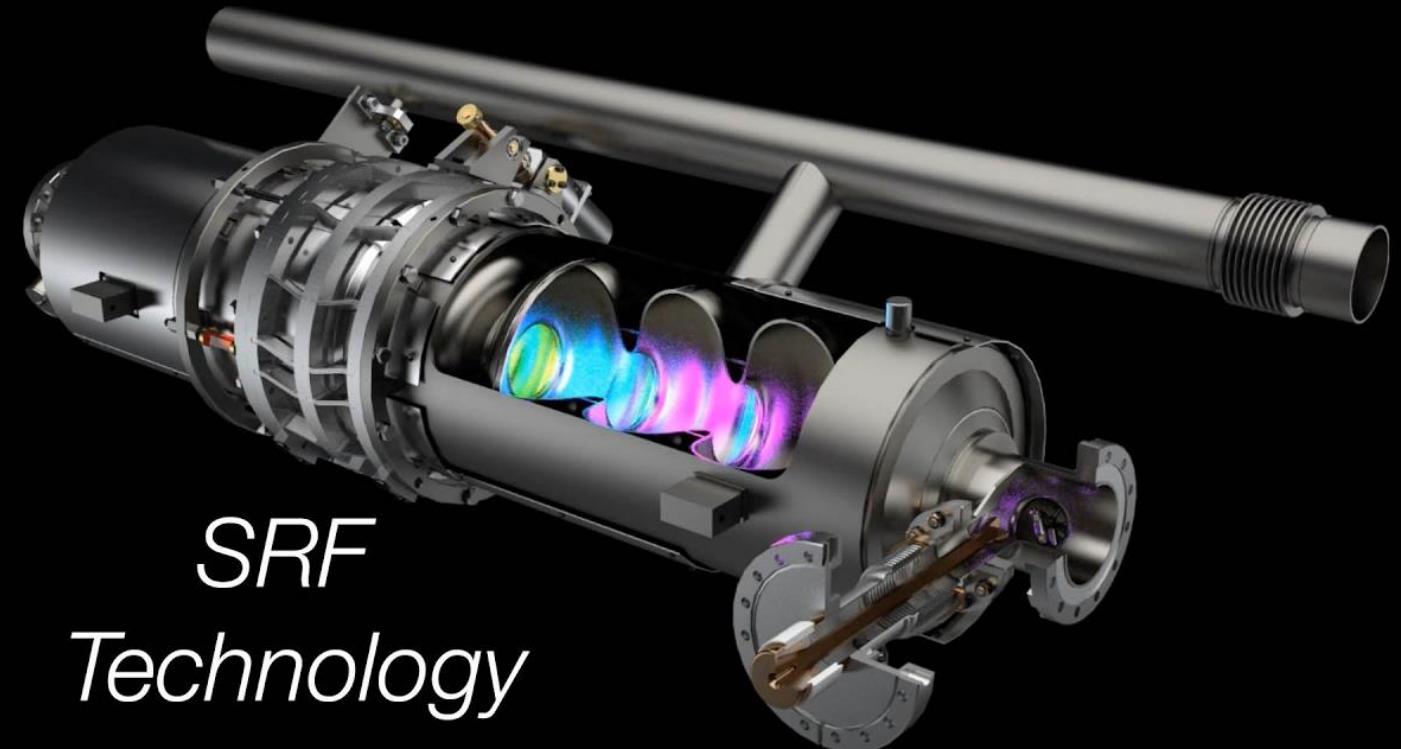
# We have the best SRF for High Energy Accelerators

Superconducting RF Cavities:

- Large fields
- High Quality

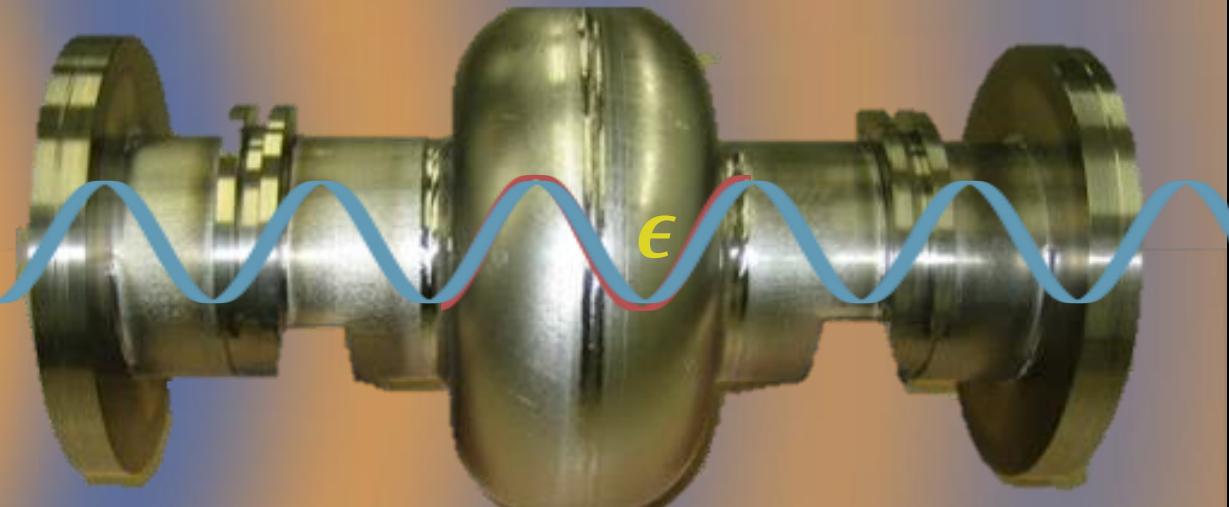
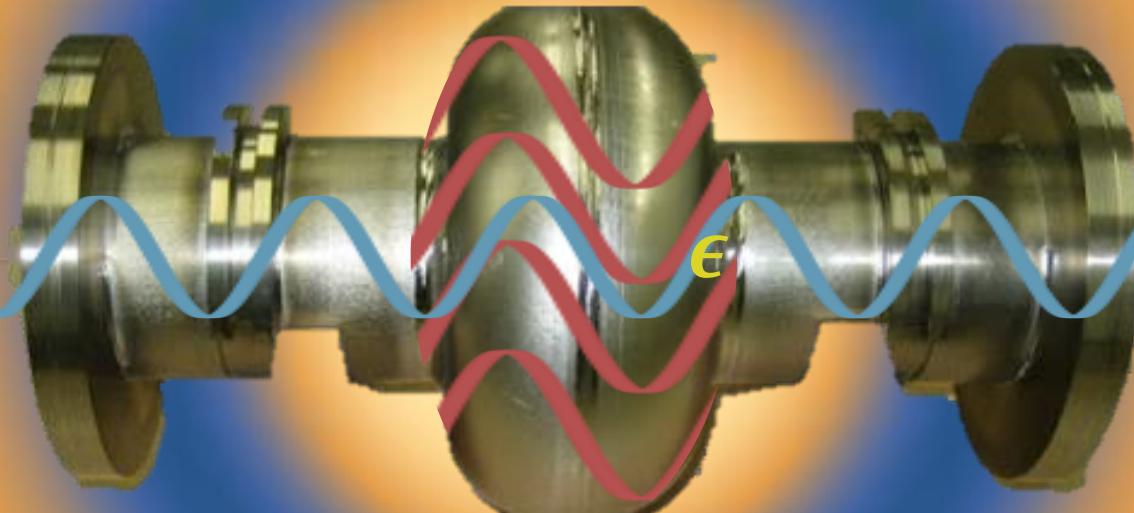


Superconducting Radio Frequency (SRF) cavity



# SRF for Dark Photon

$$\vec{E}_{\text{receiver}}(\vec{r}, t) = -\frac{Q_{\text{rec}}}{\omega} \left[ \frac{\int d^3x \vec{E}_{\text{cav}}^*(\vec{x}) \cdot \vec{j}(\vec{x})}{\int d^3x |\vec{E}_{\text{cav}}(\vec{x})|^2} \right] \vec{E}_{\text{cav}}(\vec{r}) e^{i\omega t}$$



Power it up:

- 40 MV/m (26 J stored energy)
- $\sim 10^{25}$  photons

SM photon does not penetrate the superconducting wall.

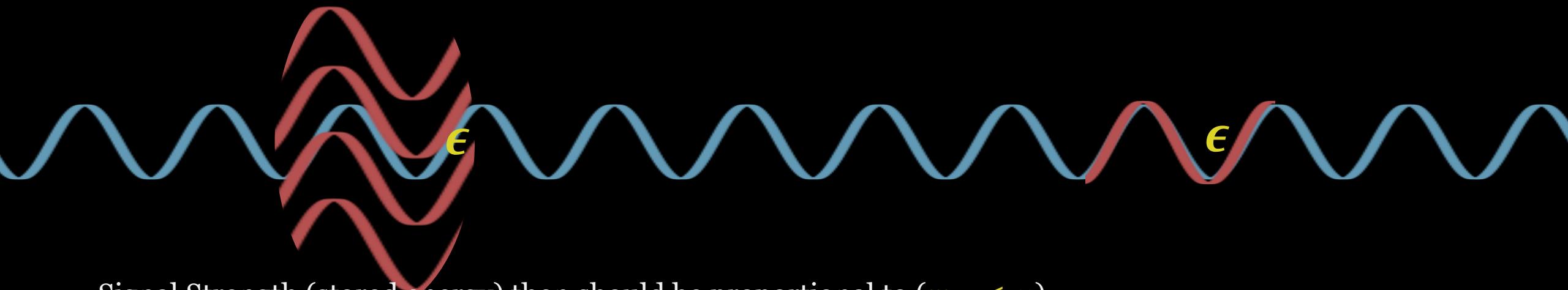
But dark photons can!

$$\vec{E}'(\vec{r}, t) \simeq -\epsilon m_{\gamma'}^2 \int_{V_{\text{emitter}}} d^3x \frac{\vec{E}_{\text{cav}}(\vec{x})}{4\pi|\vec{r} - \vec{x}|} e^{i(\omega t - k|\vec{r} - \vec{x}|)}$$

$$\vec{j}(\vec{r}) e^{i\omega t} = -\frac{i\epsilon}{\omega} \left( m_{\gamma'}^2 \vec{E}' - \vec{\nabla}(\vec{\nabla} \cdot \vec{E}') \right)$$

Isolated receiver  
• High Q of  $10^{10}$  (accumulate tiny signal power)

# SRF for Dark Photon: naïve parametrics



Signal Strength (stored energy) then should be proportional to ( $m_{\gamma'} < \omega$ )

$$S \propto \frac{m_{\gamma'}^4}{\omega^4} \epsilon^4 Q_{receiver} Q_{emitter} P_{emitter} |G|^2$$

Background noise should be proportional to. e.g., thermal dominance

$$B \propto \text{Temperature}$$

Background fluctuation controlled at

$$\Delta B \propto \text{Temperature} \sqrt{\frac{t_{rungup}}{t_{integration}}}$$

