THE INSTITUTE FOR UNDERGROUND SCIENCE AT SURF CETUP* 2024

Journey with Sourced Millicharged Particles and Dark Photons

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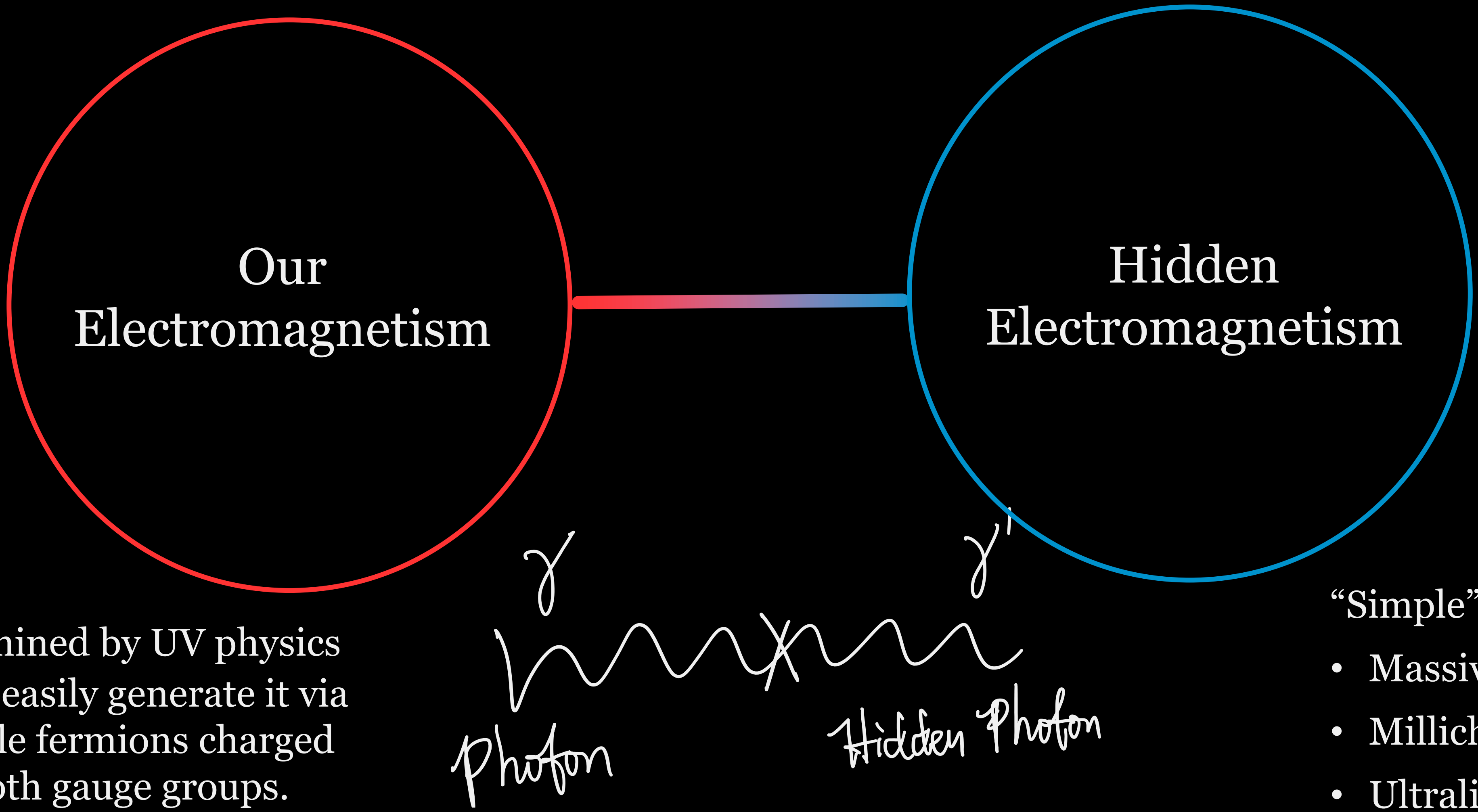
07/02/2024

Now: Journey to the unknown and seeking opportunities

A generic light hidden photon



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

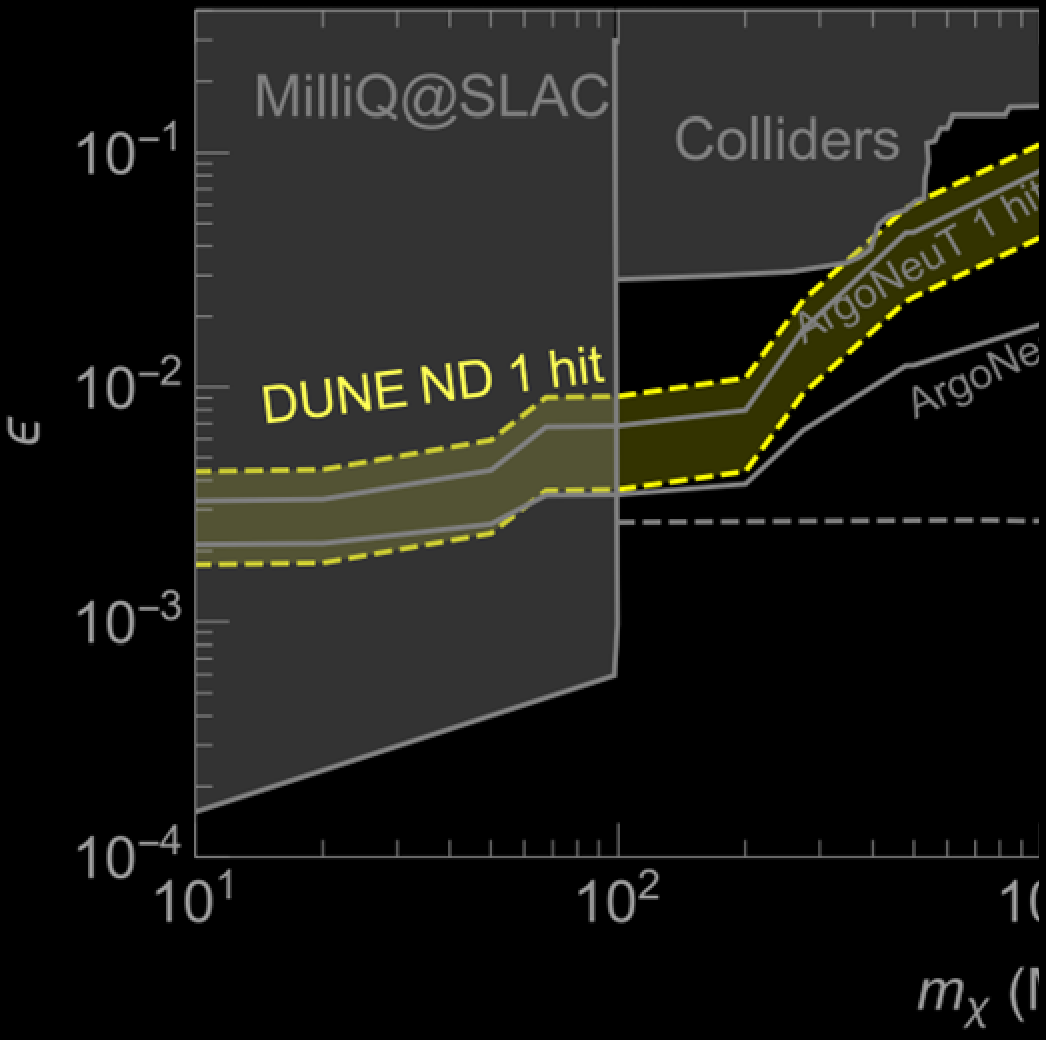
See the discussion on the ϵ size, e.g., Gherghetta, Kersten, Olive, Pospelov, 1909.00696

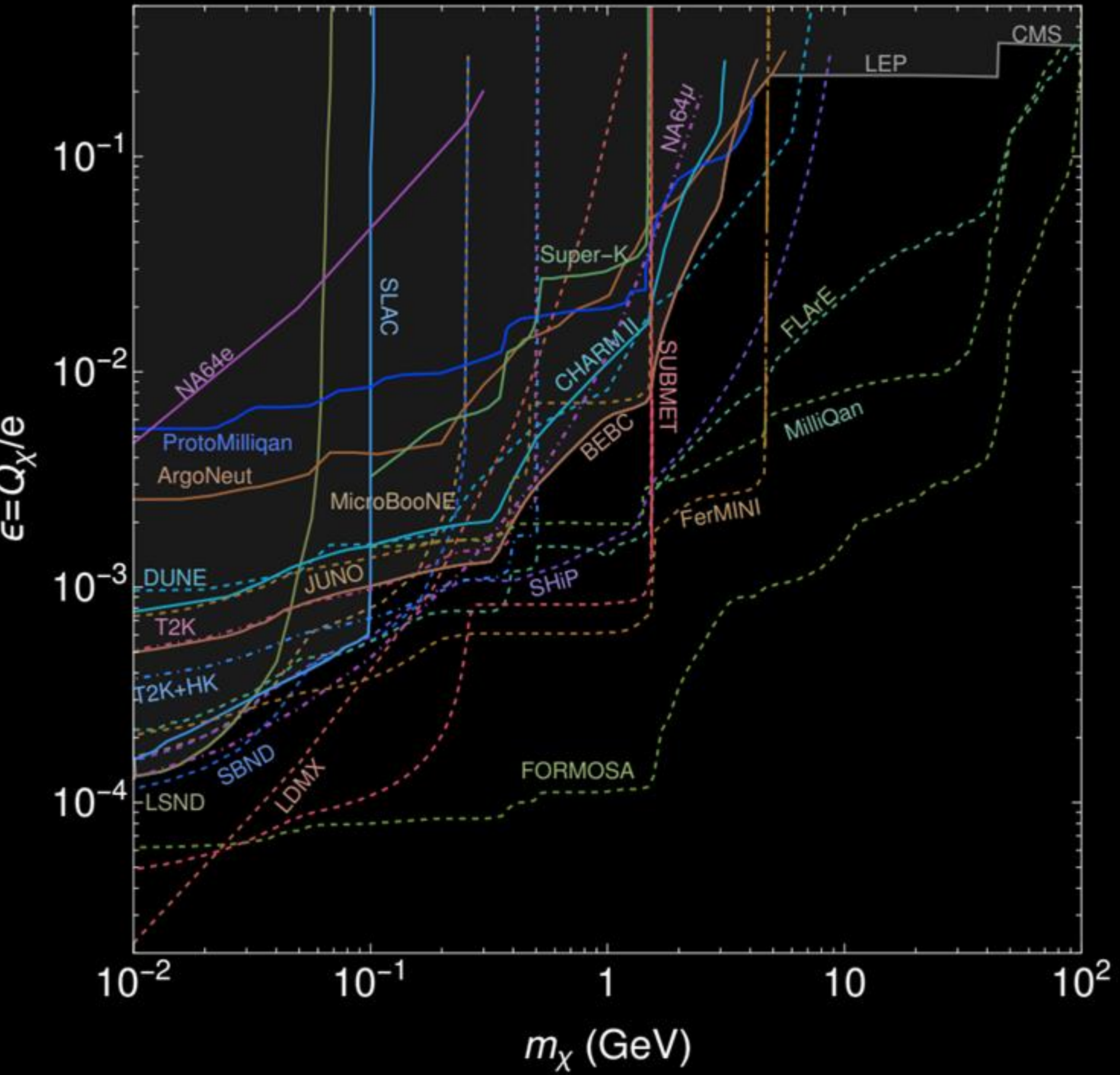
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2_{\gamma'} A'_\mu A'^\mu$$

"Simple" and Heuristic
- Massive dark photon;
- Millicharged particles;
- Ultralight dark photon;
- …