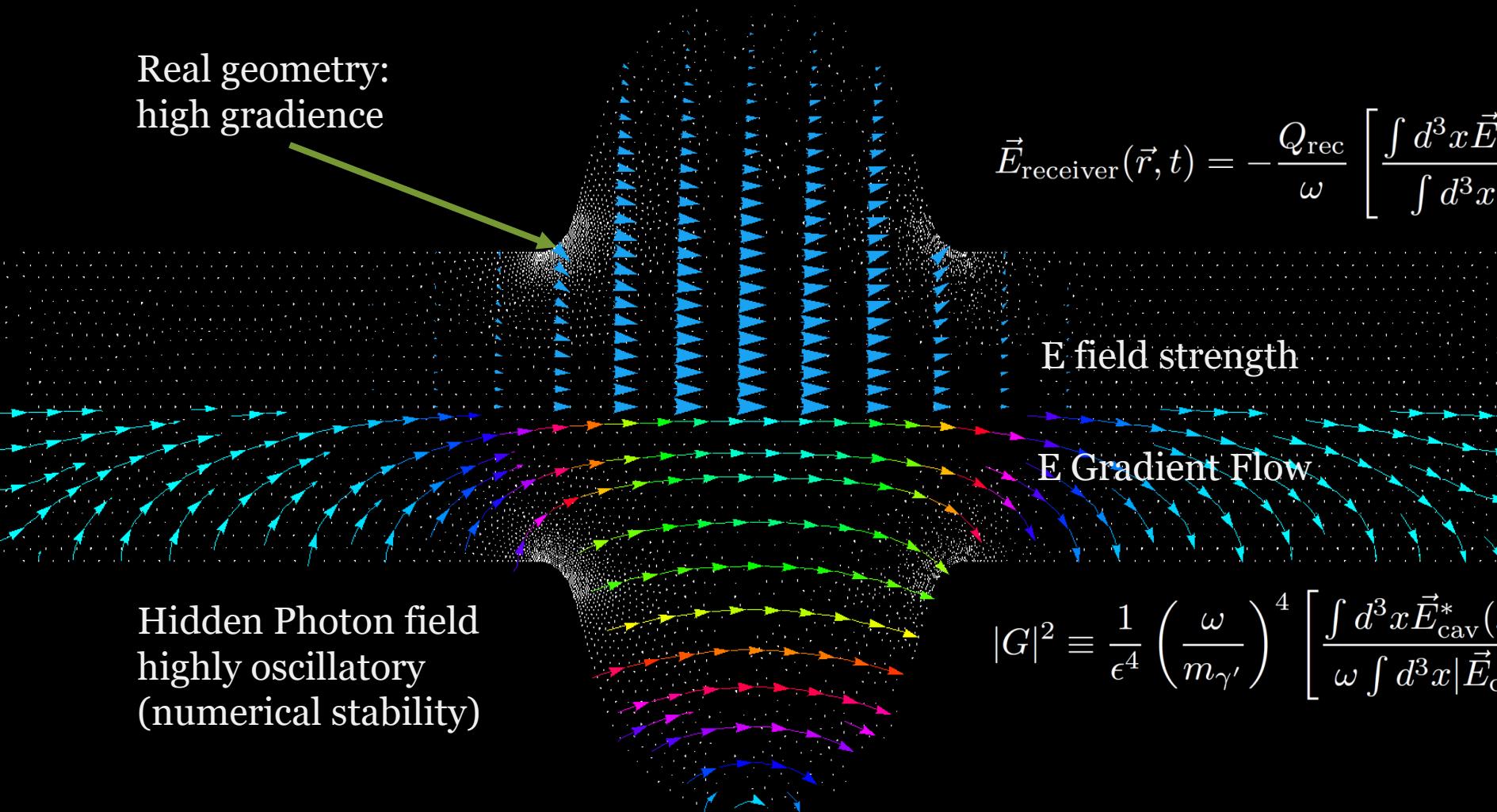
$$t_{rungup} = \frac{Q}{\omega} \sim 1 \text{ sec}$$

Background noise also received contribution from possible cross-talks:

$$B \propto P_{emitter}$$

# Real Cavity Configuration

Real geometry:  
high gradience



$$\vec{E}_{\text{receiver}}(\vec{r}, t) = -\frac{Q_{\text{rec}}}{\omega} \left[ \frac{\int d^3x \vec{E}_{\text{cav}}^*(\vec{x}) \cdot \vec{j}(\vec{x})}{\int d^3x |\vec{E}_{\text{cav}}(\vec{x})|^2} \right] \vec{E}_{\text{cav}}(\vec{r}) e^{i\omega t}$$

E field strength

E Gradient Flow

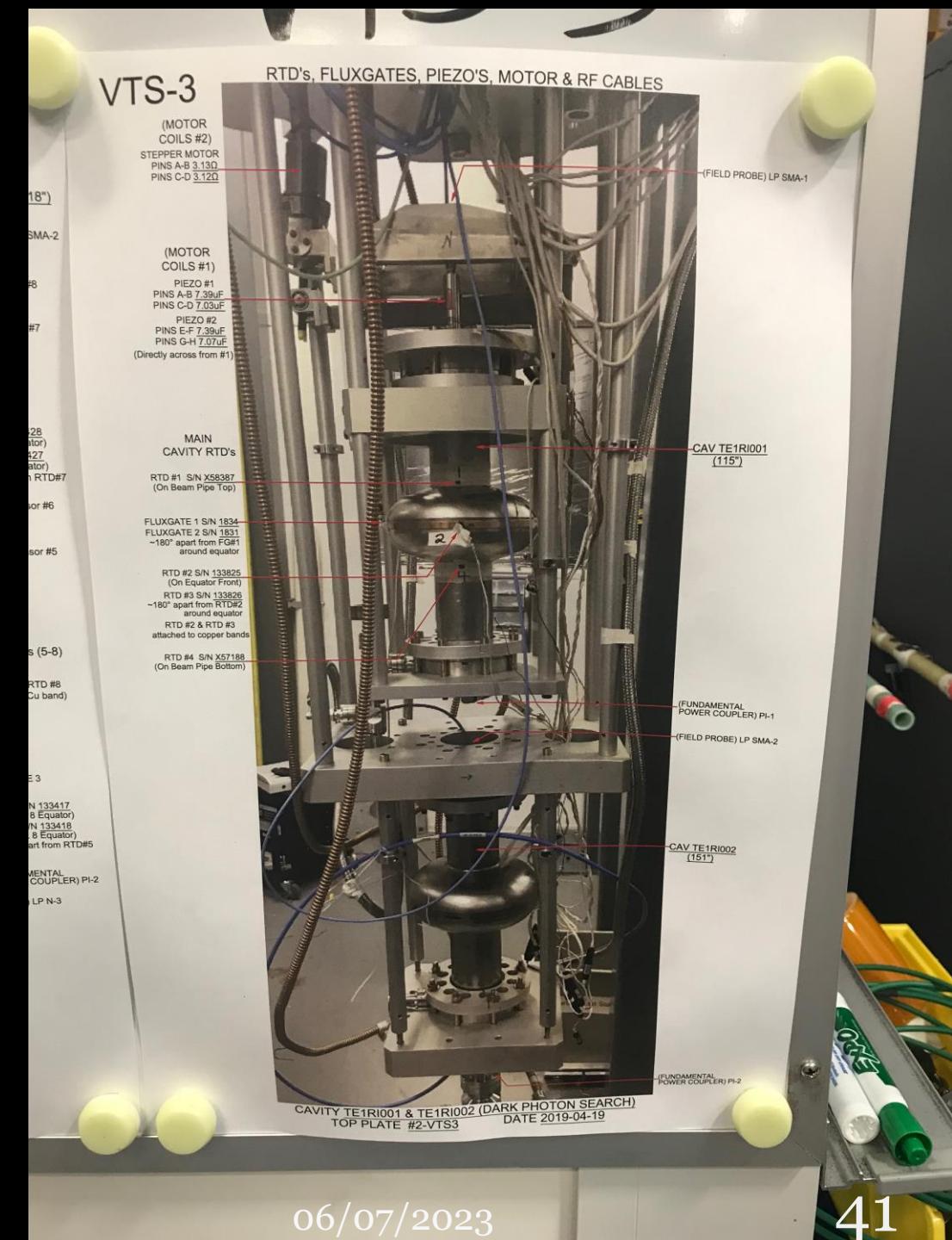
$$|G|^2 \equiv \frac{1}{\epsilon^4} \left( \frac{\omega}{m_{\gamma'}} \right)^4 \left[ \frac{\int d^3x \vec{E}_{\text{cav}}^*(\vec{x}) \cdot \vec{j}(\vec{x})}{\omega \int d^3x |\vec{E}_{\text{cav}}(\vec{x})|^2} \right]^2$$

# Dark SRF Pathfinder Runs

# Pathfinder run(s) summary

**It works!**

- ✓ Design
- ✓ Tuner operation
- ✓ Microwave scheme for matching the frequencies
- ✓ Actual data – first acquisition



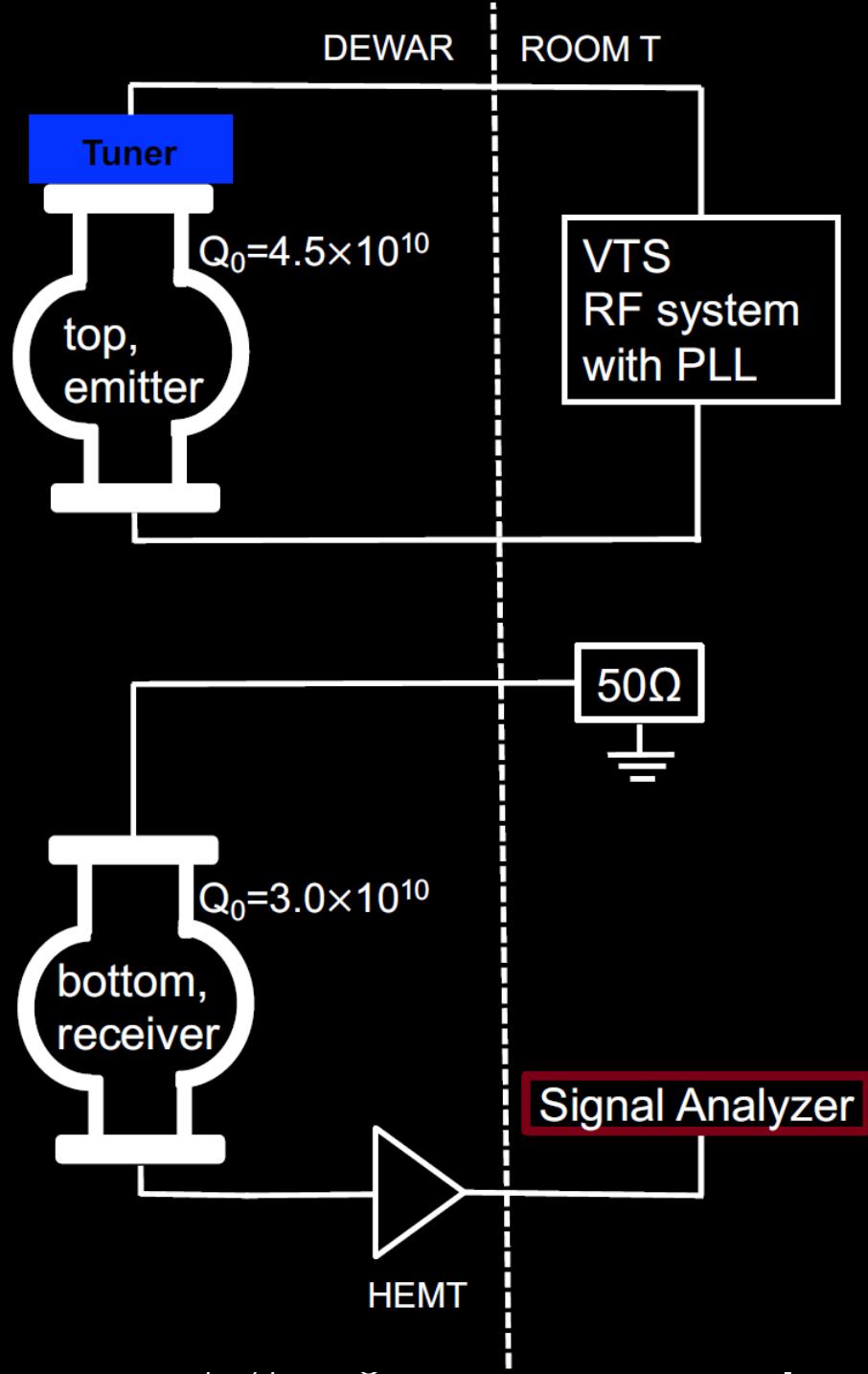


Zhen Liu

Dark Journey



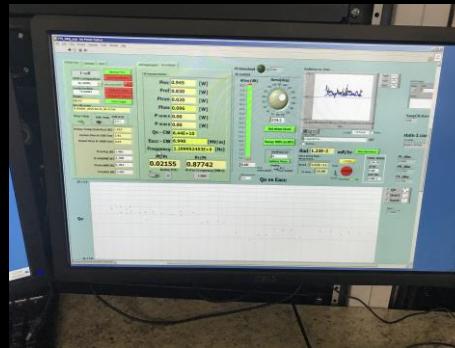
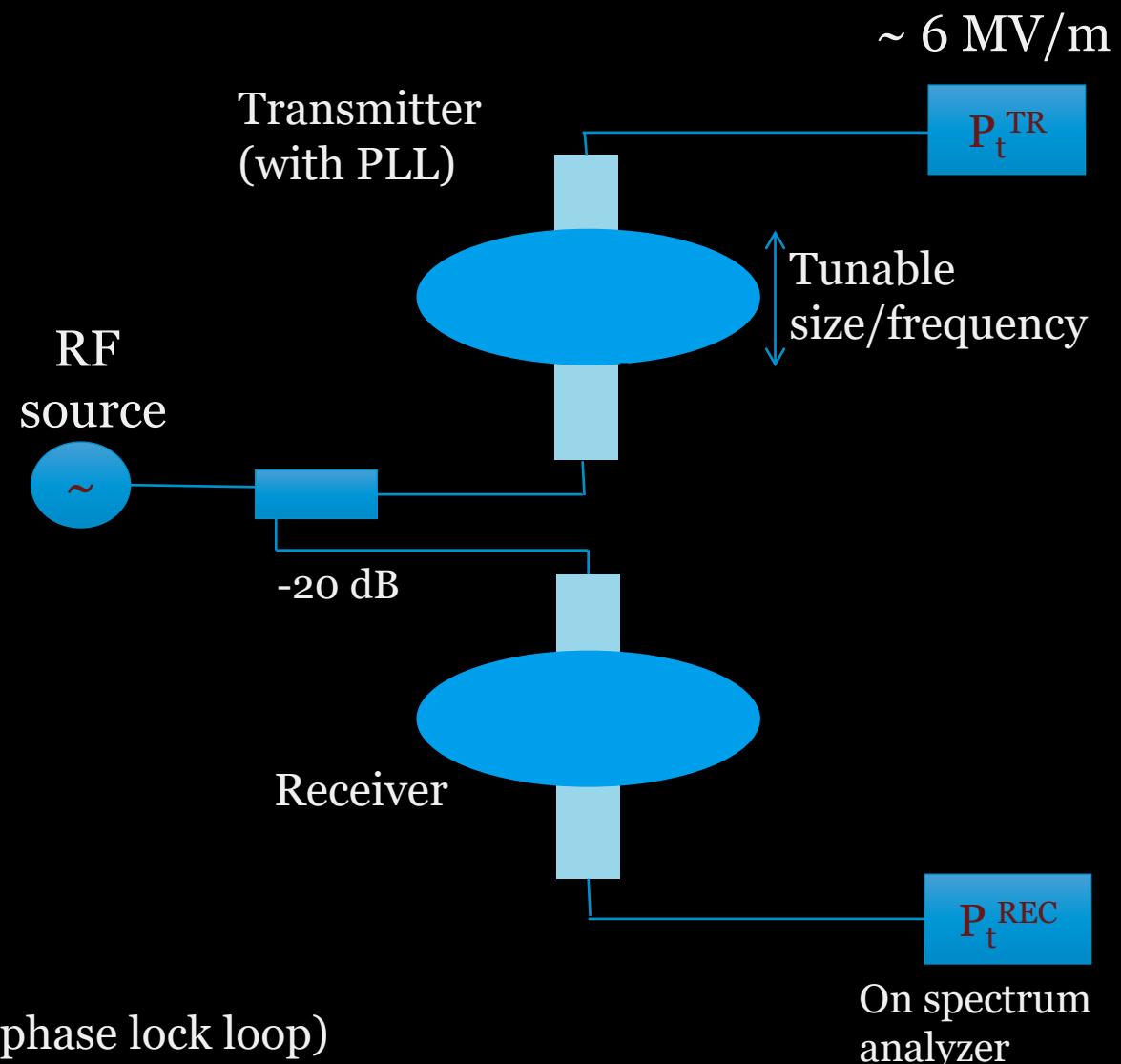
PAC Webinar-51



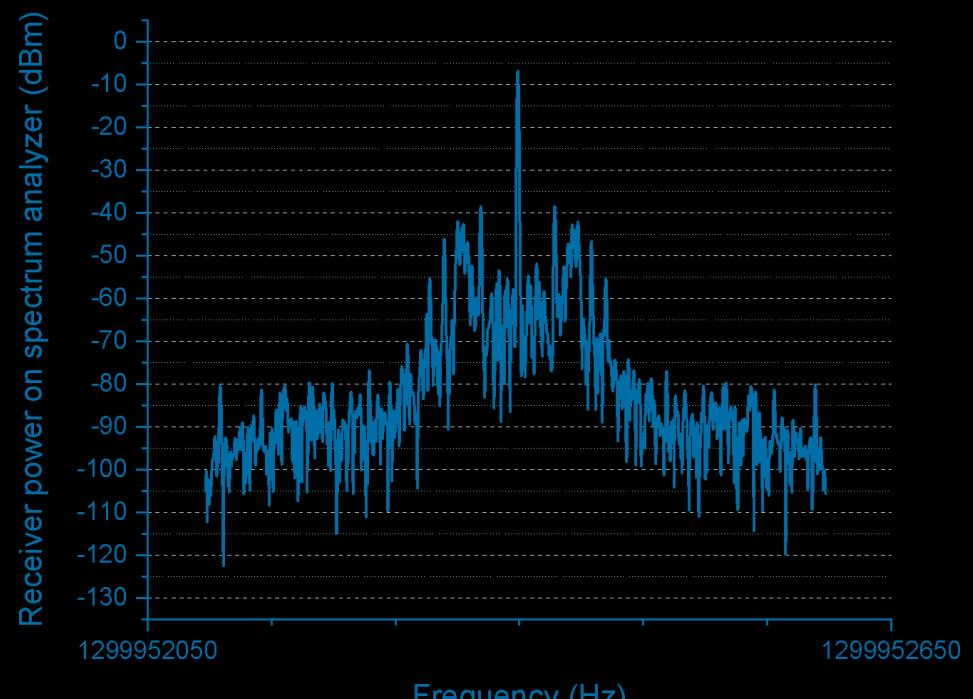
# 2019 Run pictures



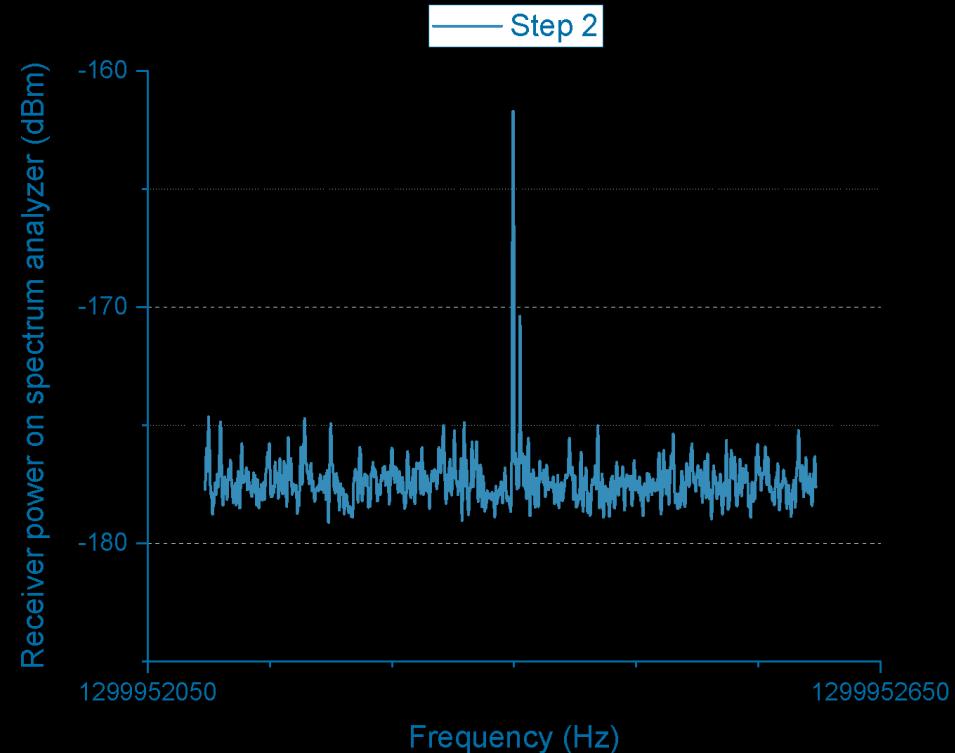
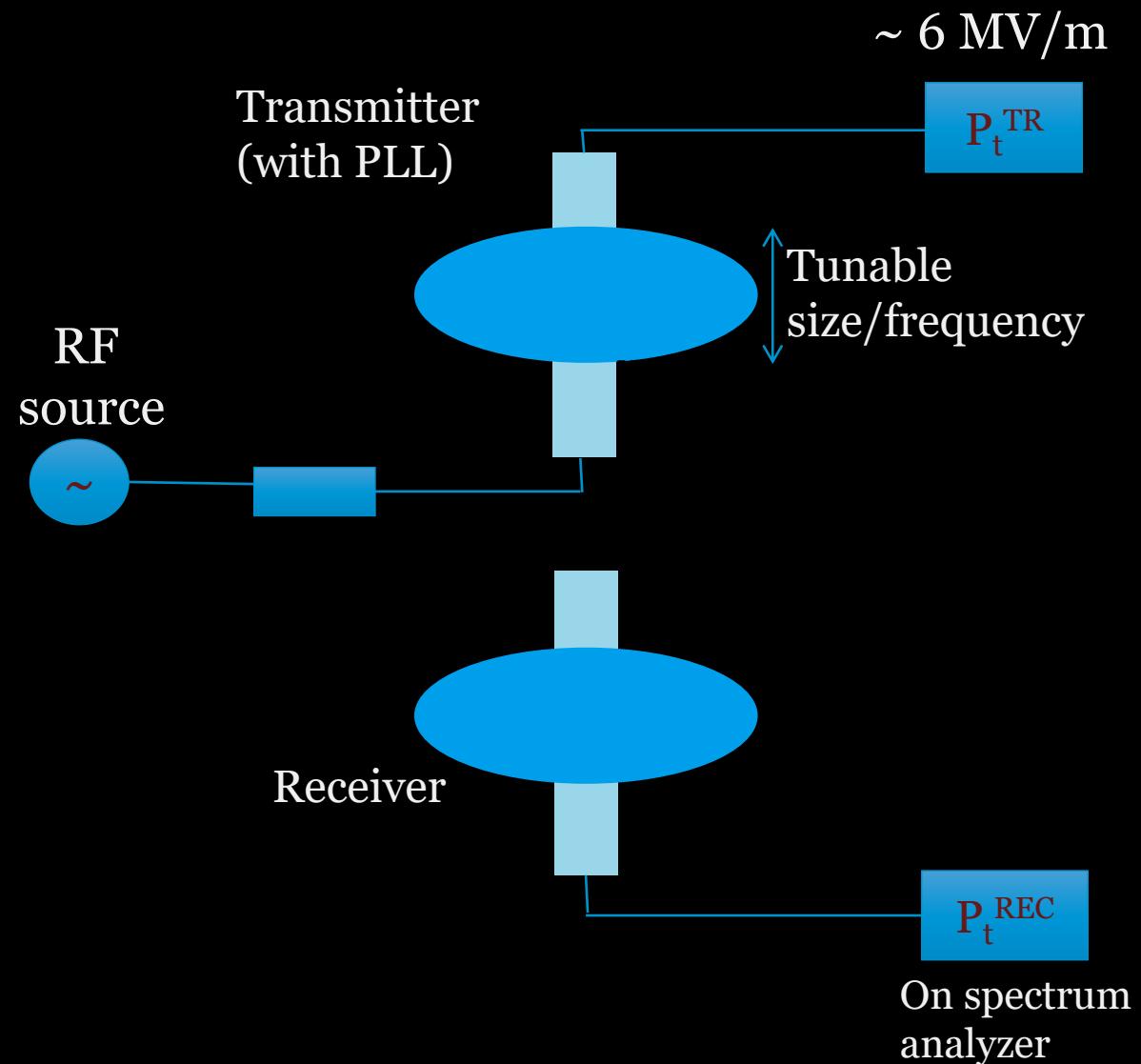
# Cavity frequency matching – Step 1