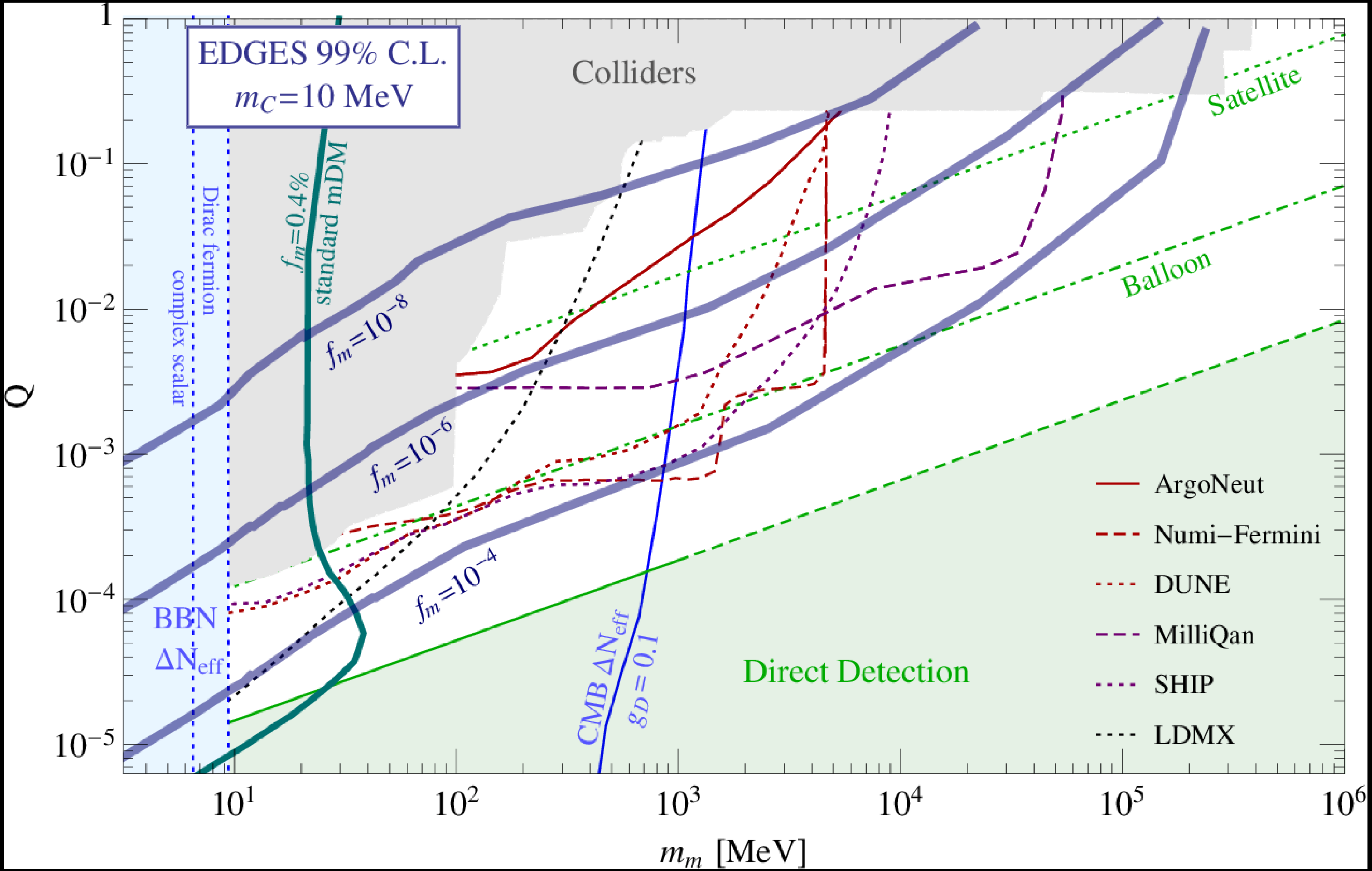
Part I: MilliCharged Particles

Current Status & Future

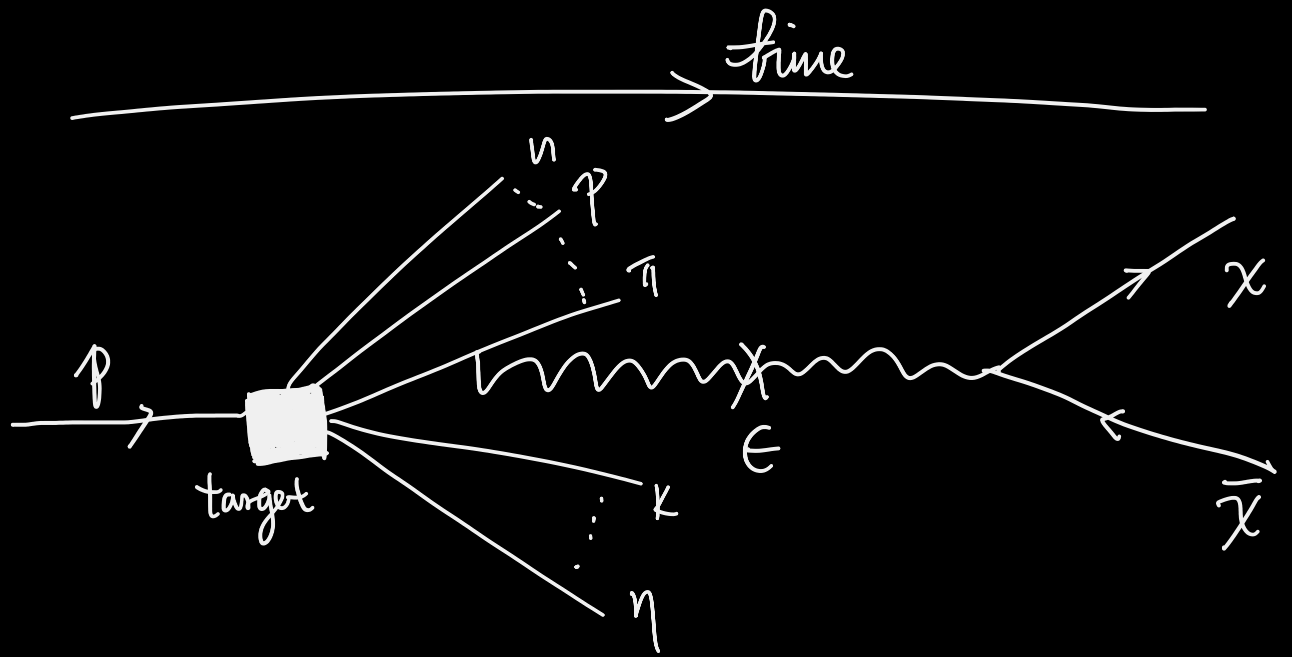




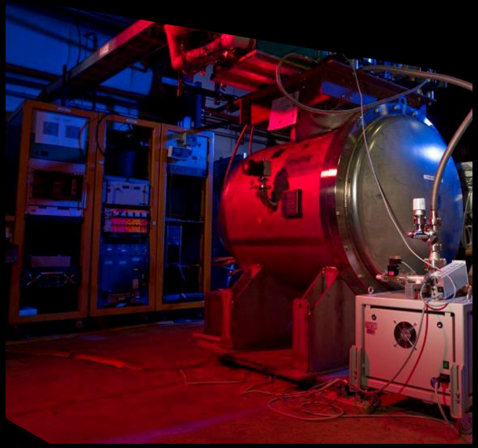
MCP as partial DM

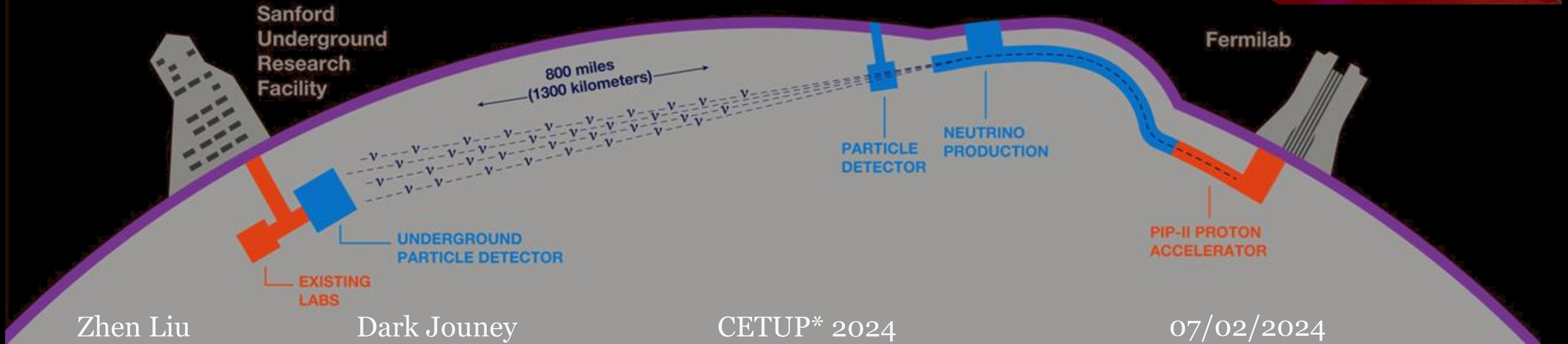


Millicharged Particles at Neutrino Experiments



High beam energy
High beam intensity (10^{20}~10^{23} Proton On Target)

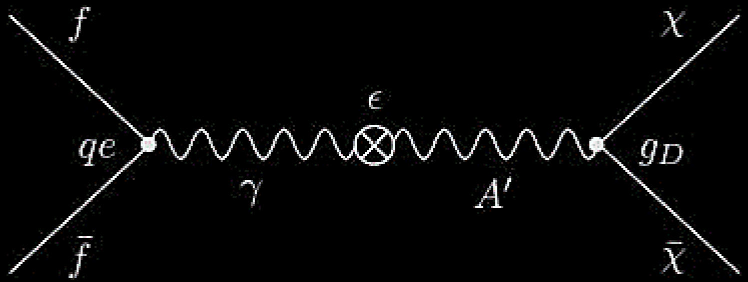


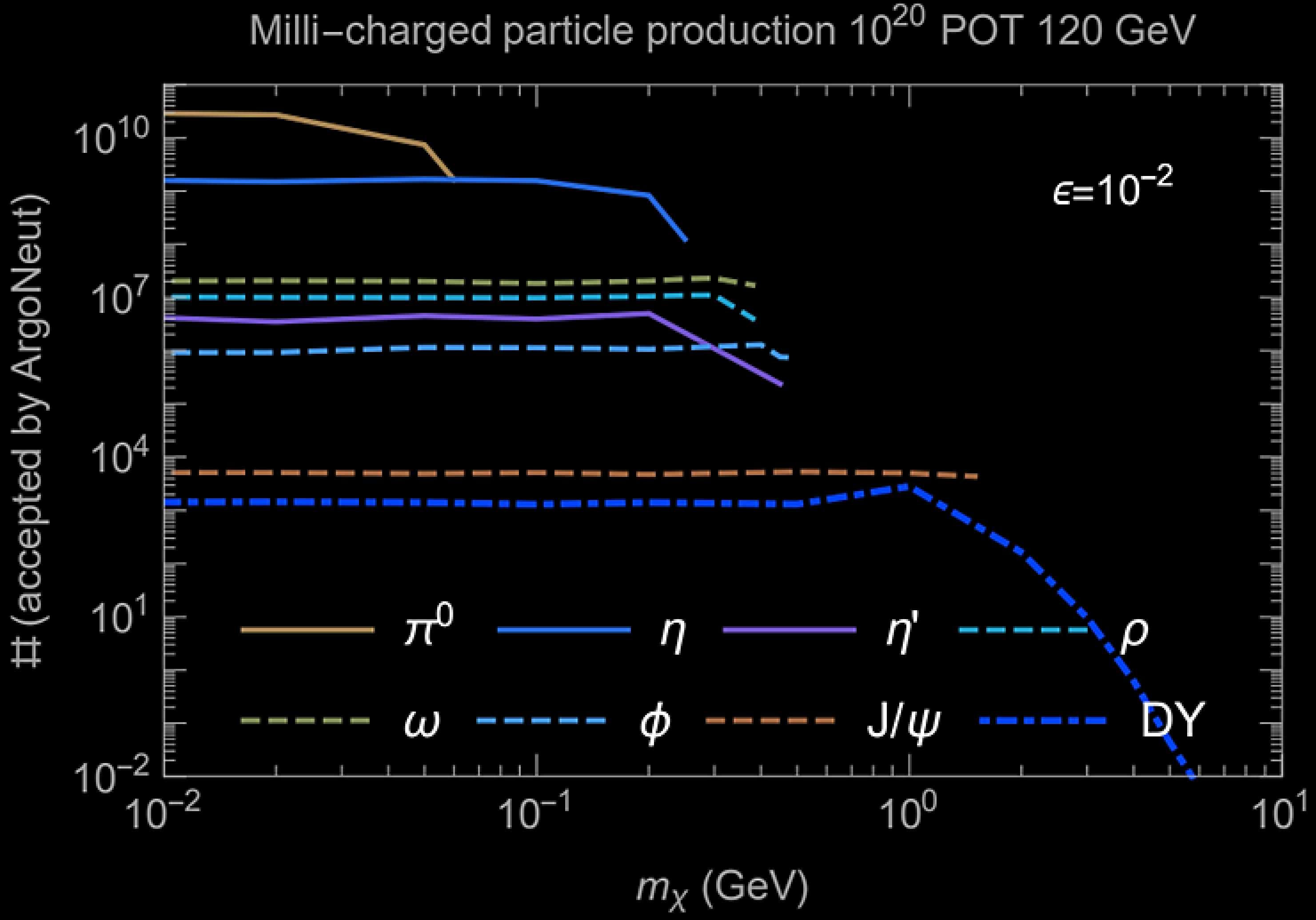


Strong Beam, strong signal

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

High beam energy
High POT

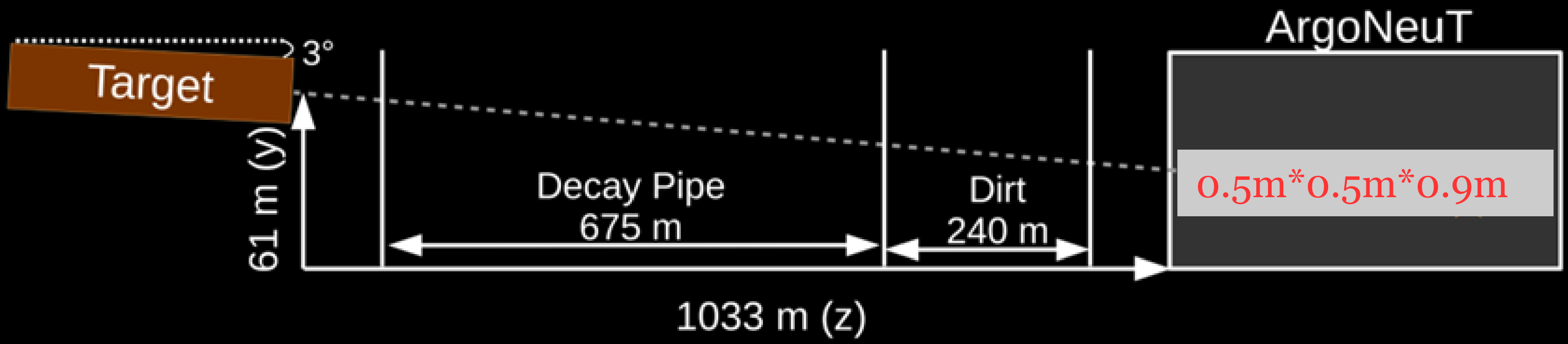




NuMI beam: good source for Millicharged particles

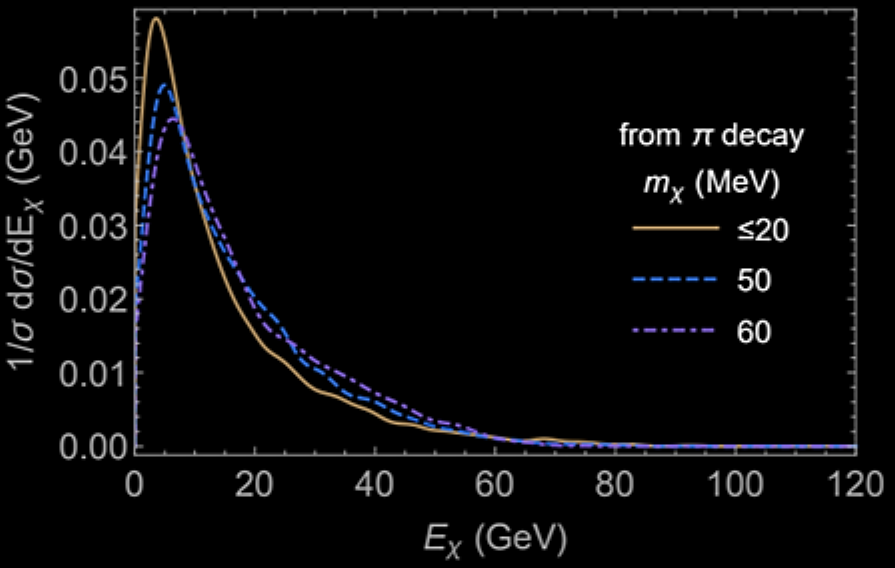
High beam energy
High POT

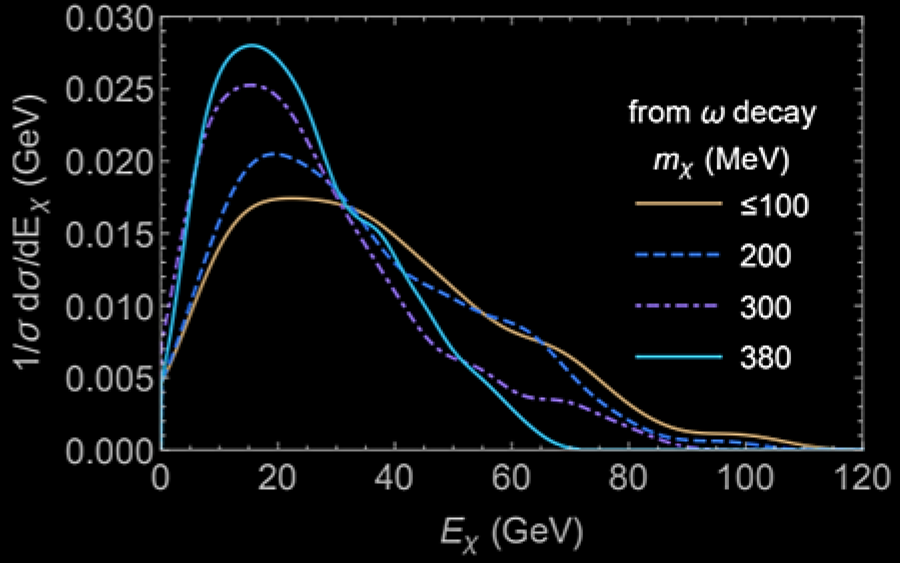
Typical geometric acceptance: $10^{-5\sim6}$

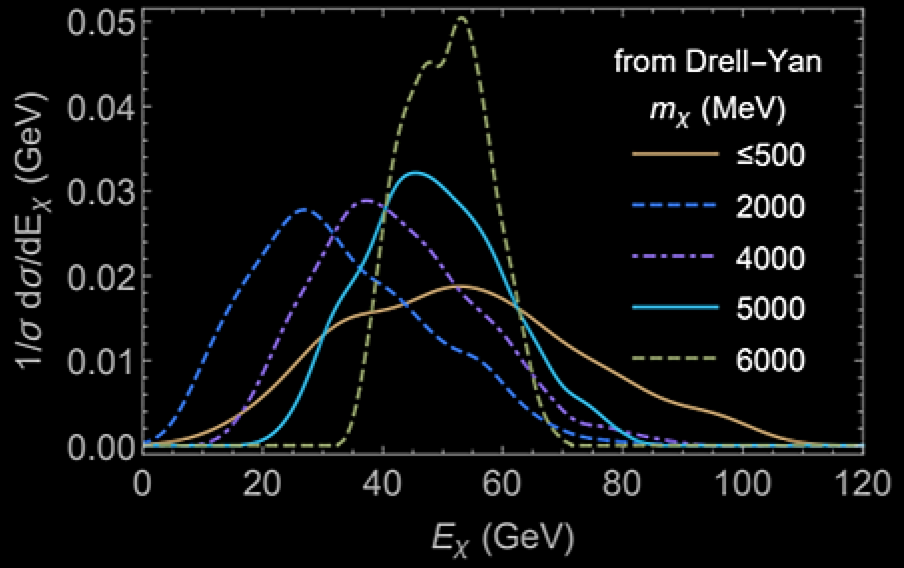


	π^0	η	η'	ρ	ω	ϕ	J/ψ	DY
#/POT	2.9	3.2×10^{-1}	3.4×10^{-2}	3.7×10^{-1}	3.7×10^{-1}	1.1×10^{-2}	5.4×10^{-7}	$4.7\times10^{-10}\epsilon^2$
$2\times \mathrm{Br}_{X\to\chi\bar{\chi}}(\%)$	$2.3\epsilon^2$	$1.4\epsilon^2$	$0.04\epsilon^2$	$0.009\epsilon^2$	$0.018\epsilon^2$	$0.058\epsilon^2$	$12\epsilon^2$	—
$A_{\mathrm{geo}}^{\mathrm{ArgoNeuT}}(m_\chi{=}20\text{ MeV})$	3.1×10^{-5}	2.1×10^{-5}	1.6×10^{-5}	1.9×10^{-5}	2.0×10^{-5}	9.1×10^{-6}	5.0×10^{-6}	3.2×10^{-6}
$A_{\mathrm{geo}}^{\mathrm{ArgoNeuT}}(m_\chi{=}200\text{ MeV})$	—	5.4×10^{-5}	3.4×10^{-5}	2.3×10^{-5}	2.2×10^{-5}	1.1×10^{-5}	4.6×10^{-6}	3.1×10^{-6}