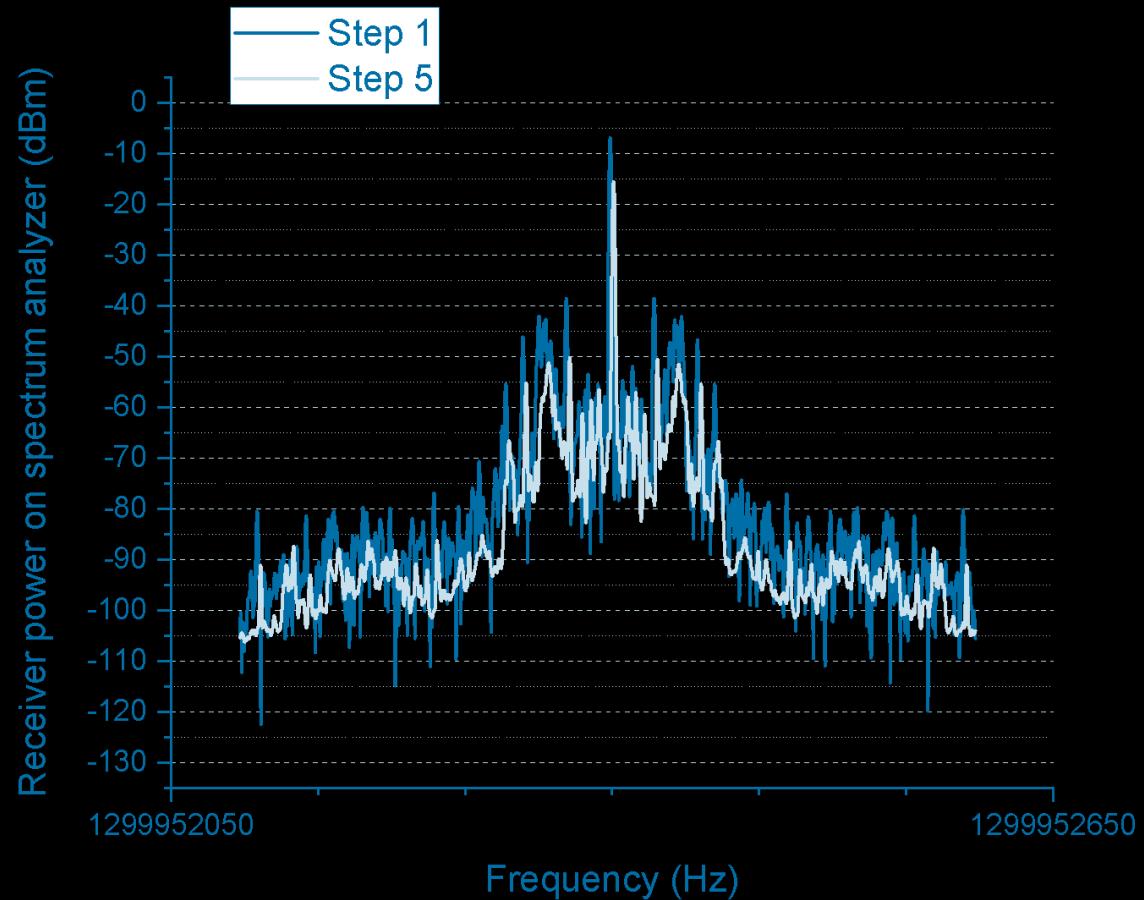
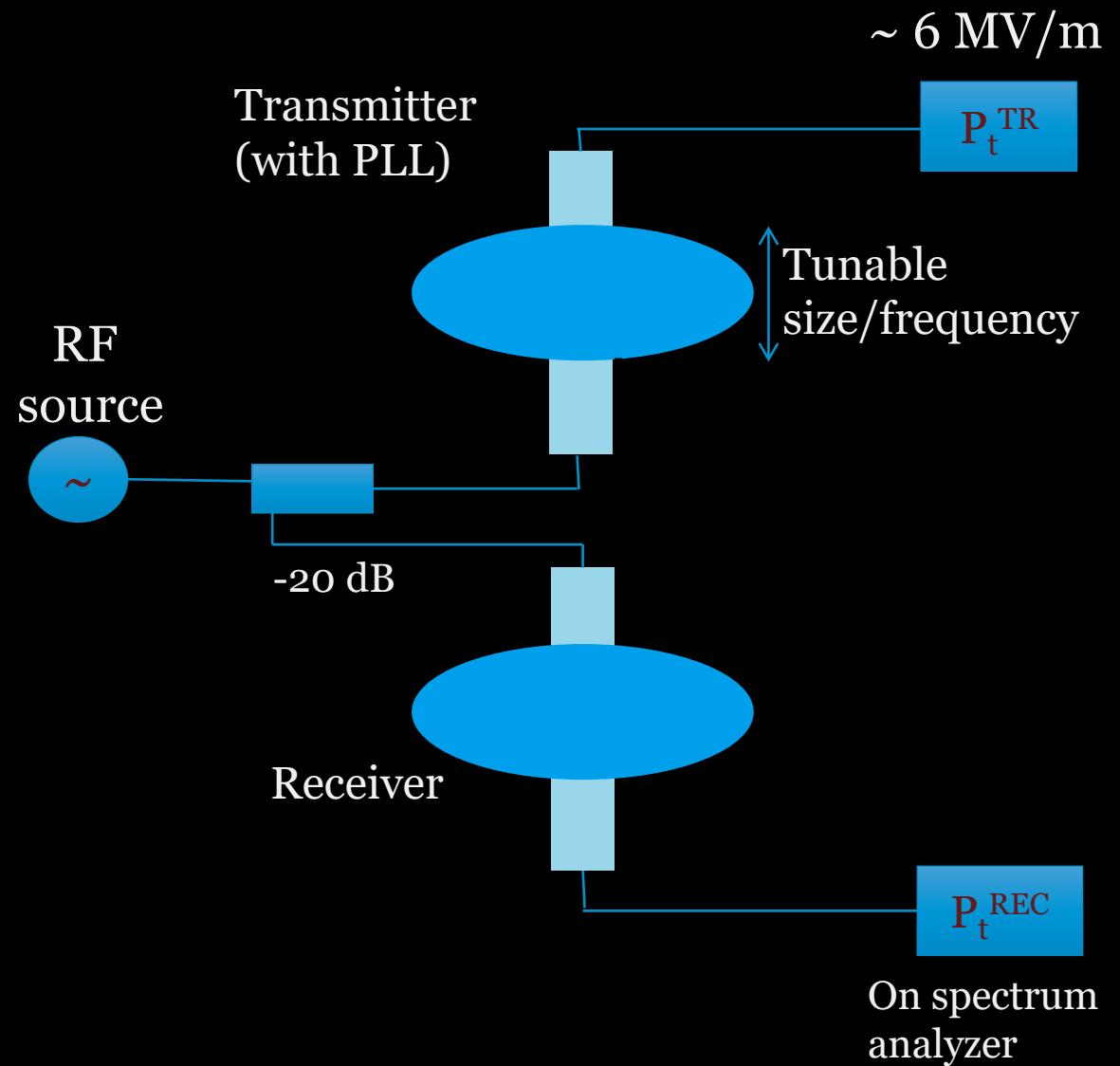
From now on, most measurement are shown in dBm ( $\text{dB } 10\log(x)$ ,  $\text{dBm} = 10\log(x/\text{mW})$ .) Note that we are always in dB-space, 3dB = factor of 2 in linear space.



# Dark Photon search! – (Step 2)



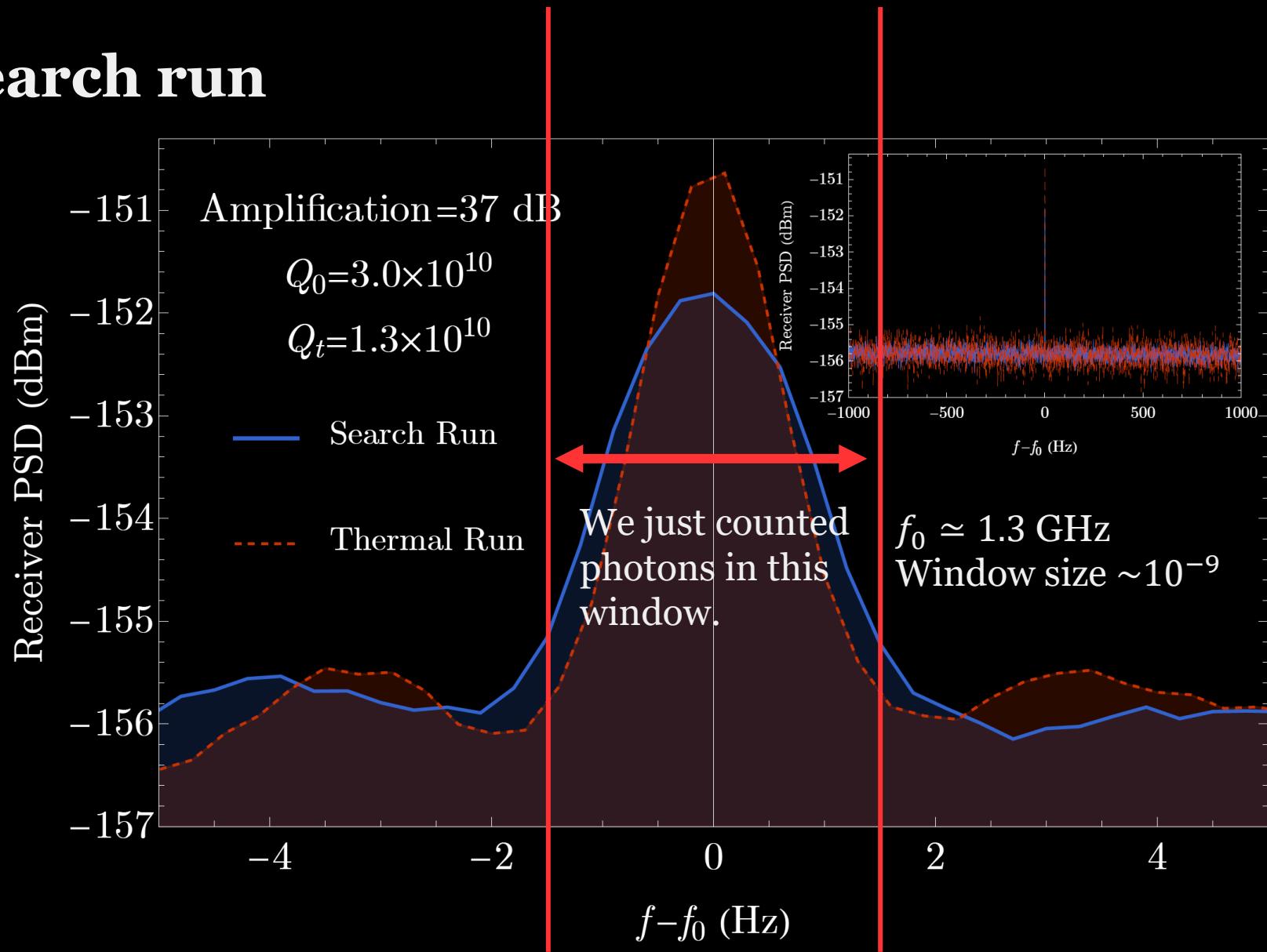
# Back to Step 5 = Step 1 – all in tune



# Measurements and Results

# Thermal run v.s. Search run

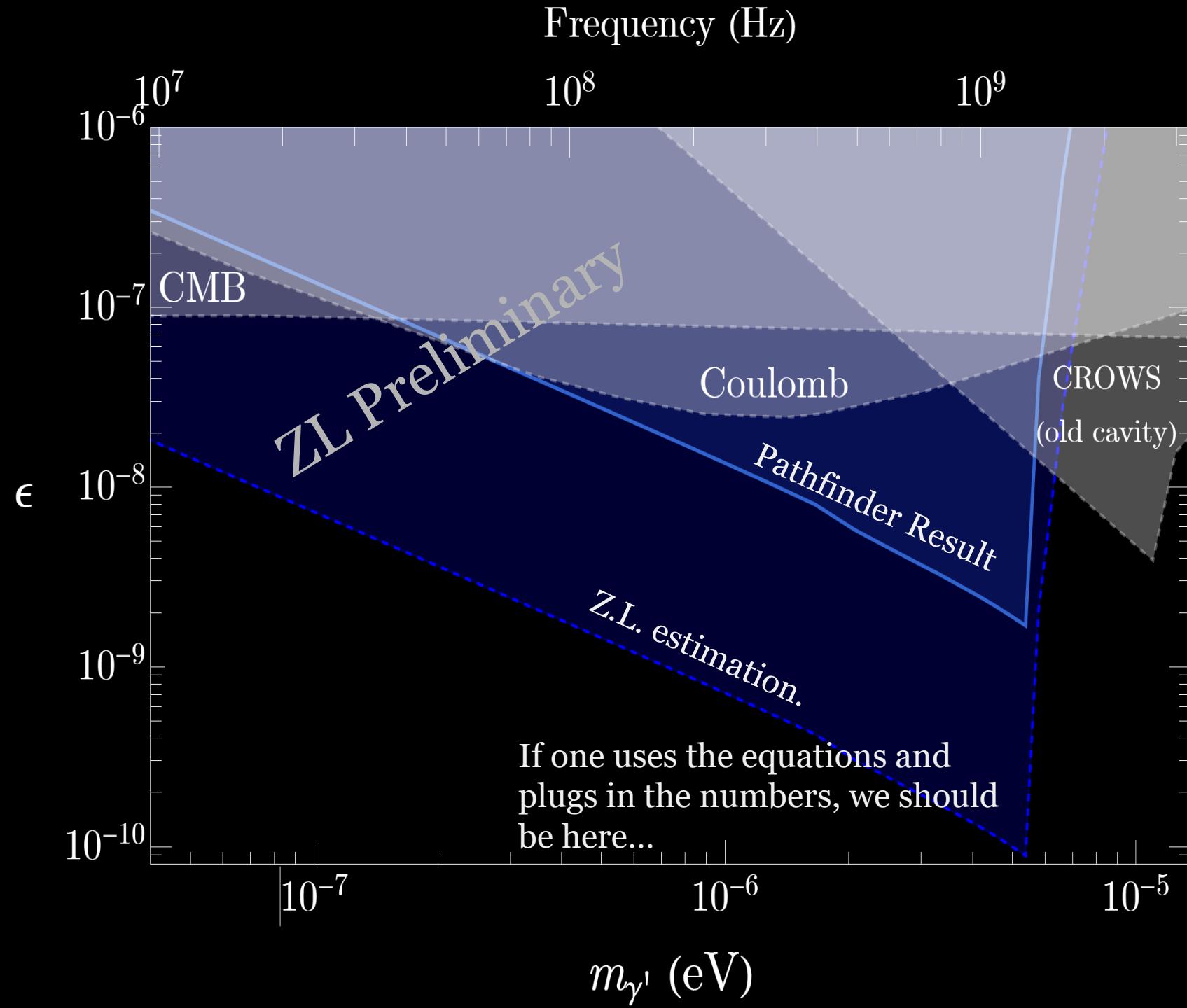
- Blue: Search run
  - $-151.8^{+0.16}_{-0.17}$  dBm
- Red: Thermal run
  - $-151.6^{+0.23}_{-0.25}$  dBm  
(uncertainty driven by the integration time)



# Exciting New Coverage

Our pathfinder run results already explore new territory in such a log-log space!

We've learned a lot about the system and published our first results and been developing many new future directions (as planned).



**High-Q not always a blessing**

# I lied (oversimplified) quite a bit:

- High-Q is a double-sided sword
- Our pathfinder result did not benefit as  $Q^2$  that we initially wanted
  - We are in a different limit that has not been explored before:  $\frac{\omega}{Q} \ll \delta\omega$  (the sources I will highlight soon)
  - Post the end-of-2019 pathfinder search run, we had to perform many validations- and cross-check runs between 2020-2022

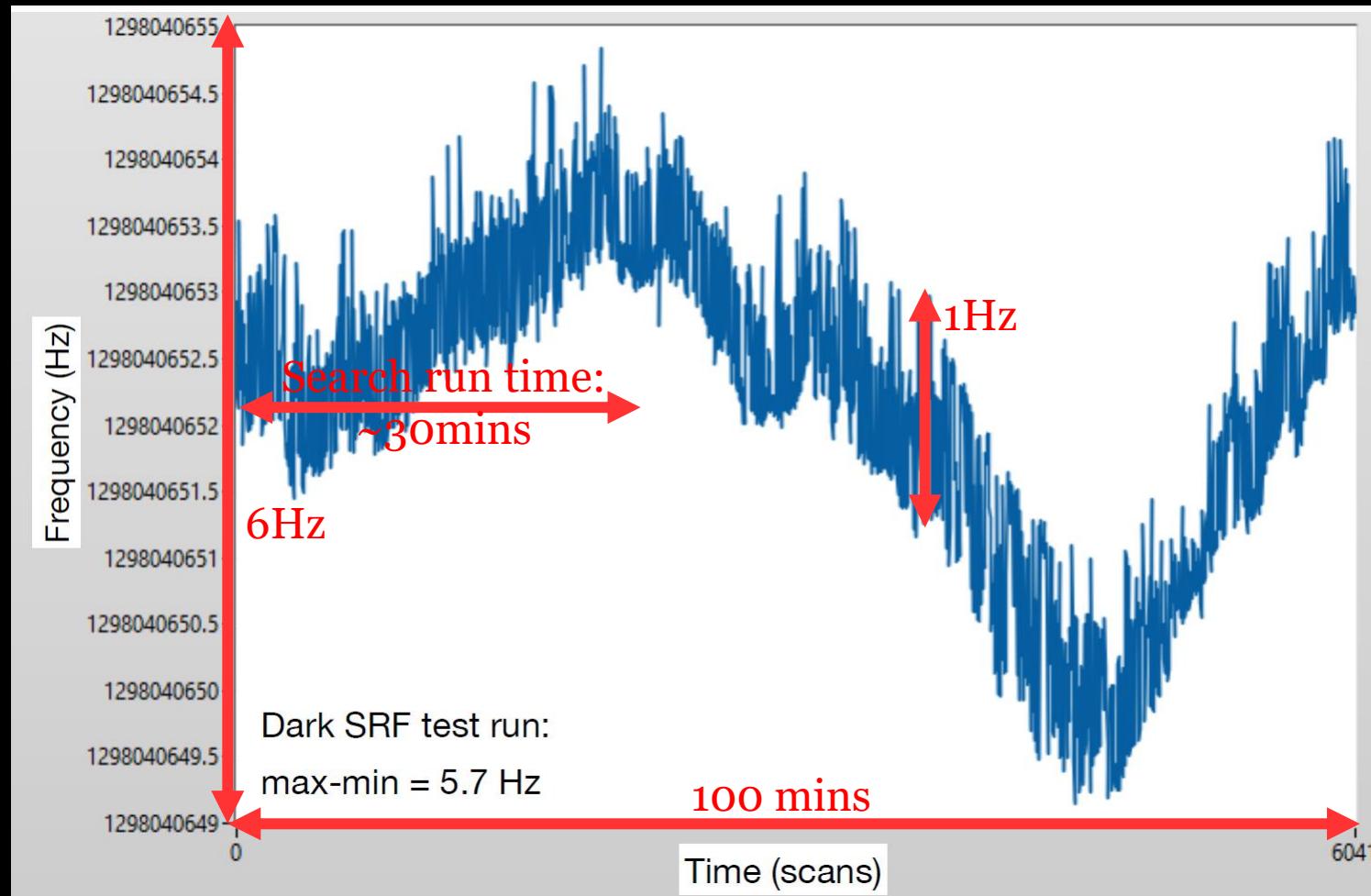
A GHz device can be stable in kHz-level ( $Q = 10^6$ ), but many of its properties are not stable at subHz-level ( $Q \geq 10^9$ ).



To get a physical sense,  
Cavity size:  $\sim 20$  cm  
Quality factor:  $10^{10}$   
Hence the line width: 0.13 Hz  
For **Hz-level** stability, one needs to ensure the cavity size does not change at the **sub-nanometer** level.

Many sources contribute to instabilities: temperature, bubbles, pressure change at the surface, etc.

# Emitter cavity frequency stability

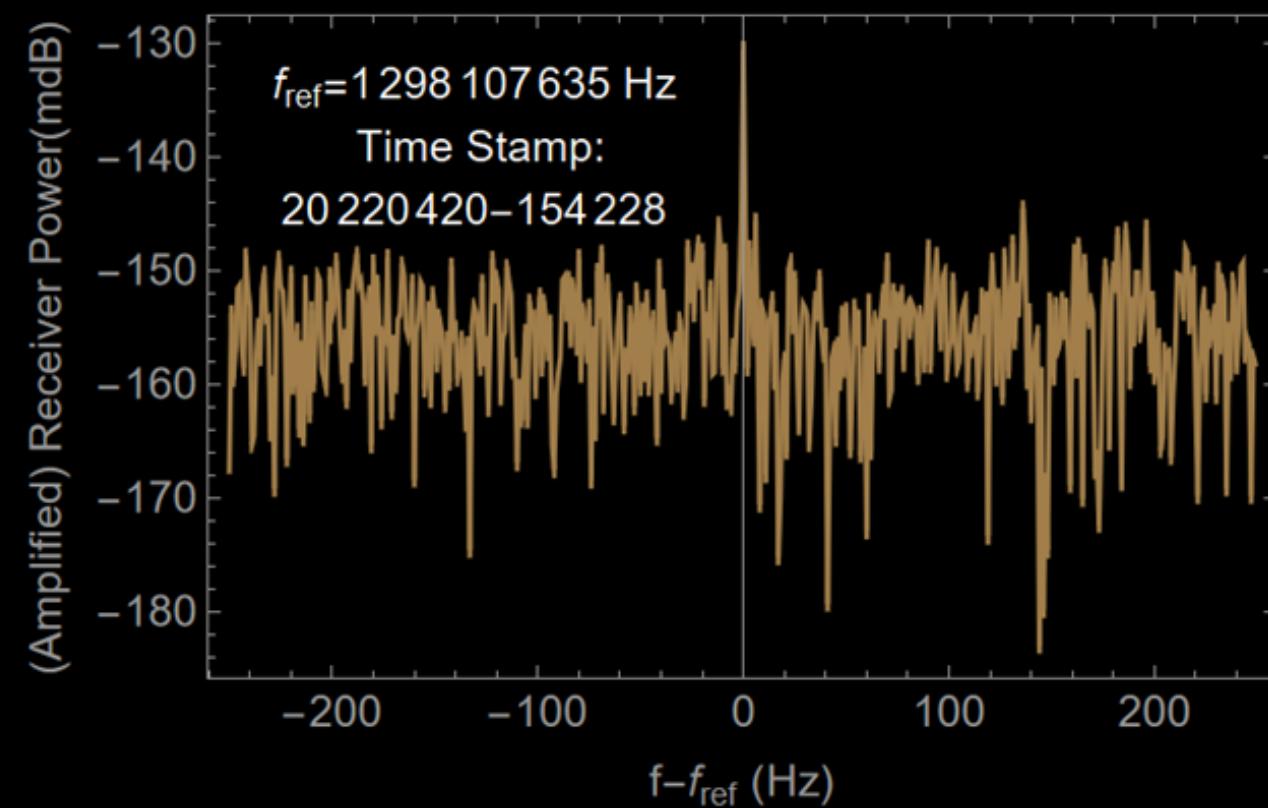
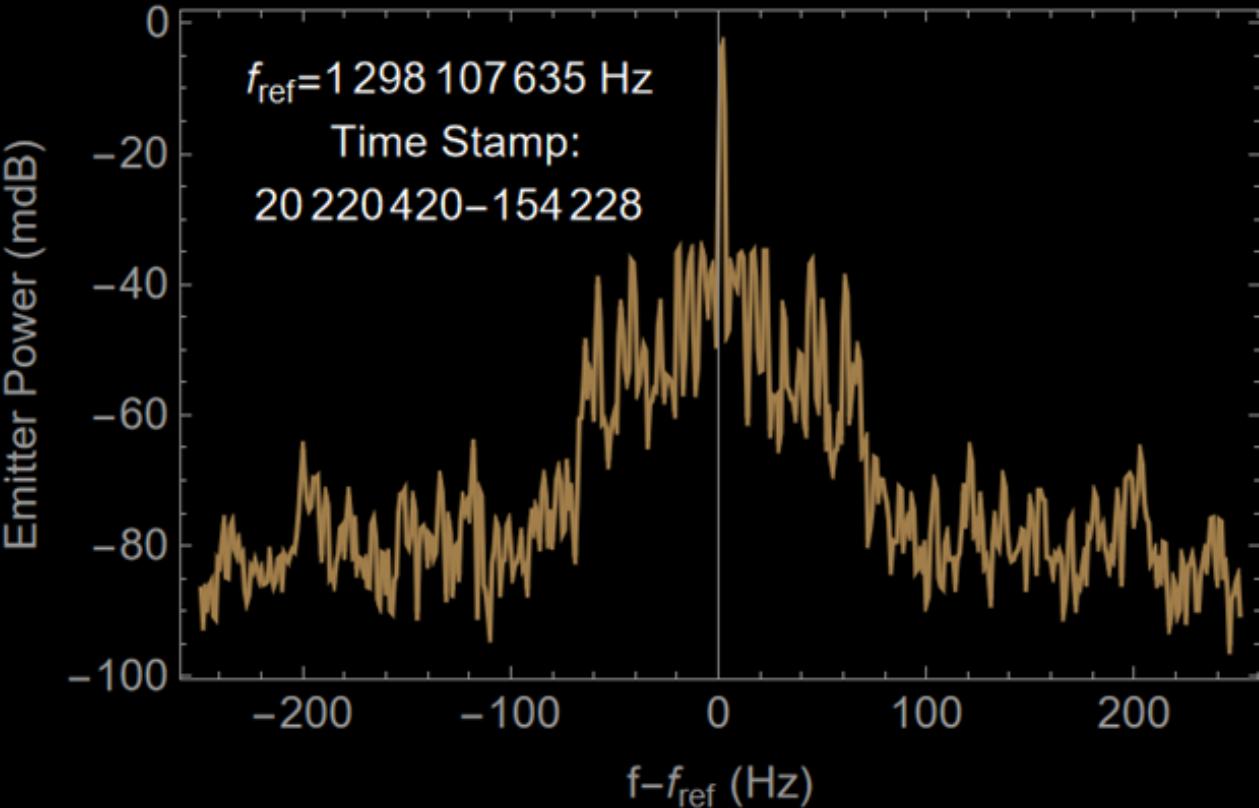