Productions: millicharged particles are boosted







Detection

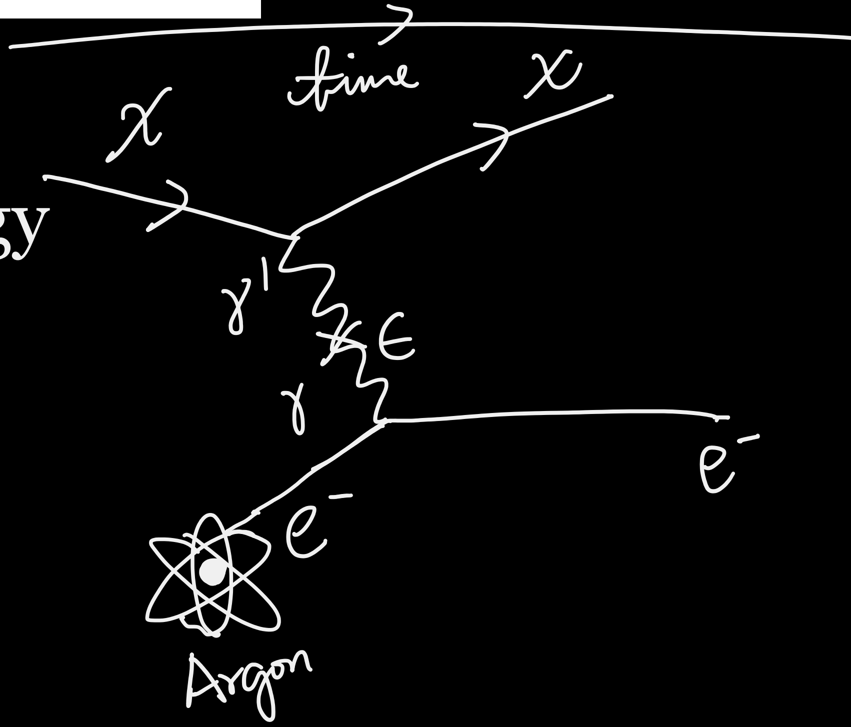
Signal scattering probability and mean free path

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

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

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

Dominated by low recoil energy scattering



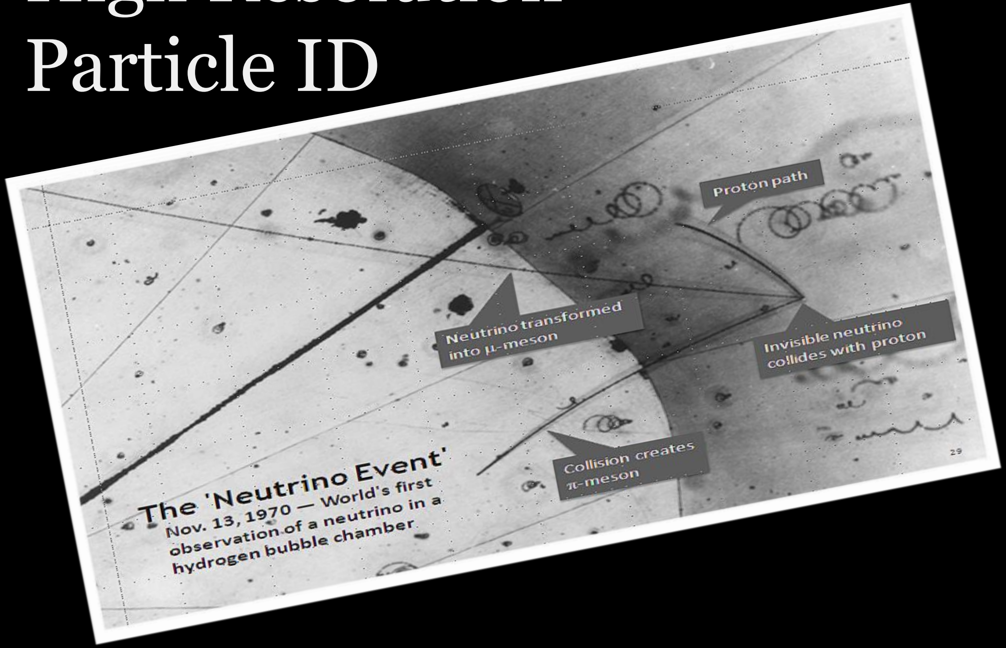
Liquid Argon (LAr) Detectors

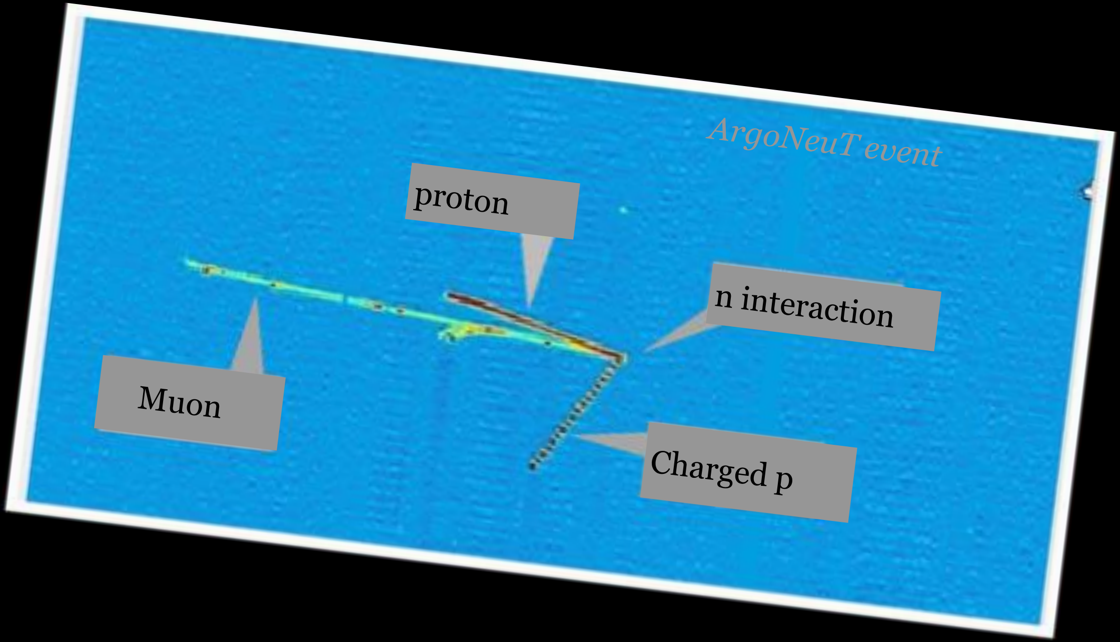
- Large
- Clean
- Tracking
- Calorimetry
- High Resolution
- Particle ID

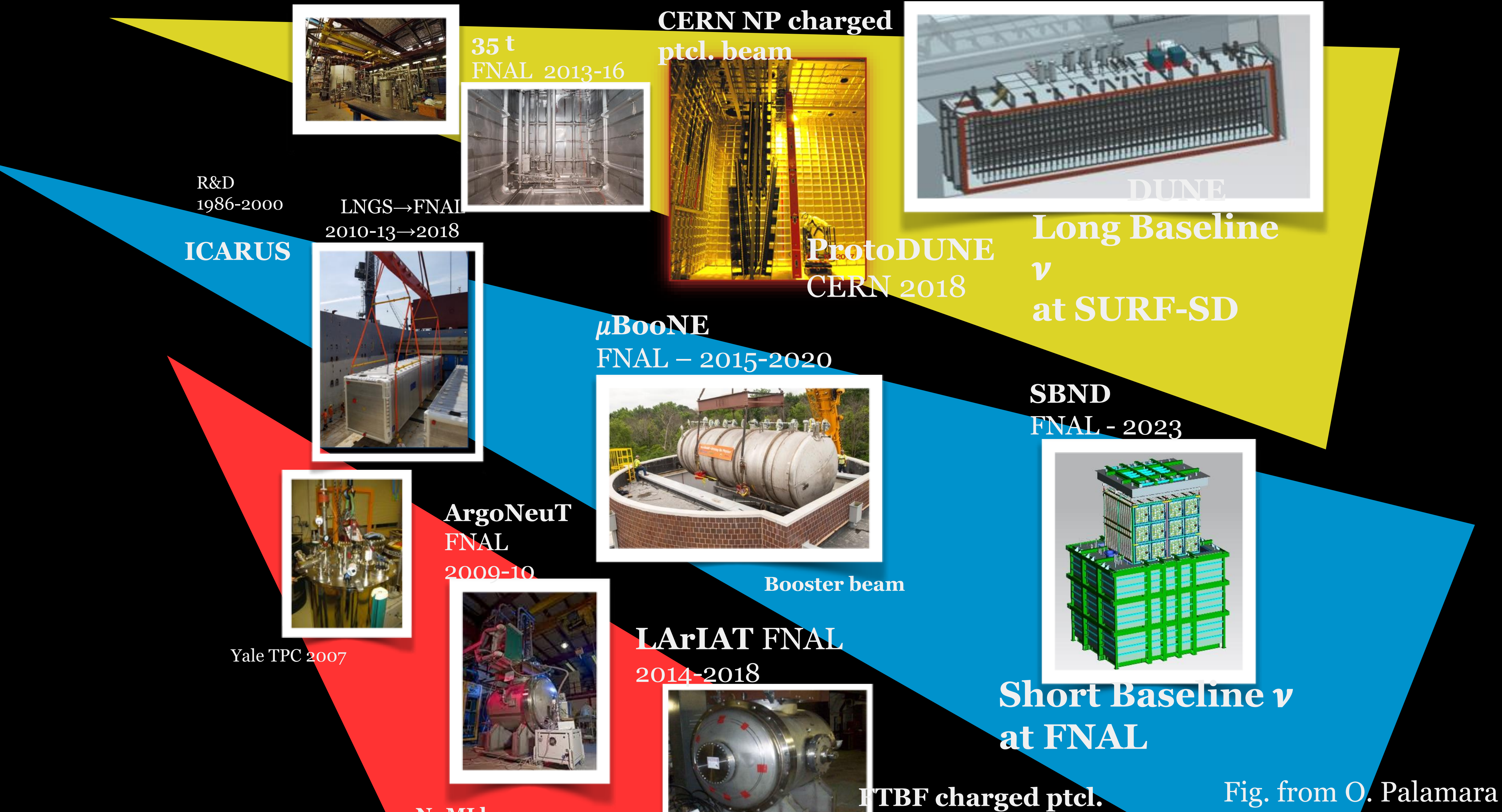
(ArgoNeuT, microBooNE, SBND, ICARUS, DUNE)

LAr TPC gives 2-in-1:

Bubble chamber quality of data with added calorimetry



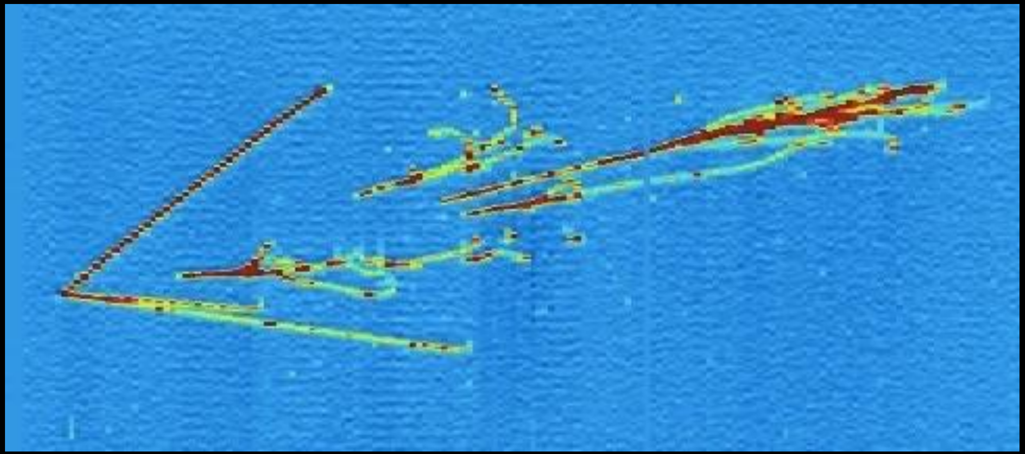


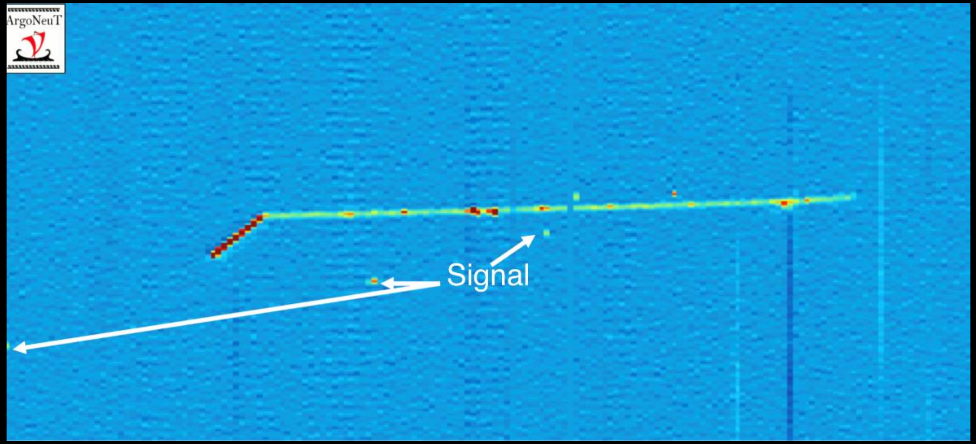

CERN NP charged ptcl. beam
35 t
FNAL 2013-16
R&D
1986-2000
LNGS→FNAL
2010-13→2018
ICARUS
ProtoDUNE
CERN 2018
DUNE
Long Baseline ν
at SURF-SD
μBooNE
FNAL – 2015-2020
SBND
FNAL - 2023
ArgoNeuT
FNAL
2009-10
Booster beam
Yale TPC 2007
LArIAT FNAL
2014-2018
Short Baseline ν
at FNAL
FTBF charged ptcl. beam
NuMI beam
Fig. from O. Palamara

Backgrounds

Soft hits. will be commonplace. Slow neutrons, γ's, cosmics, electronics, radioactives (Ar39)…

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





Average occupation number per frame:
ArgoNeuT: 0.13

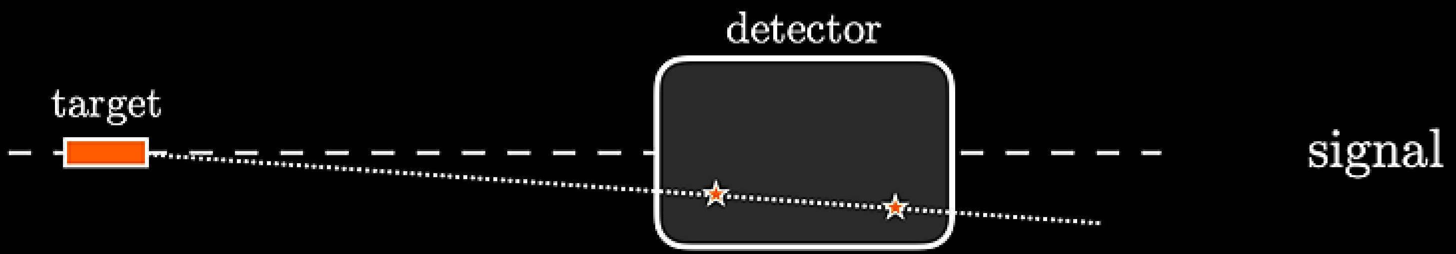
We then recalled a key feature of LAr detectors, and designed a new search:

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

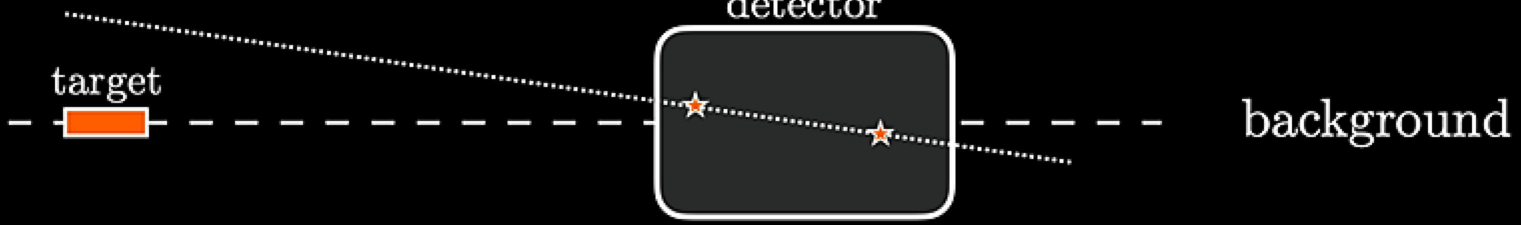
Background Reduction

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

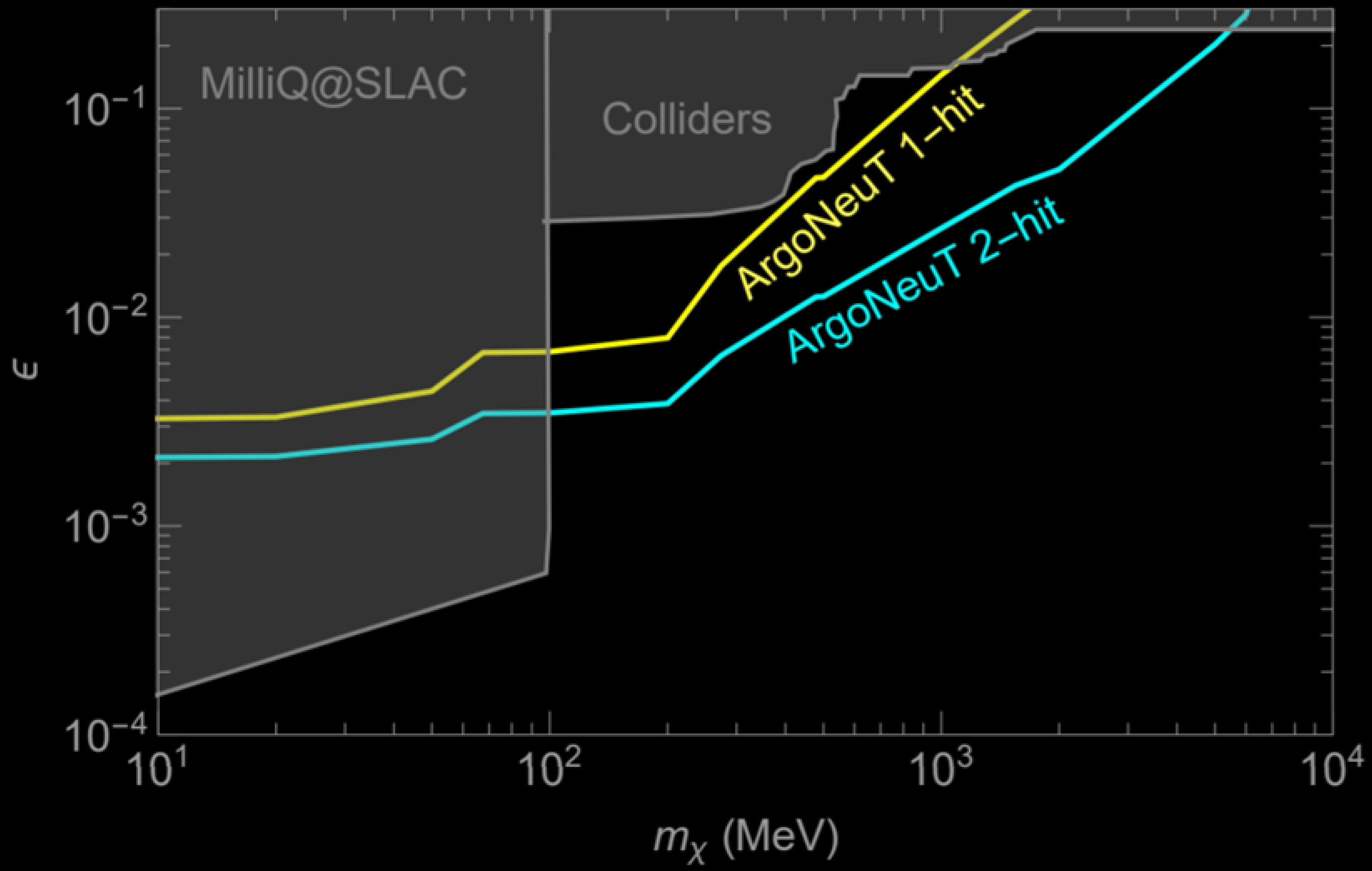
$$N_{2\,\text{hit}}^{\text{aligned}} = N_{2\,\text{hit}} \times \left(\frac{\delta x}{\Delta x} \frac{\delta y}{\Delta y} \right)$$



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

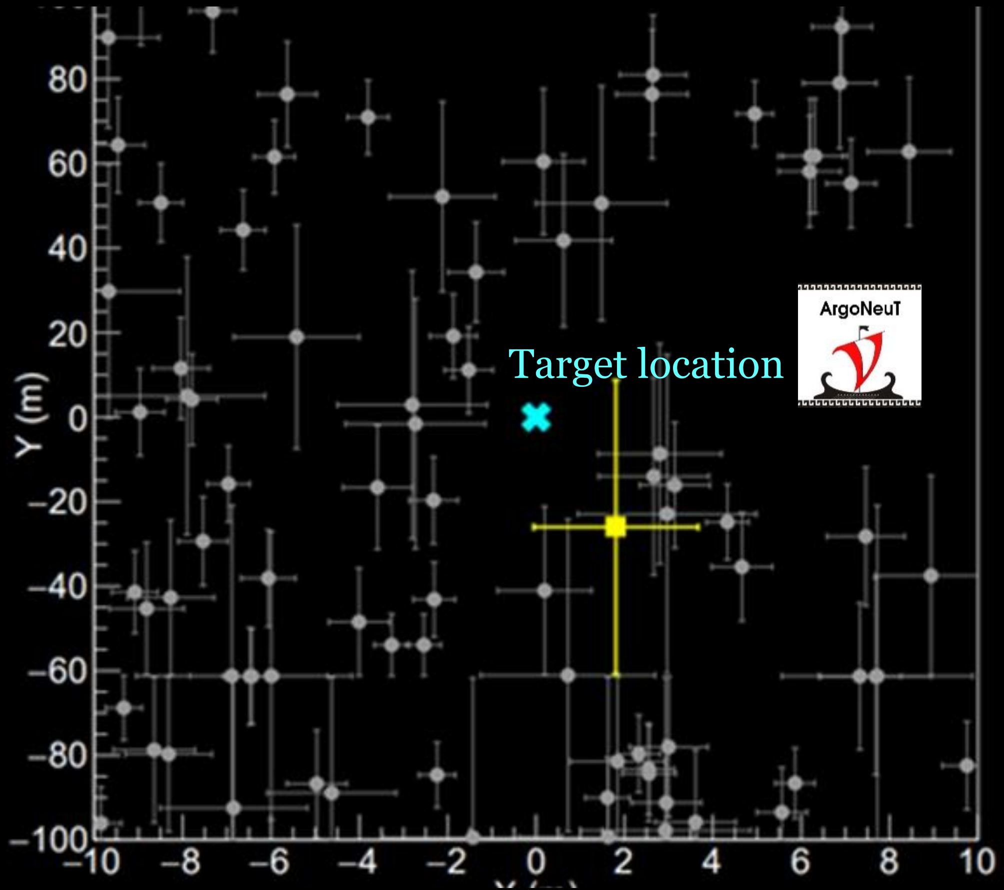


Expected reach



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

Search for mCP in ArgoNeuT

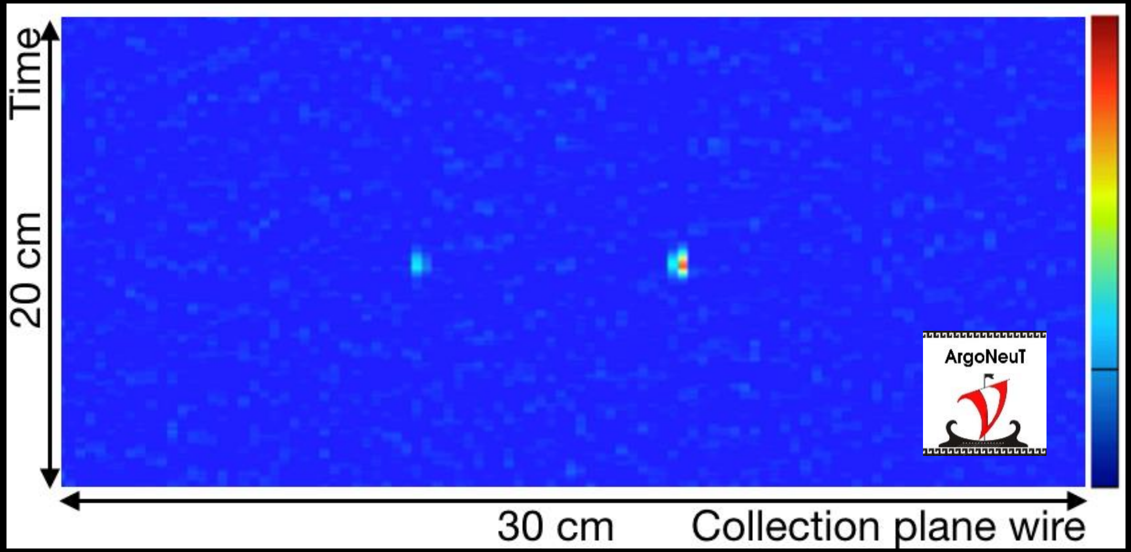


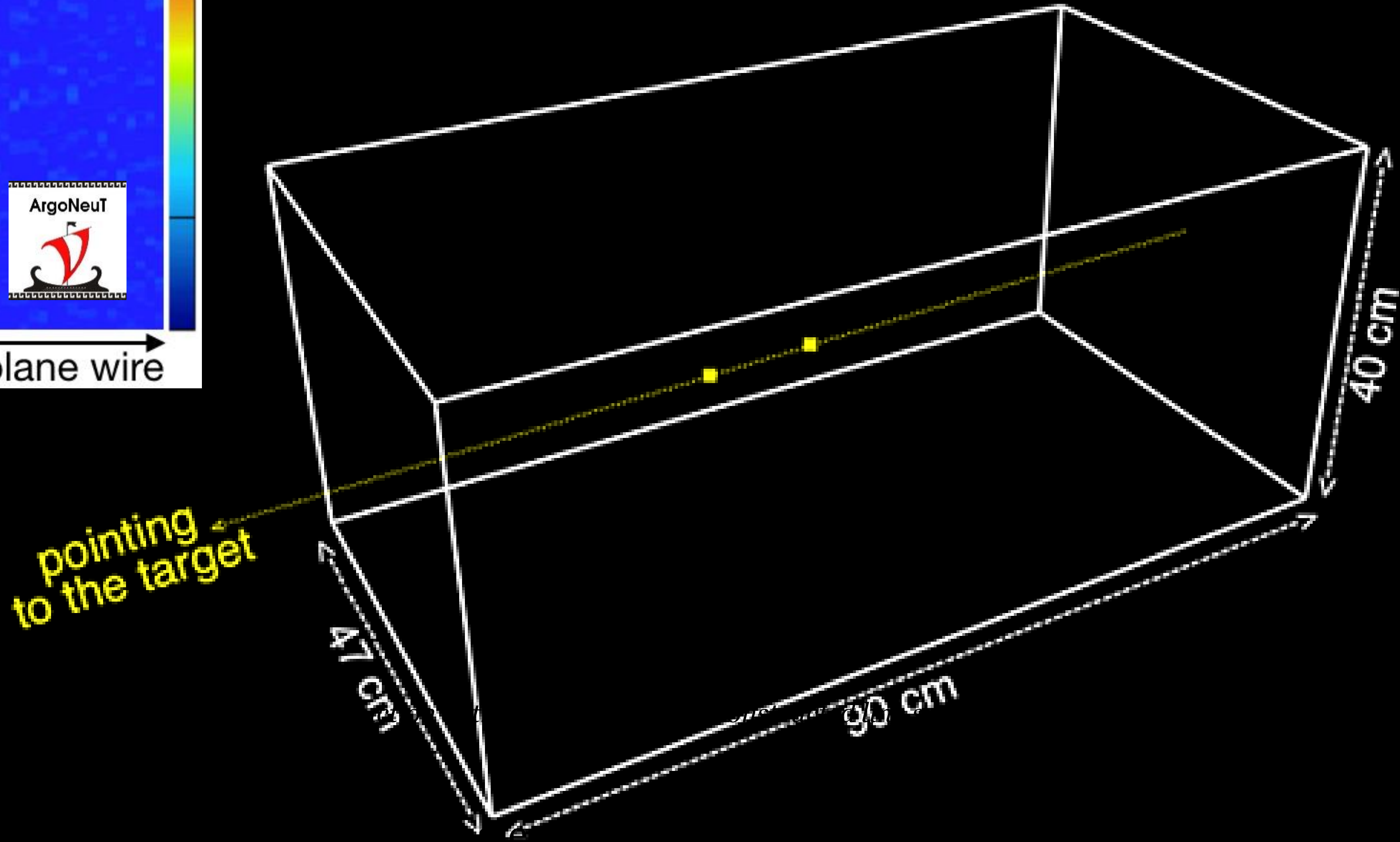
- Uncertainties are determined by
  - the uncertainties in the locations of the clusters inside the detector
    - *0.015 cm in the horizontal drift direction*
    - *0.28 cm in the vertical direction*
    - *0.16 cm along the beam direction*
  - while small compared to the size of the detector, uncertainties 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