Dedicated frequency stability runs, two effects:

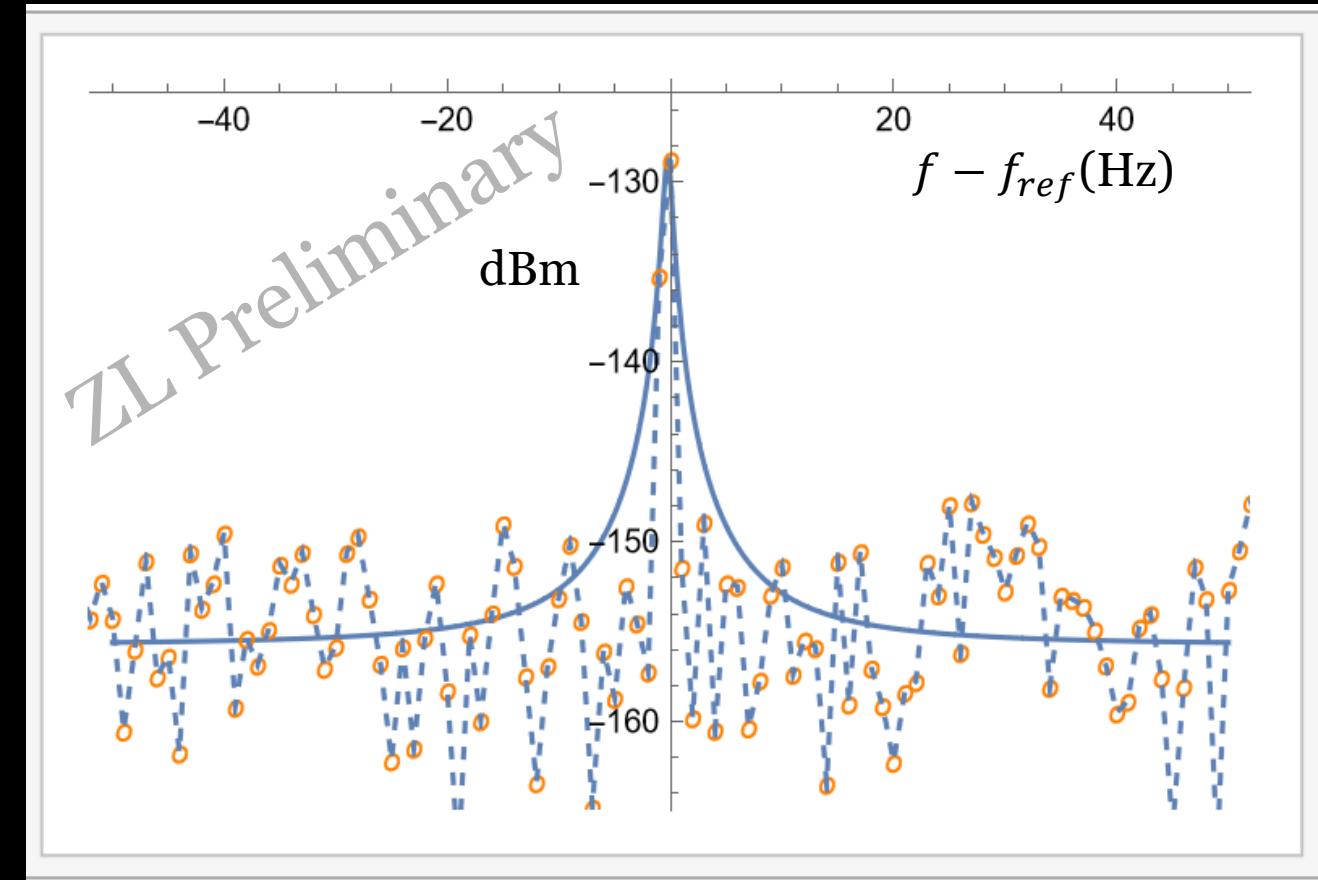
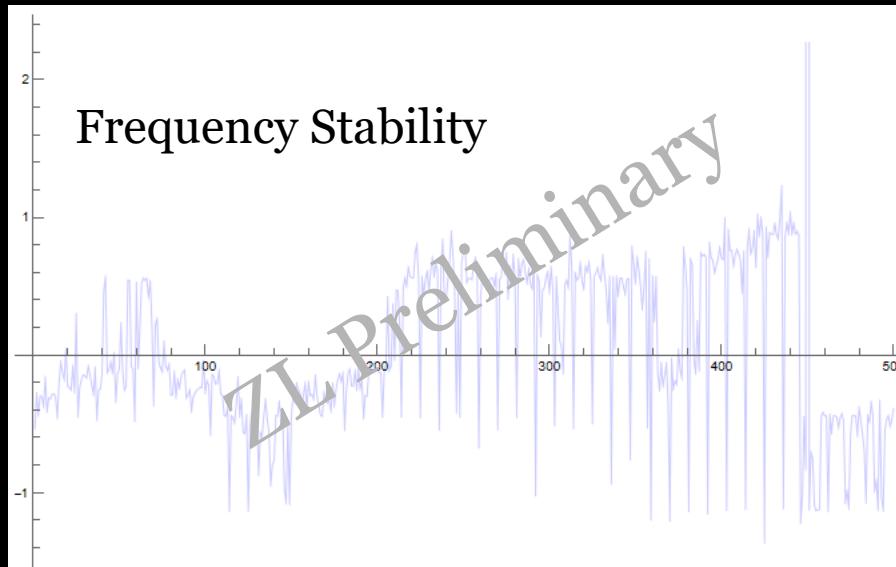
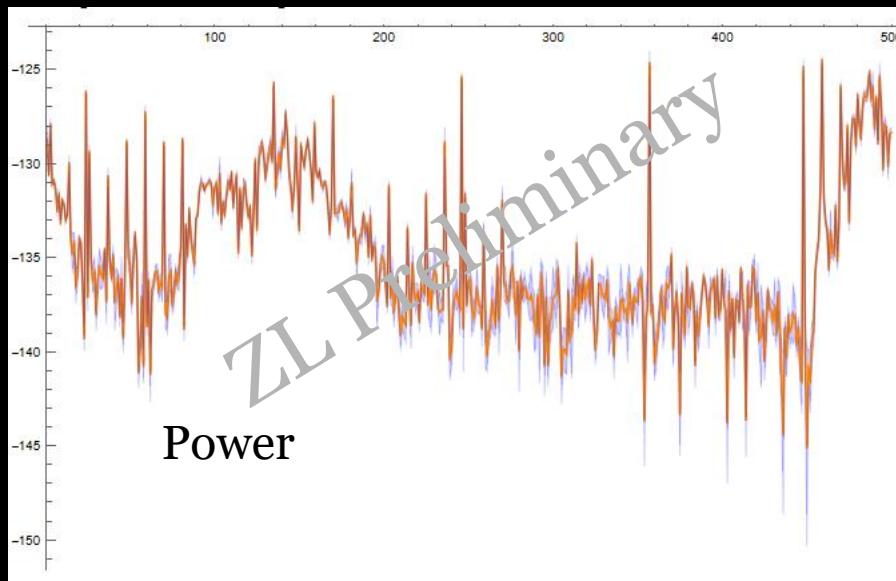
- Frequency drift
- Microphonics

Parameter	Emitter	Receiver
$Q_0$	$4.5 \times 10^{10}$	$3.0 \times 10^{10}$
$Q_{\text{in}}$	$1.8 \times 10^9$	$4.5 \times 10^{11}$
$Q_t$	$2.9 \times 10^{11}$	$1.3 \times 10^{10}$
freq. drift	5.7 Hz	3.0 Hz
microphonics	3.1 Hz	3.1 Hz

# The PSD of the Emitter and Receiver at a given moment



# Data Visualization and checks (receiver fit; validation run 19, 2022)

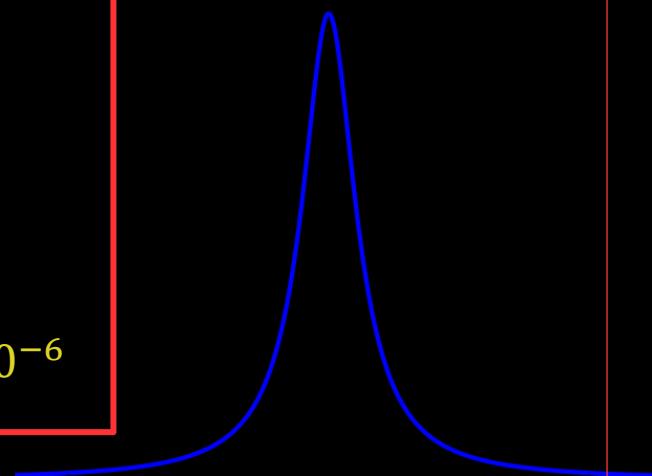


# We presented a very conservative limit

$$|G|^2 \equiv \frac{1}{\epsilon^4} \left( \frac{\omega}{m_{\gamma'}} \right)^4 \left[ \frac{\int d^3x \vec{E}_{\text{cav}}^*(\vec{x}) \cdot \vec{j}(\vec{x})}{\omega \int d^3x |\vec{E}_{\text{cav}}(\vec{x})|^2} \right]^2$$

$$|G|^2 \rightarrow \frac{\omega^2}{\omega^2 + 4\delta_\omega^2 Q_{\text{rec}}^2} |G|^2$$

$$\begin{aligned} & \frac{\omega^2}{\omega^2 + 4\delta_\omega^2 Q_{\text{rec}}^2} \\ & \rightarrow \frac{\left(\frac{\omega}{Q_{\text{rec}}}\right)^2}{\left(\frac{\omega}{Q_{\text{rec}}}\right)^2 + 4\delta_\omega^2} \\ & \rightarrow \frac{(\sim 0.04 \text{ Hz})^2}{(\sim 16 \text{ Hz})^2} \rightarrow 7 \times 10^{-6} \end{aligned}$$

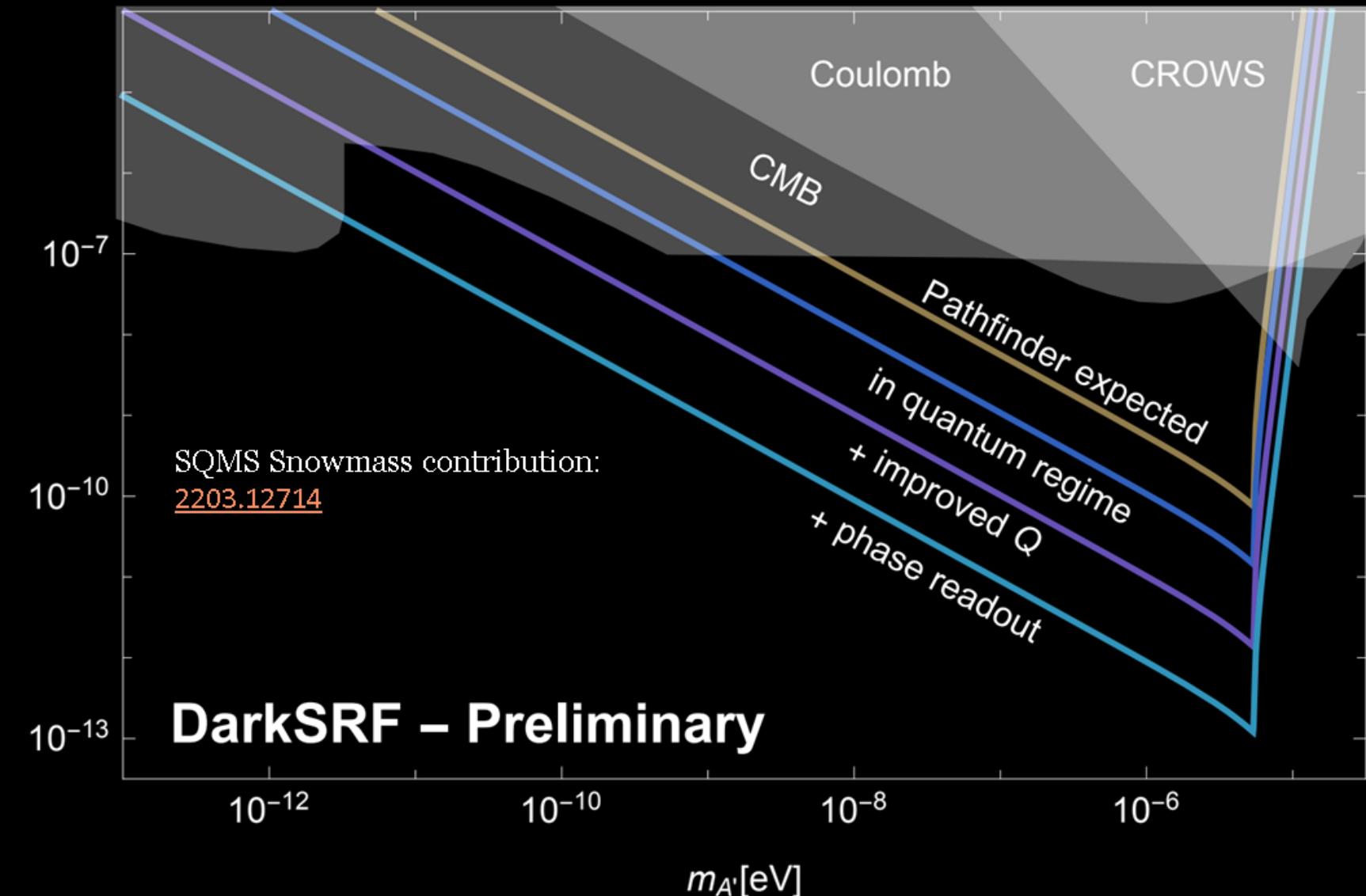


- Frequency drift took as a constant frequency **mismatch** at **5.7 Hz  $\oplus$  3.0 Hz**
  - These are drifts at 100 mins scale, our search is 30 mins scale;
  - One can live-monitor and take the data with no drifts.
- Microphonics modeled as constant frequency **mismatch** at **3.1 Hz  $\oplus$  3.1 Hz**
  - Theoretically, it is a much less suppression as it reduces effective integration time. (Working on proper modeling.)

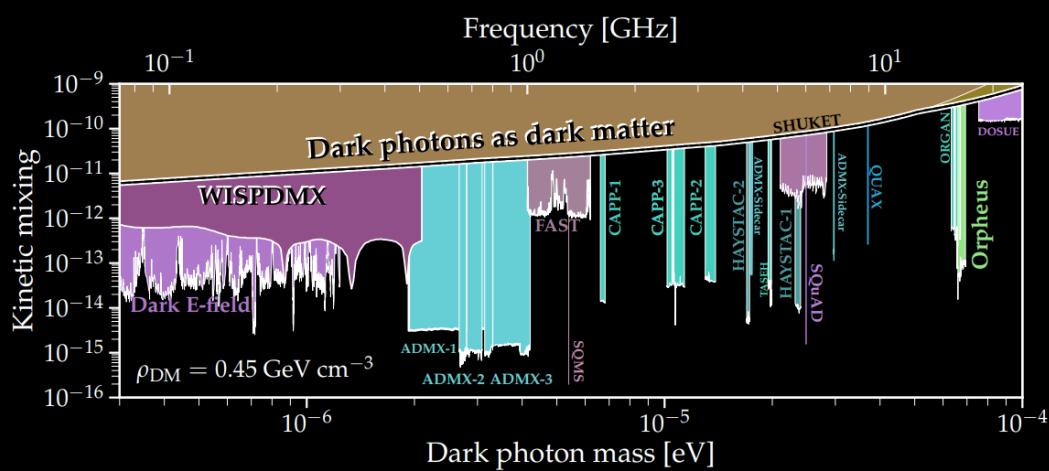
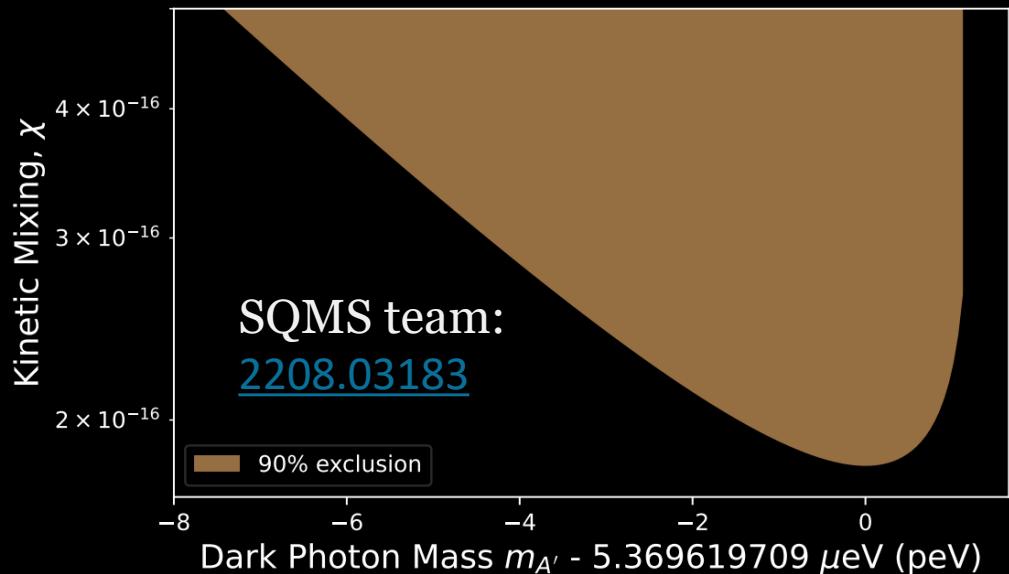
Essentially, modeled as searching off-resonance.

# Near (or far?) Future

- Improving noise isolation and control into few photon limits;
- Improve Q (seems require careful discussion)
- Phase-sensitive readout
- Off-the-shelf cavities → better designed and treated ones
  - New design
  - New search protocol



# Other and related activities



- Dark photon DM search ([SQMS 2208.03183](#); J. Shu et al [2305.09711](#));
  - Axion LSW validation and search;
    - Single cavity design
    - Double cavity multi-mode design
    - Double cavity plus conversion region design
  - Axion DM search;
  - Gravity Wave validation and search;
  - Millicharged particle search;
  - Photon mass constraints;
  - ...
- See many recent studies, and also partial summaries in SQMS SRF paper: [2203.12714](#)

# Outlook

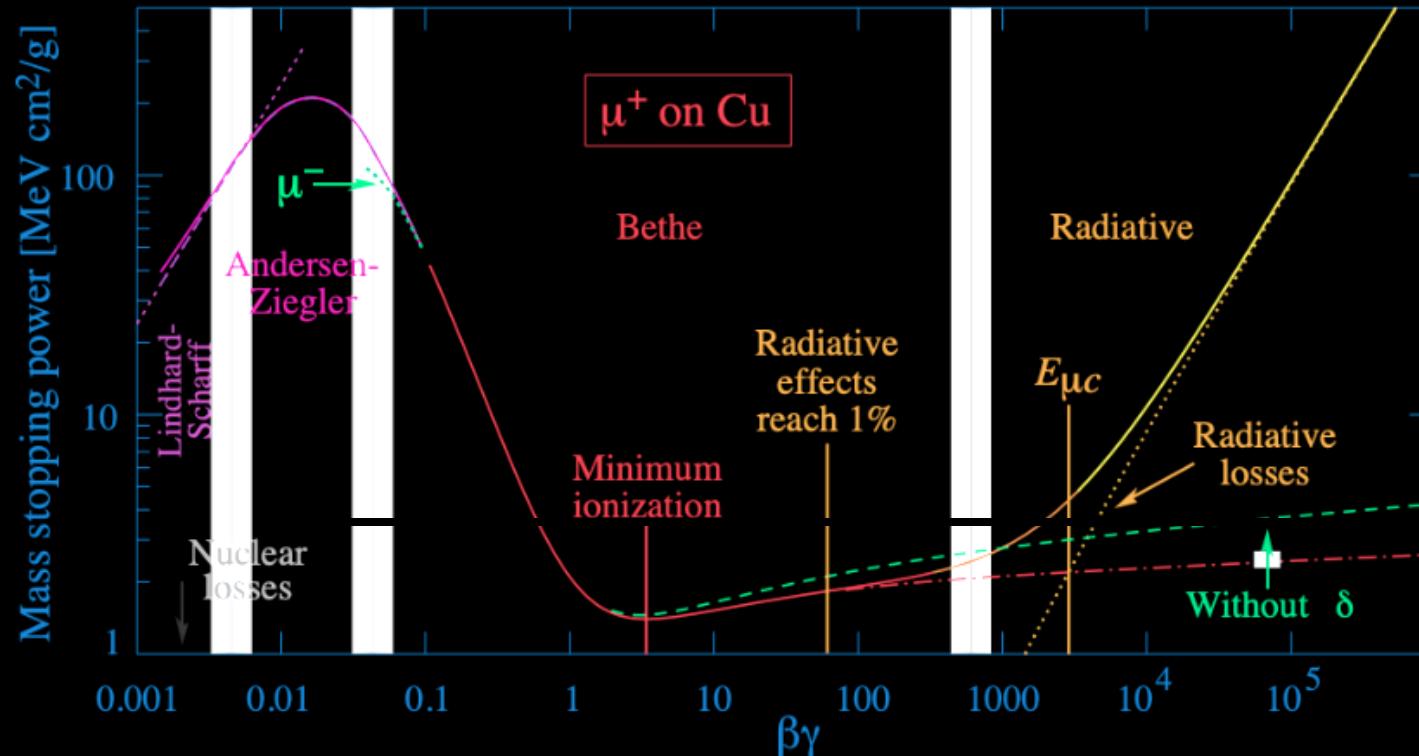
- Fun journey to the unknown and physics at different scales
- Millicharged particles:
  - New Search Strategy proposed and results obtained
  - Future runs with liquid Argon Experiments
  - New Search Strategy proposed and results obtained
  - Future runs with CCD tech
- Dark Photons:
  - Designed new SRF cavity based experiments;
  - Covered new parameter regions in the log-log space;
  - Learnt & learning to handle ultrahigh Q opportunities;
  - Establishing and developing schemes for robust tests;
- An active program ahead:
  - Many planned steps improve the results significantly;
  - Many possible theory research directions to improve the results & treatments (interested parties highly welcome!);
  - Many “adjacent” exploration and searches possible;



Thank you!