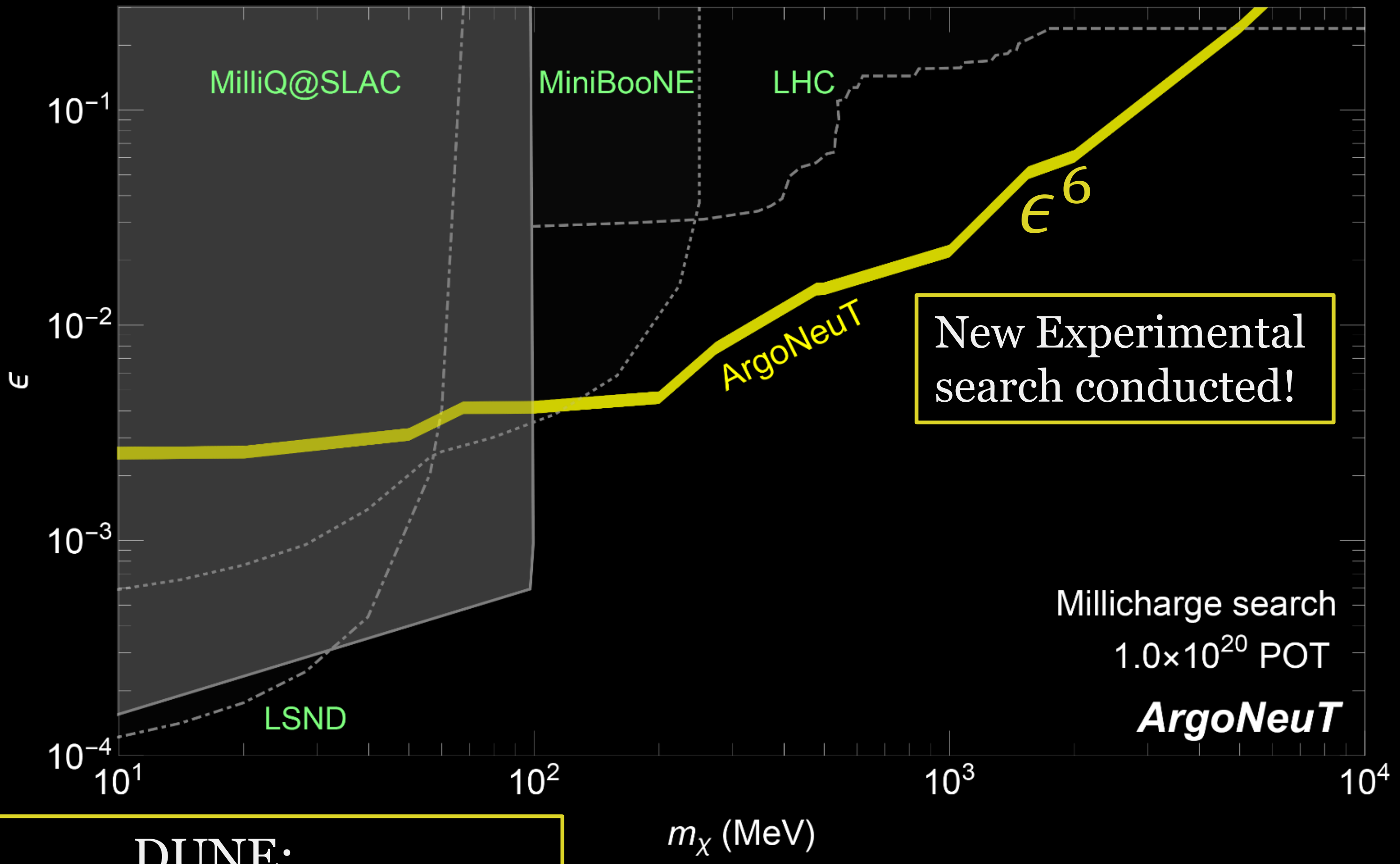
The Candidate Signal Event



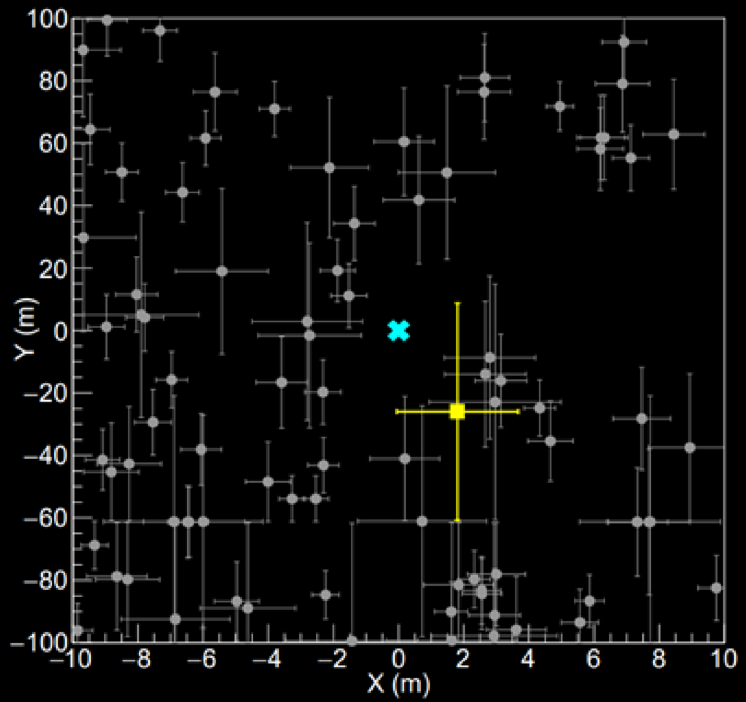


Harnik, Liu, Palamara, 19'
Liu with ArgoNeuT Collaboration, 20'

New exciting coverage



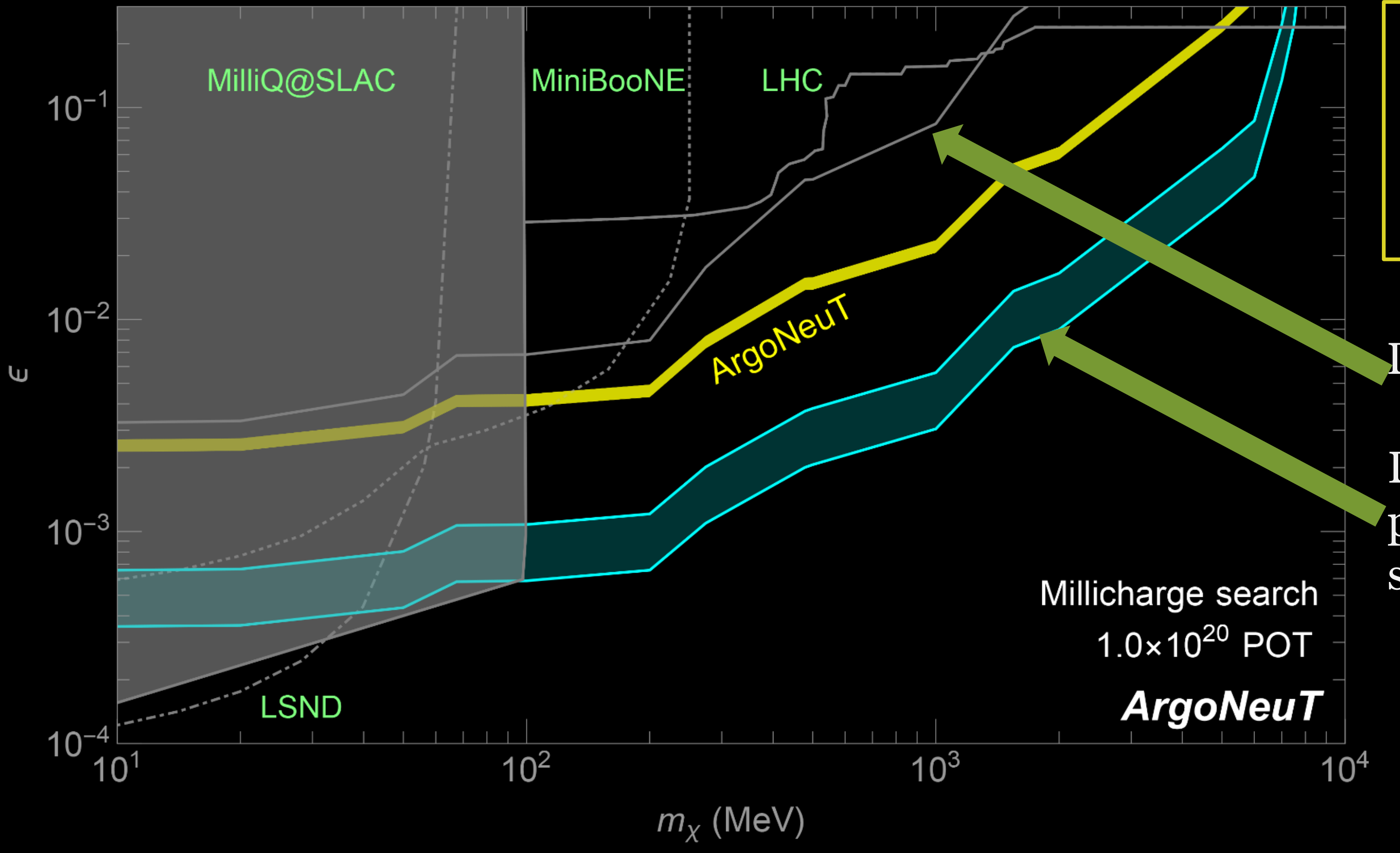
New Experimental search conducted!



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

Harnik, Liu, Palamara, 19’
Liu with ArgoNeuT Collaboration, PRL, 20’

Looking into the future



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

DUNE & ArgoNeuT 1 hit

DUNE projections (with our proposed 2 hits and timing strategy)

How to see Millicharged Particles (Again)?

Signal scattering probability and mean free path

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

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

Dominated by low recoil energy scattering

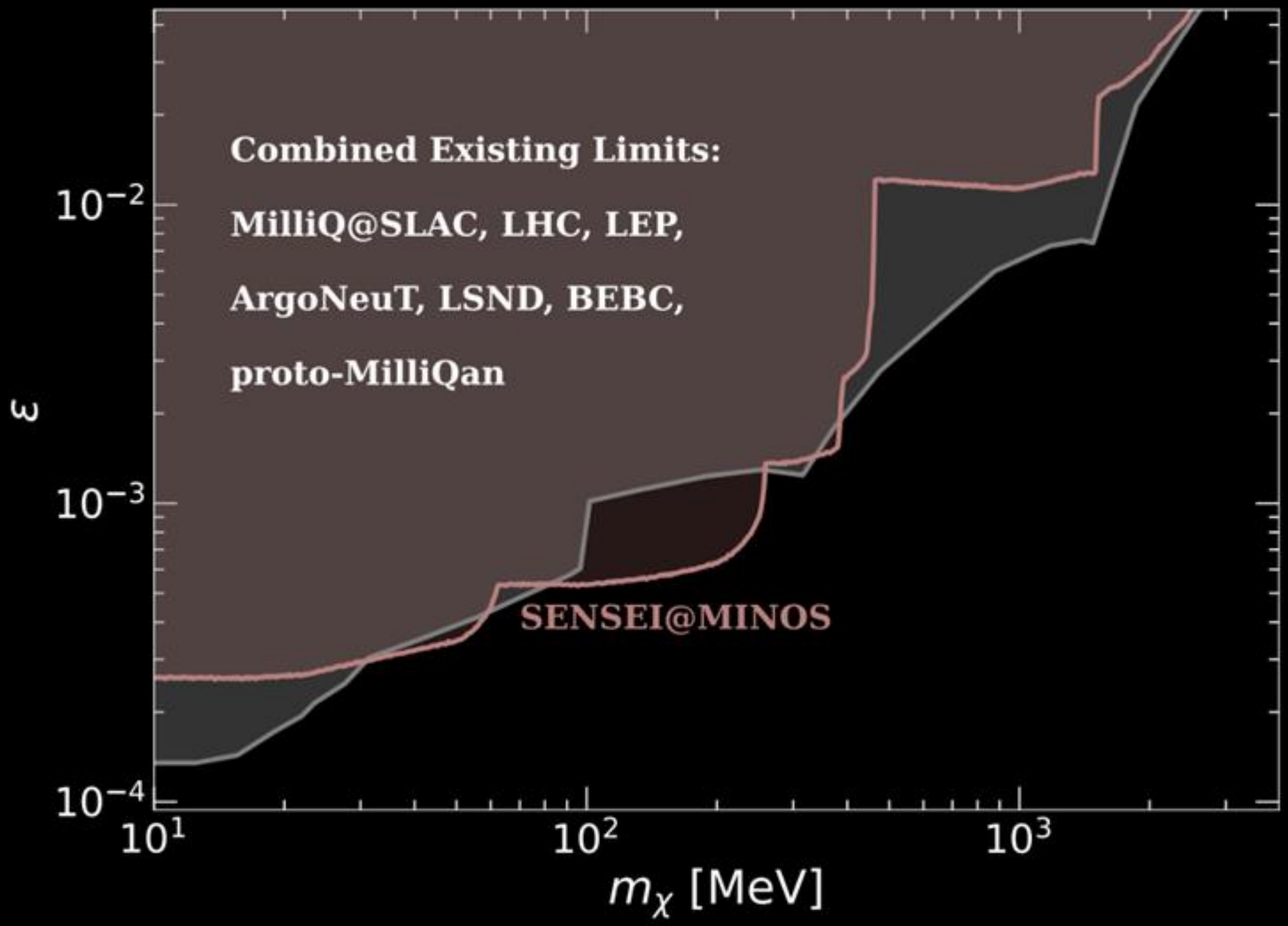
What if we lower the threshold?

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

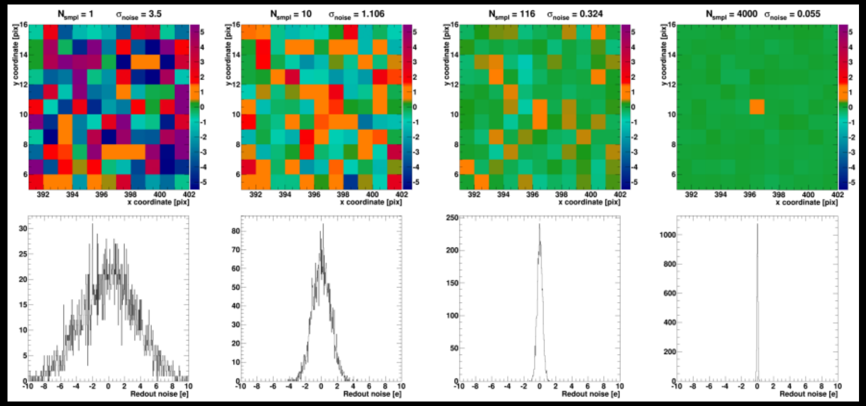
Single Scatter Detection Parametric:

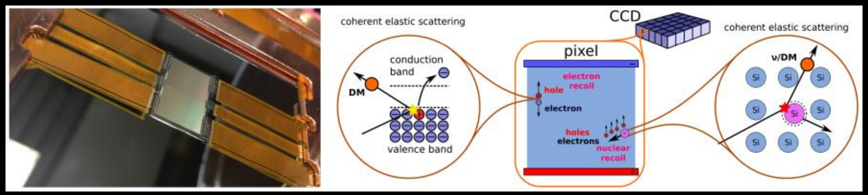
- Detection Rate proportional to Volume
  - SENSEI 3gram is small in volume, about $1/10^5$ compared to ArgoNeuT
- Detection Rate proportional to effective POT

New Results with SENSEI Collaboration (2305.04964)

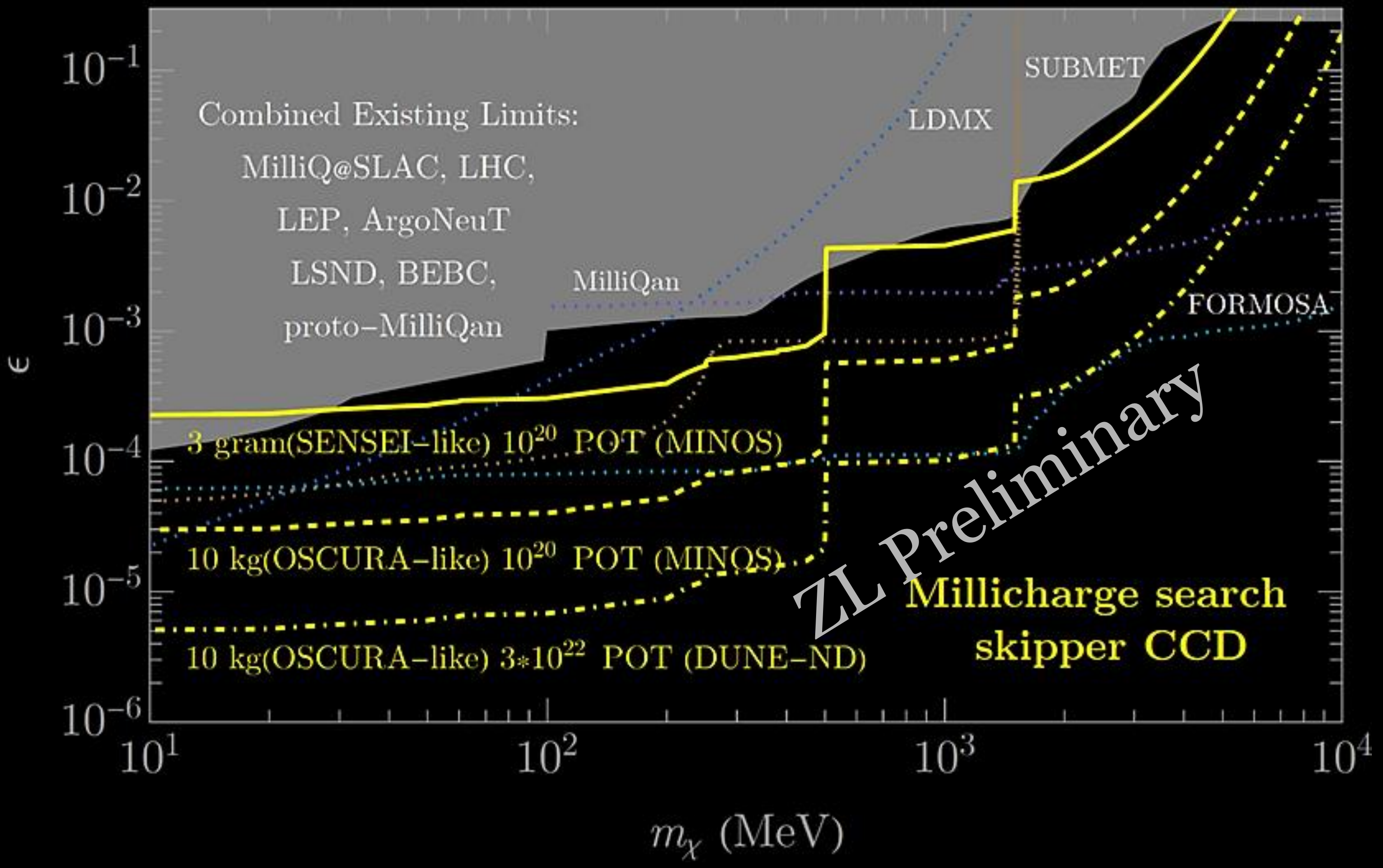


3 gram of detectors with 3 days equivalent of data already achieving new results.