# (Milli)Charges through Matter

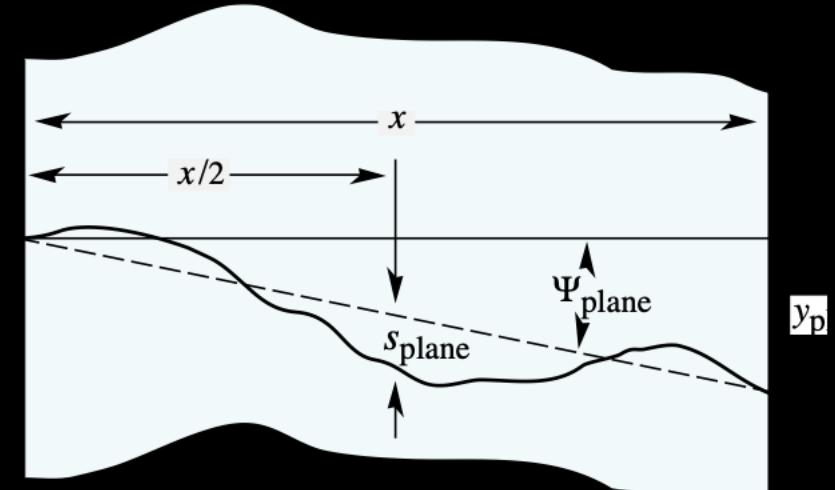
average energy loss



Soft hits dominate:

$$\left. \frac{d\sigma}{dE_r} \right|_{E_\chi \gg m_\chi, m_e, E_r} \approx \frac{2\pi\alpha^2\epsilon^2}{E_r^2 m_e}$$

angular deflection



- mCP's do the same, but less so. Below detection threshold.
- Above threshold - individual coulomb scatters

## Matter Effects

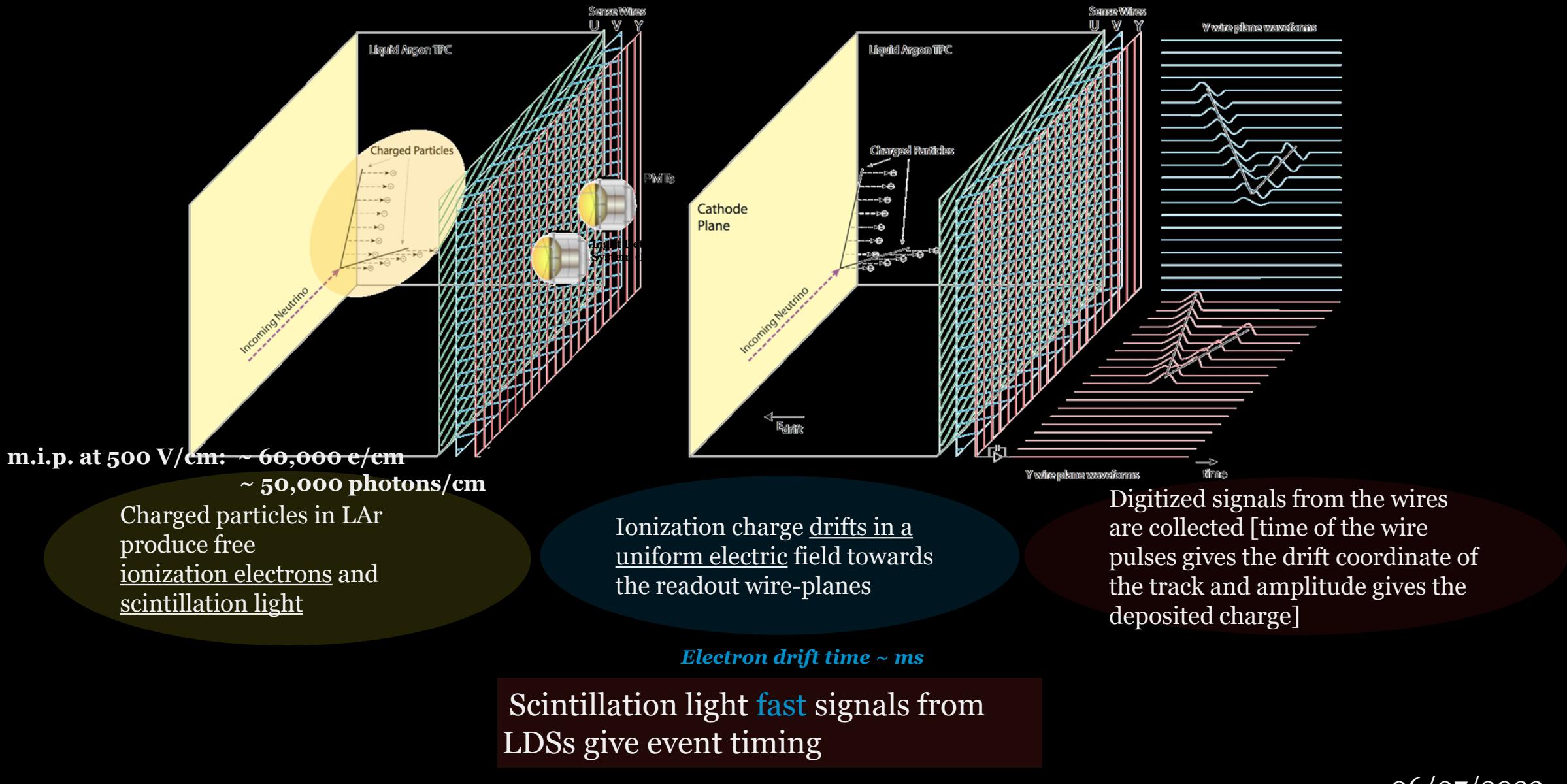
- En route to a detector, mCPs travel through  $\sim 240$  meters of dirt.
- Energy loss is negligible in region of interest.
- A random walk of soft scatterings (off nuclei) leads to small **angular deflection**

$$\Delta\theta_\chi \sim \langle\theta_\chi\rangle \sqrt{N_{\text{col}}} = \frac{\text{average deflection per collision.}}{\times \sqrt{\# \text{ of collisions.}}}$$

$$\Delta\theta_\chi \sim 2 \times 10^{-3} \left( \frac{5 \text{ GeV}}{E_\chi} \right) \left( \frac{\epsilon}{10^{-2}} \right) \left( \frac{L_{\text{dirt}}}{500 \text{ meters}} \right)^{1/2}$$

**The mCPs point back to the target.**

# LArTPC at work





# Microphonics: How does it appear?

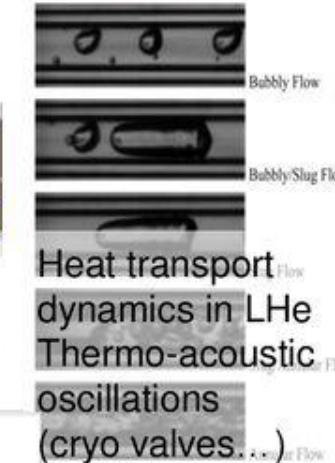
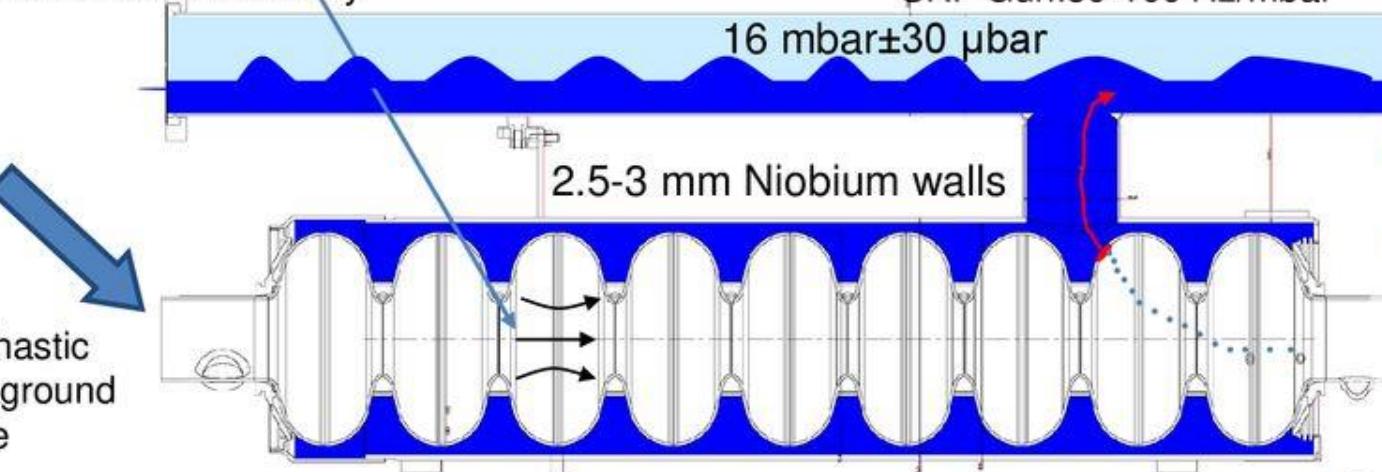
- Field amplitude variation:

$$\text{Dynamic Lorentz force, } \Delta f / \Delta E_{\text{acc}}^2 = 1 \text{ Hz} / (\text{MV/m})^2$$

→ Ponderomotive instability

- Helium pressure fluctuations

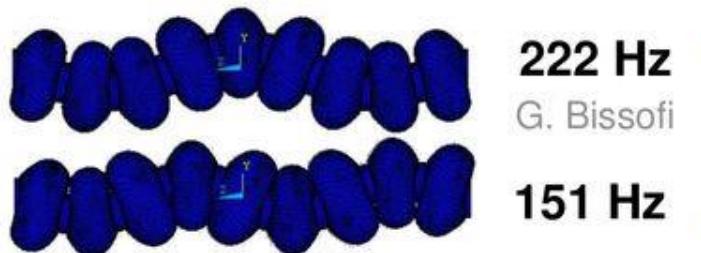
$$\Delta f / \Delta p = 50-60 \text{ Hz/mbar,}\\ \text{SRF Gun: } 30-100 \text{ Hz/mbar}$$



- Stochastic background noise

- Deterministic, narrow-band sources:  
Vacuum pumps

- Response of the Cavity-Helium vessel-Tuner system:  
Mechanical Eigenmodes



**Is that the whole story?**

# Journey with Sourced Millicharged Particles and Dark Photons

A lecture by Zhen Liu



#### Speaker:

Zhen Liu is currently an Assistant Professor at the University of Minnesota. Zhen received his Ph.D. from the University of Pittsburgh in 2015. After completing his Ph.D., Zhen conducted postdoctoral research in the Theory Department at Fermi National Accelerator Laboratory between 2015-2018 and Maryland Center for Fundamental Physics at the University of Maryland between 2018-2020. Zhen's research has a broad scope on phenomenology in high energy physics, spanning from new physics searches at collider facilities, such as the LHC and various future colliders (CEPC, muon colliders), neutrino facilities, such as the DUNE and ArgoNeuT experiment, as well as small-scale experiments, such as dark SRF, Windchime.

#### Abstract:

Hidden U(1) symmetries are widely prevalent across numerous new physics models and have garnered significant attention. These symmetries give rise to intriguing testable phenomena, such as "dark photons" as the force mediators and "millicharged" particles representing the matter content. A diverse range of physics experiments and search strategies have been developed to investigate these phenomena. In this talk, I will discuss my recent work in exploring these elusive particles, covering both theoretical foundations and experimental results. I will focus on the unique aspects of controlled search approaches, where we actively source the fields under investigation and discuss the future prospects in this exciting research area.

2023.06.07 | 10:00 AM |

ZOOM: 831 7344 3588 |

PASSCODE: 001690