There are many already “under construction”



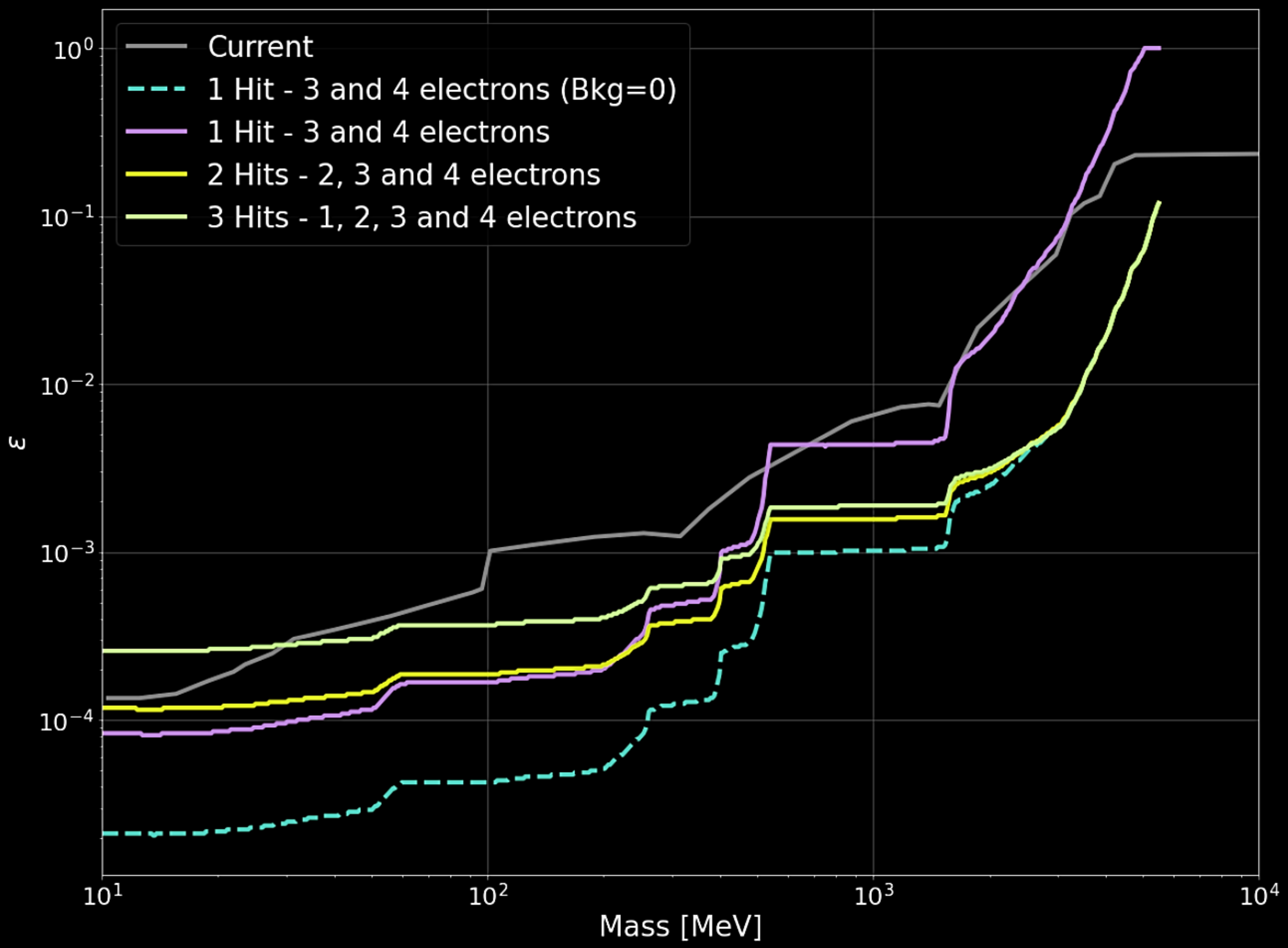
Solid: one month of current beam;

Dashed: one month of current beam with OSCURA

Dot-Dashed: DUNE beam with OSCURA

ϵ^4-scaling

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:

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

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

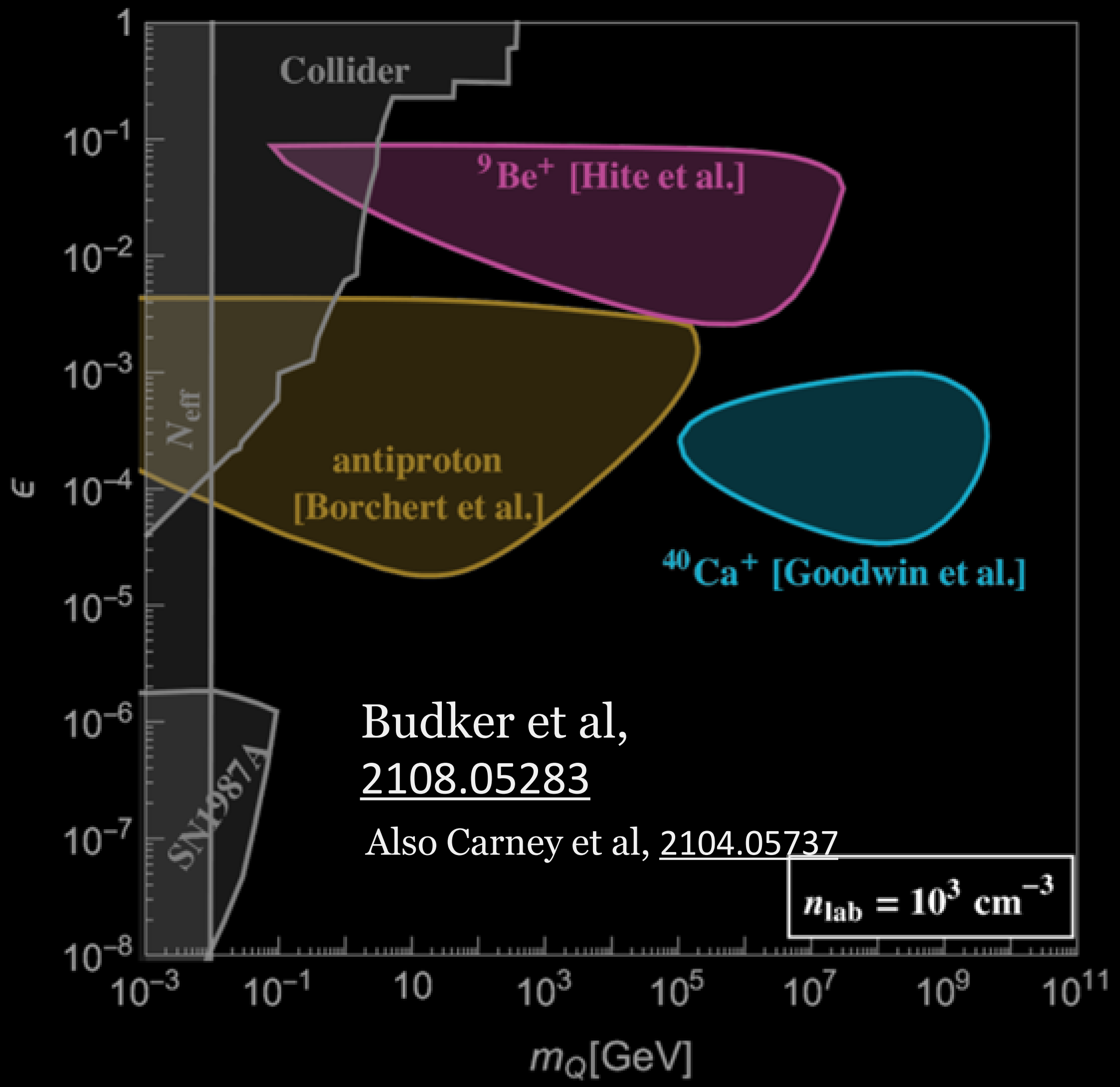
Fast developing frontier:

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.



Budker et al, 2108.05283

Also Carney et al, 2104.05737

Part II: Dark Photons @ Dark SRF

Mainly based upon A. Romanenko et al, 2301.11512

Intro

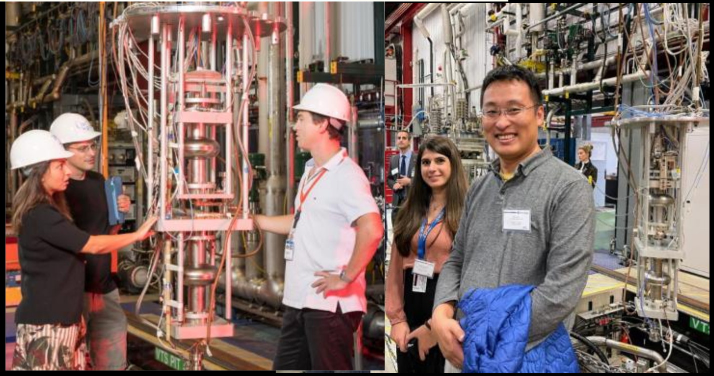
There are many past, ongoing, and future searches.

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

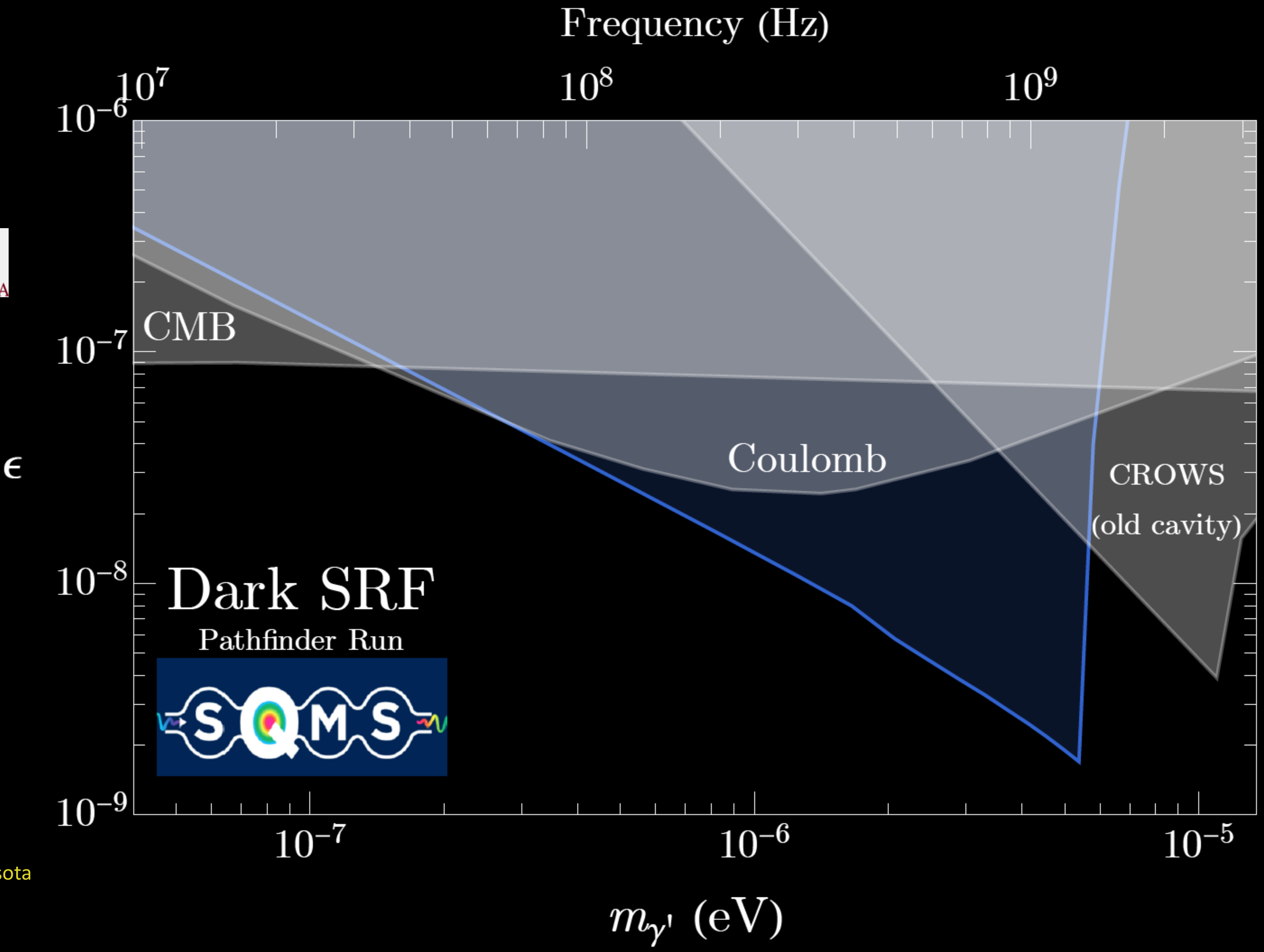
Graham et al, Phys.Rev. D90 (2014) no.7, 075017
S. R. Parker et al, Phys. Rev. D 88, 112004 (2013)
J. Hartnett et al, Phys. Lett. B 698 (2011) 346
J. Jaeckel and A. Ringwald, Phys. Lett. B 659, 509 (2008)

Pathfinder result

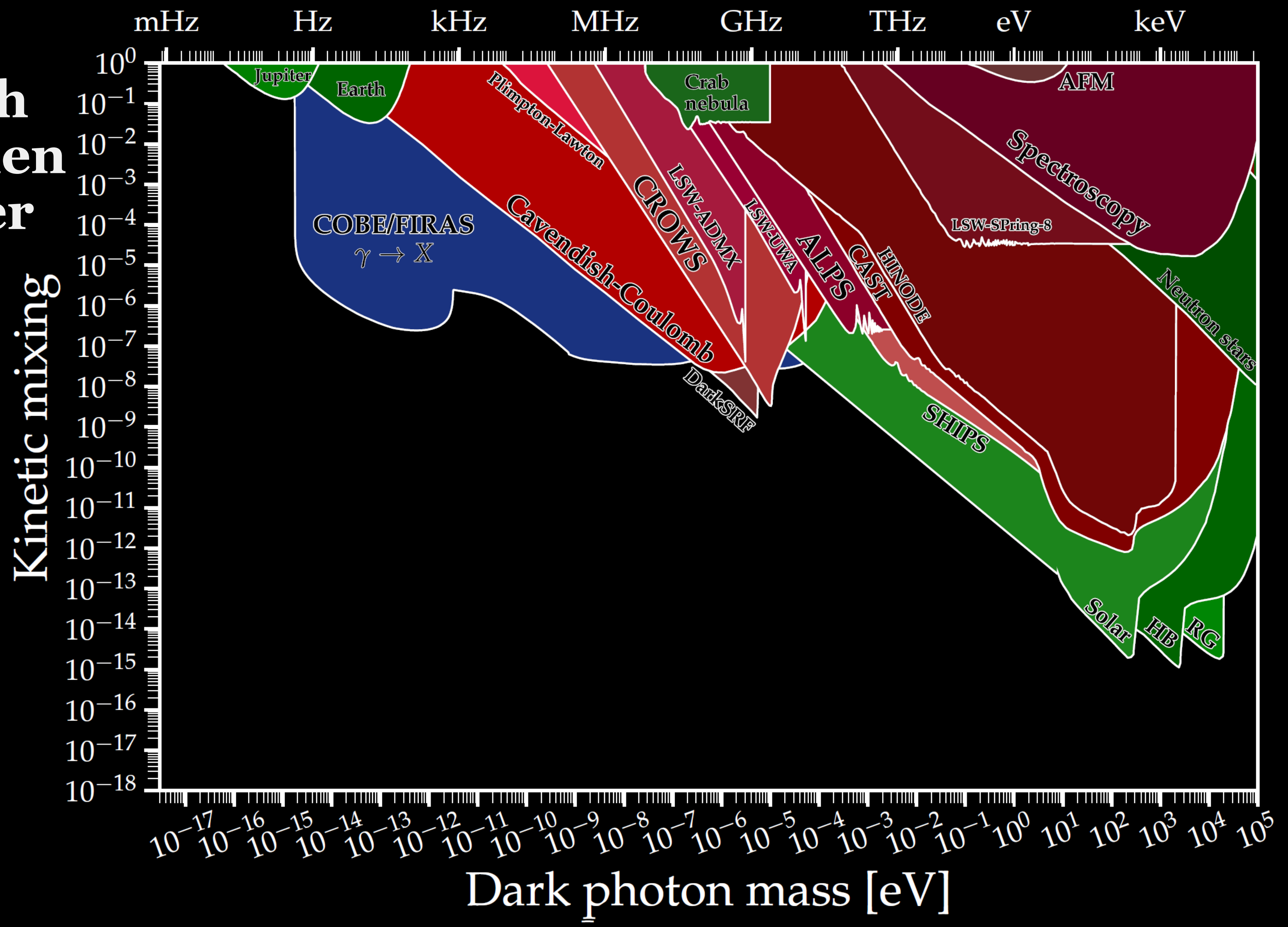
Our pathfinder run results already explore new territory!



Work was performed at Fermilab and University of Minnesota

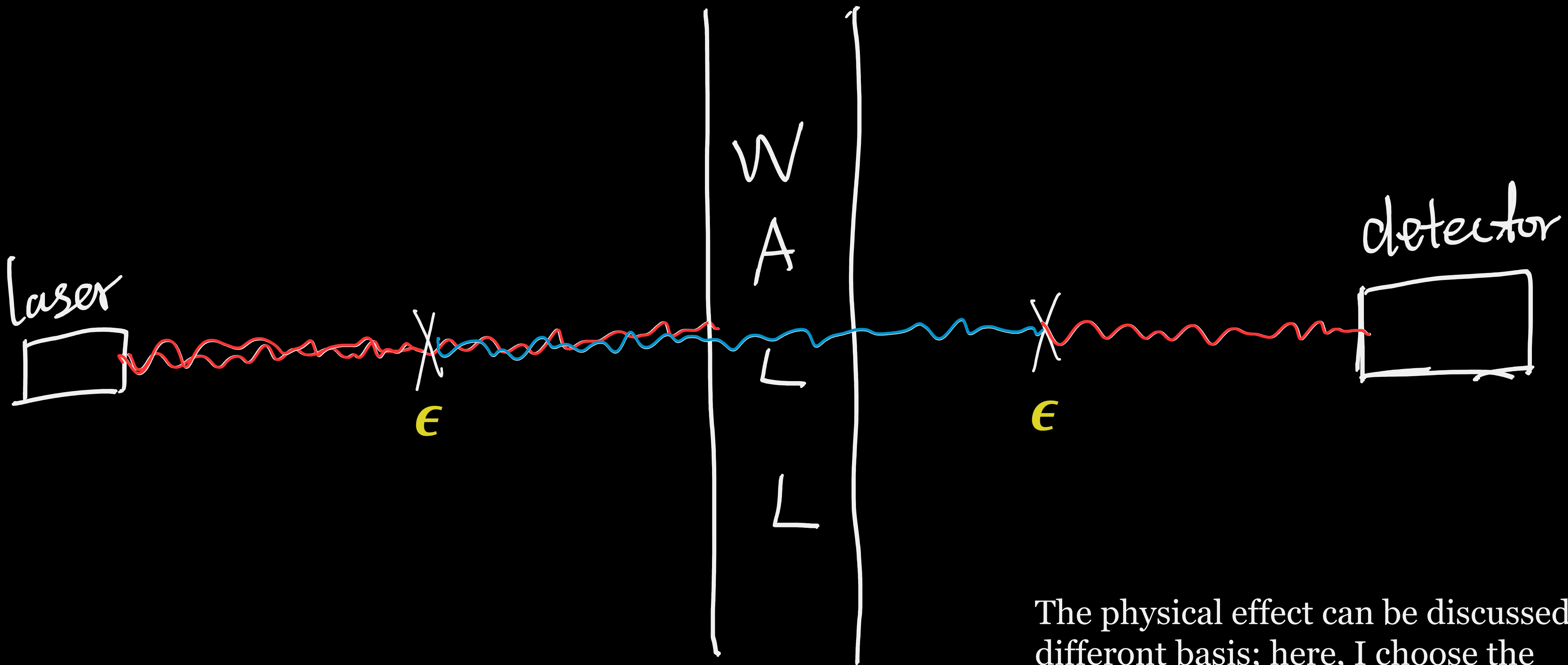


An active program: much less known when not dark matter



What is Dark SRF?

Light Shining through Wall (LSW)



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

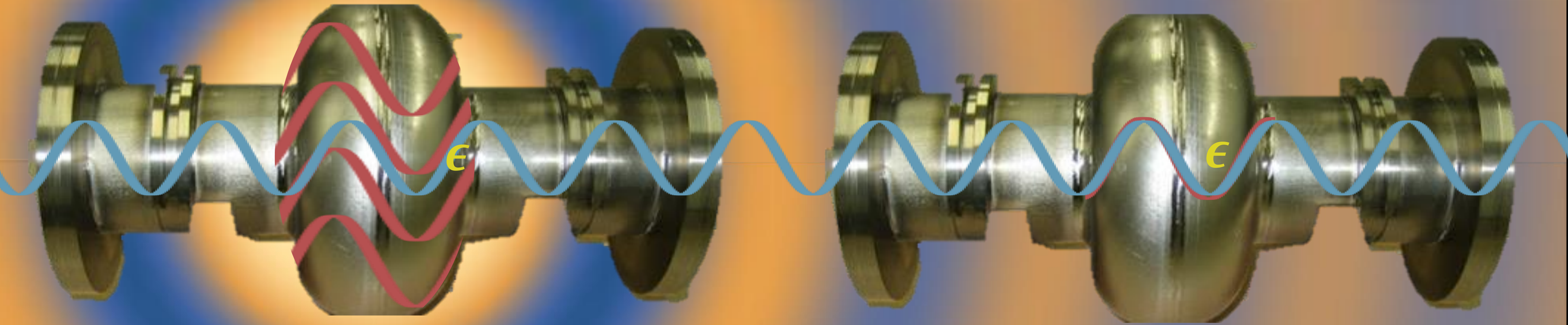
We have the best SRF for High Energy Accelerators

Superconducting RF Cavities:
- Large fields
- High Quality

Superconducting Radio Frequency (SRF) cavity

SRF for Dark Photon

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



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

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

Power it up:
- 40 MV/m (26 J stored energy)
- ~10^{25} photons

SM photon does not penetrate the superconducting wall.
But dark photons can!

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

$$B \propto Temperature$$

Background fluctuation controlled at

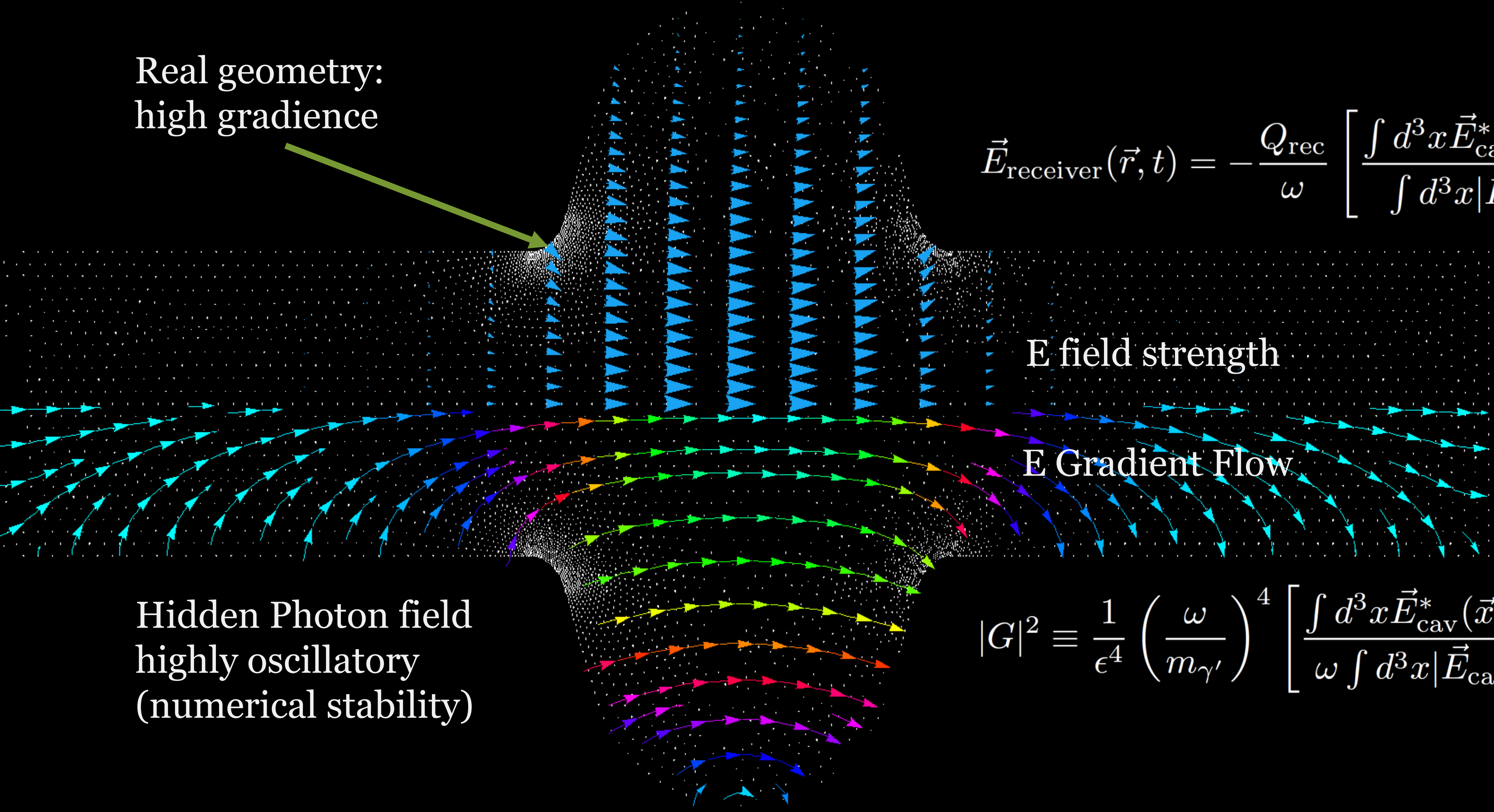
$$\Delta B \propto Temperature \sqrt{\frac{t_{rungup}}{t_{integration}}}$$

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

Background noise also received contribution from possible cross-talks:

$$B \propto P_{emitter}$$

Real Cavity Configuration



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

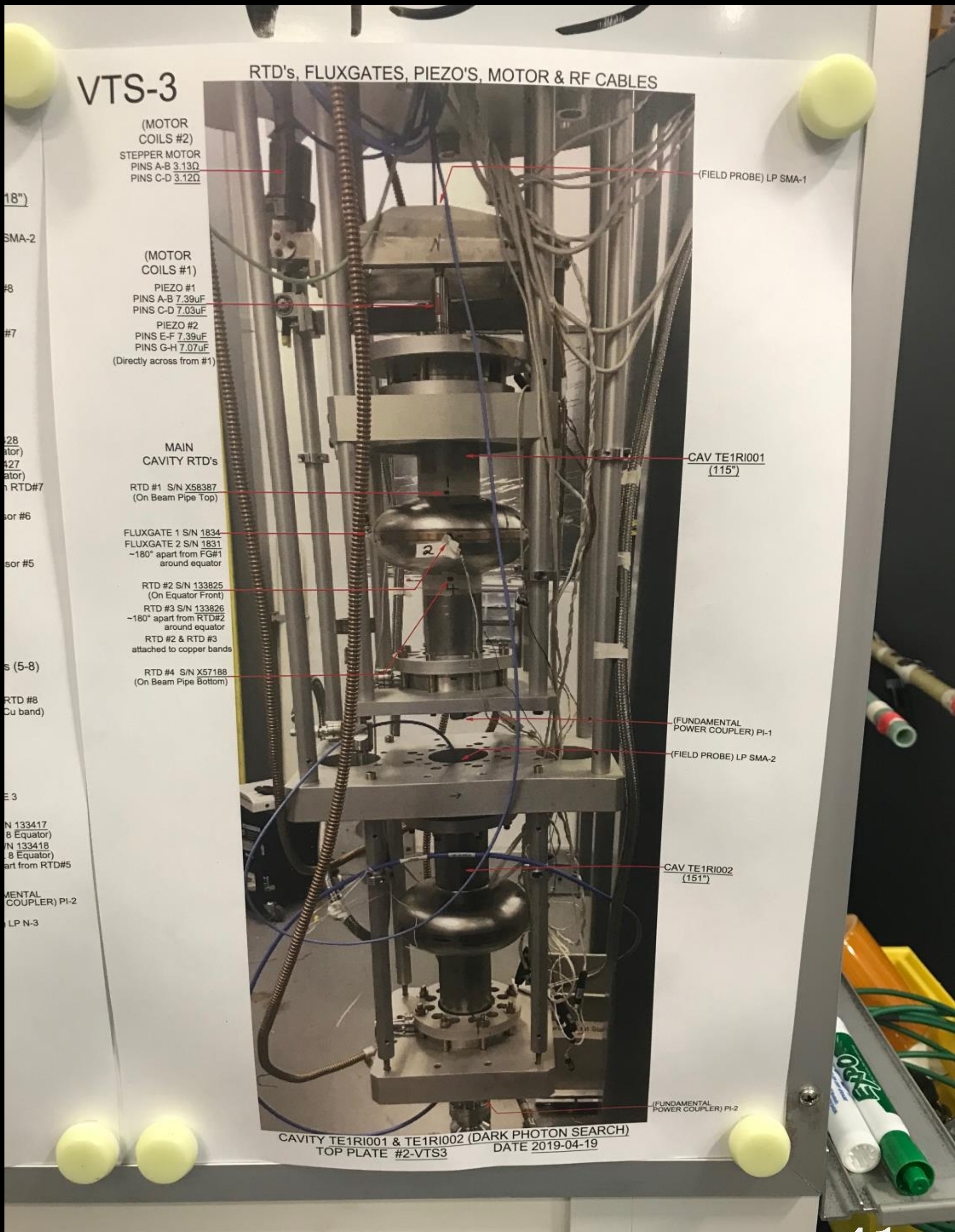
$$|G|^2 \equiv \frac{1}{\epsilon^4} \left(\frac{\omega}{m_{\gamma'}} \right)^4 \left[\frac{\int d^3x \vec{E}^*_{\text{cav}}(\vec{x}) \cdot \vec{j}(\vec{x})}{\omega \int d^3x |\vec{E}_{\text{cav}}(\vec{x})|^2} \right]^2$$

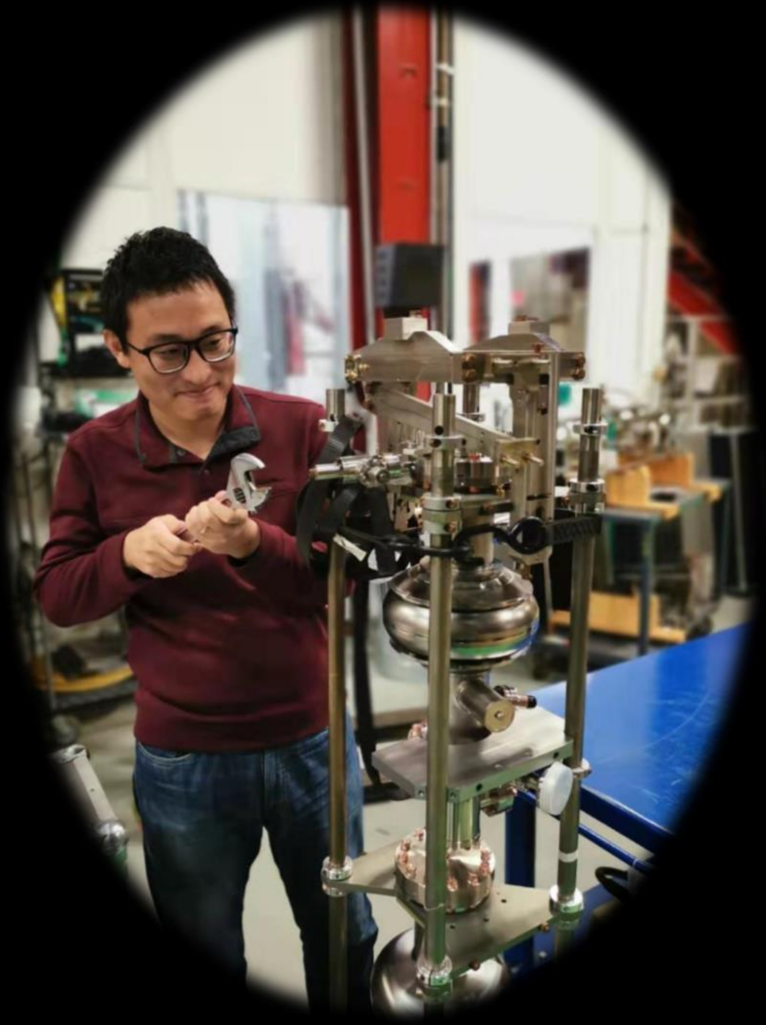
Dark SRF Pathfinder Runs

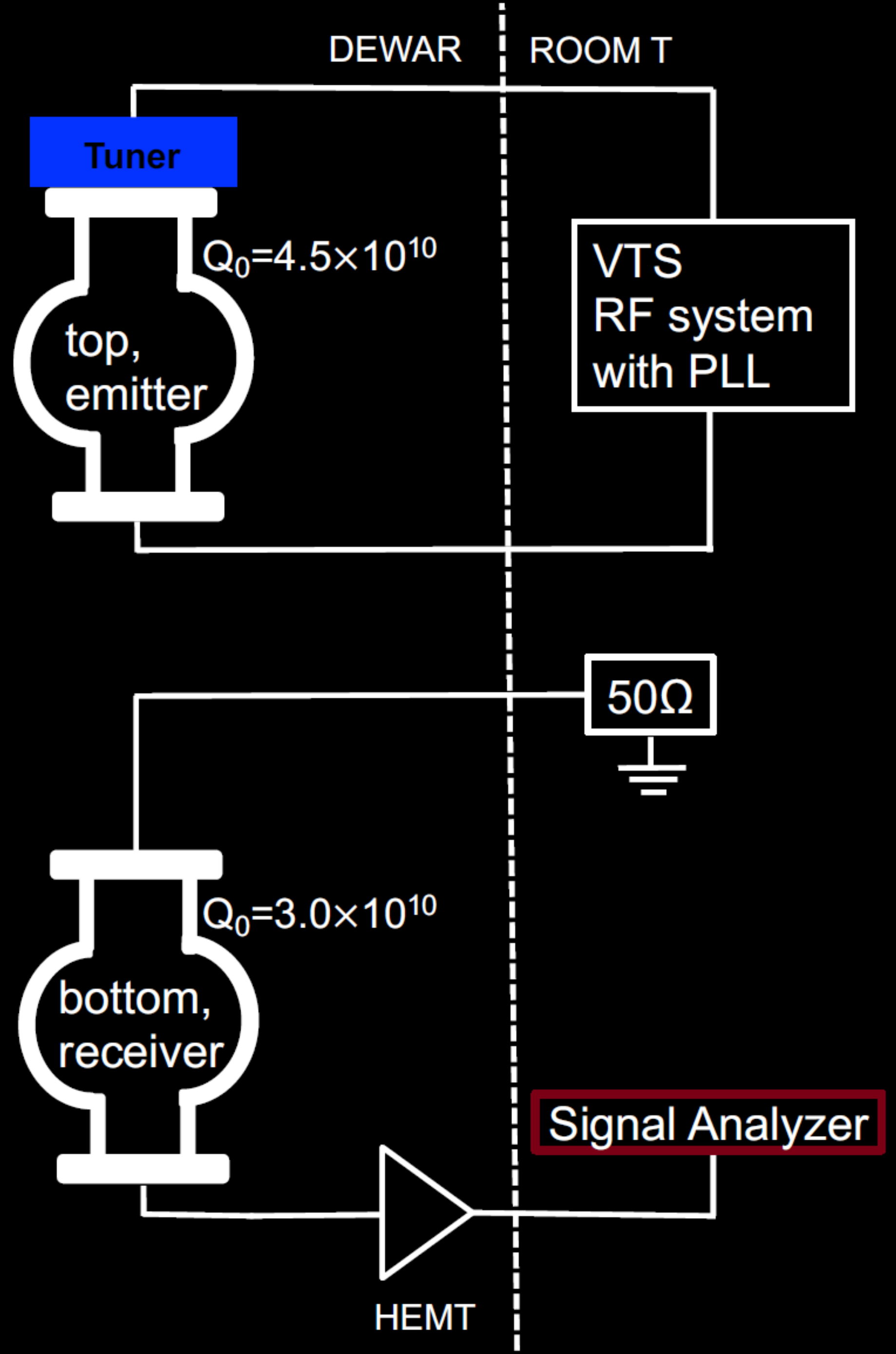
Pathfinder run(s) summary

<u>It works!</u>

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

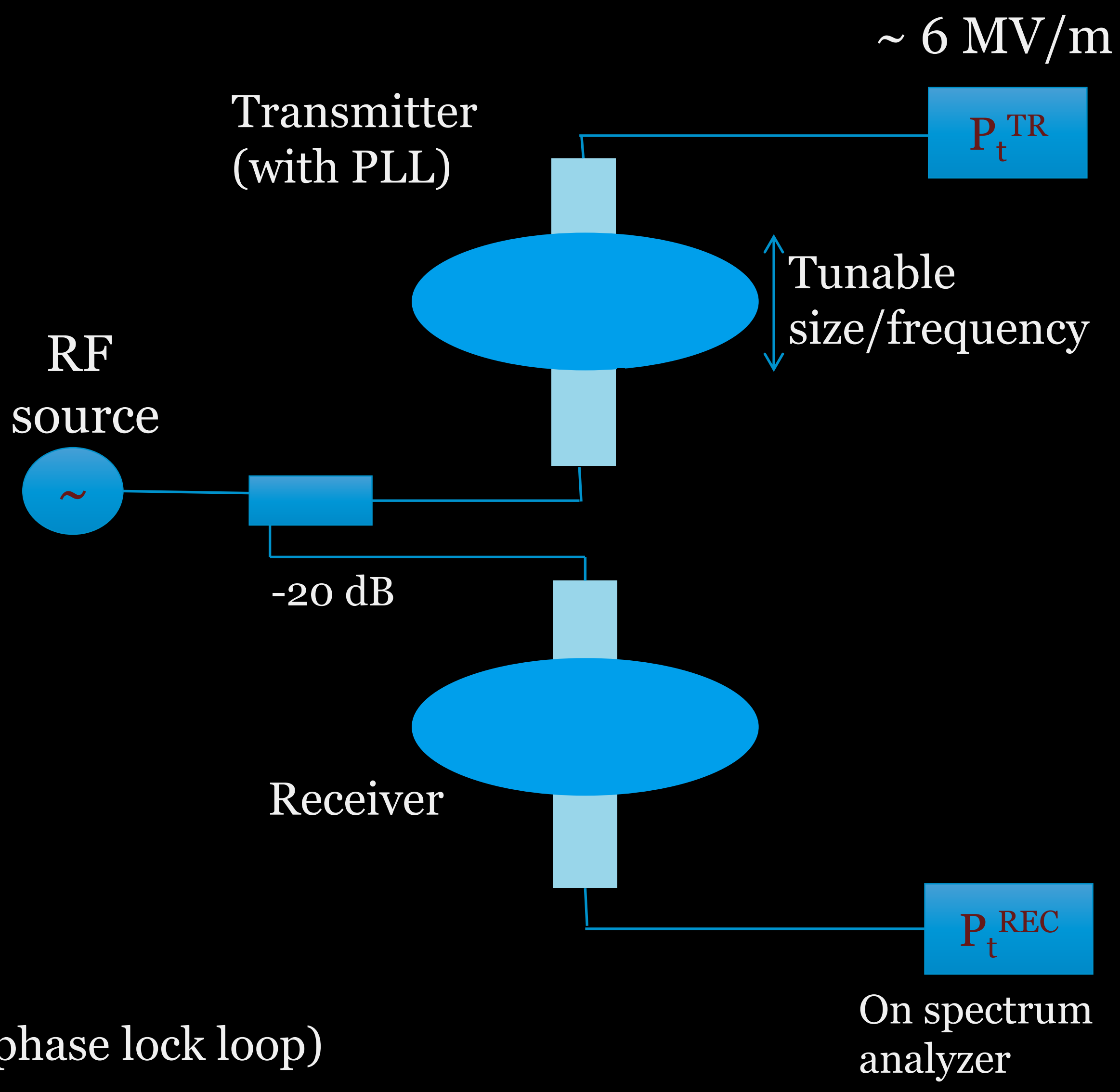


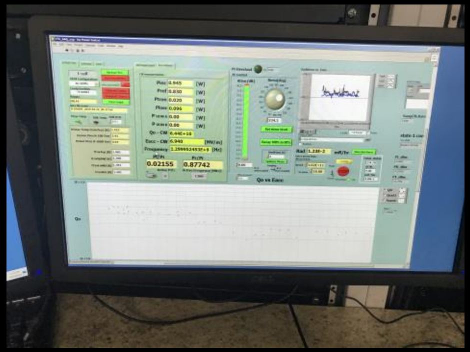



DEWAR
ROOM T
Tuner
Q0=4.5×10^10
top, emitter
VTS RF system with PLL
50Ω
Q0=3.0×10^10
bottom, receiver
Signal Analyzer
HEMT

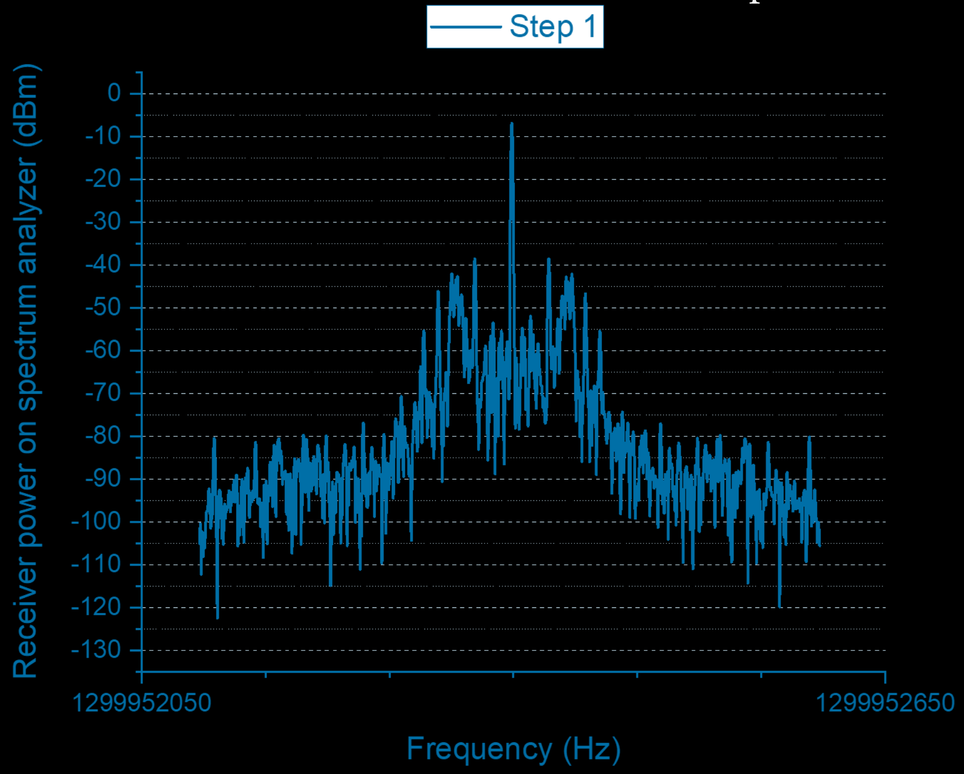
2019 Run pictures

Cavity frequency matching – Step 1



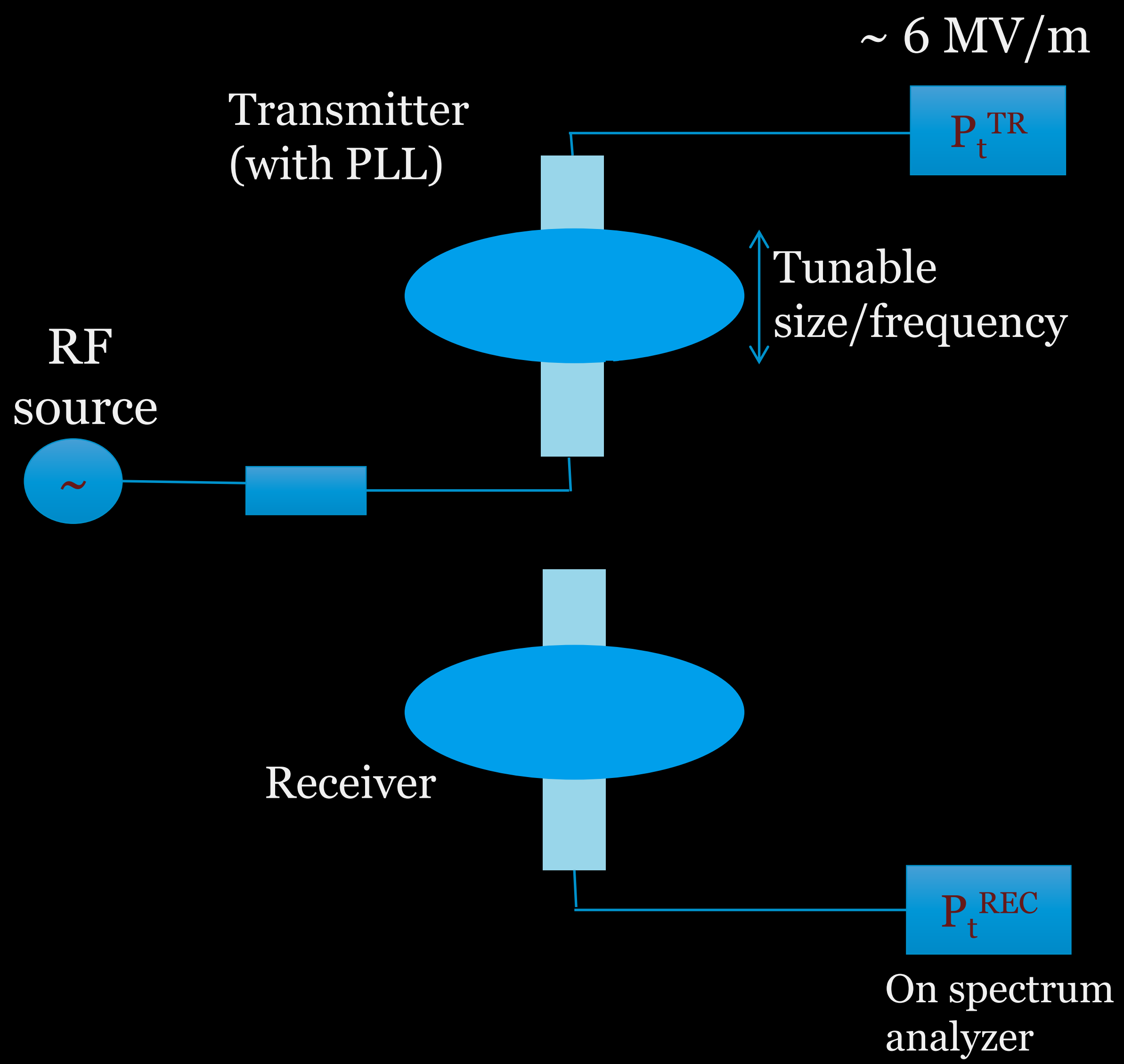


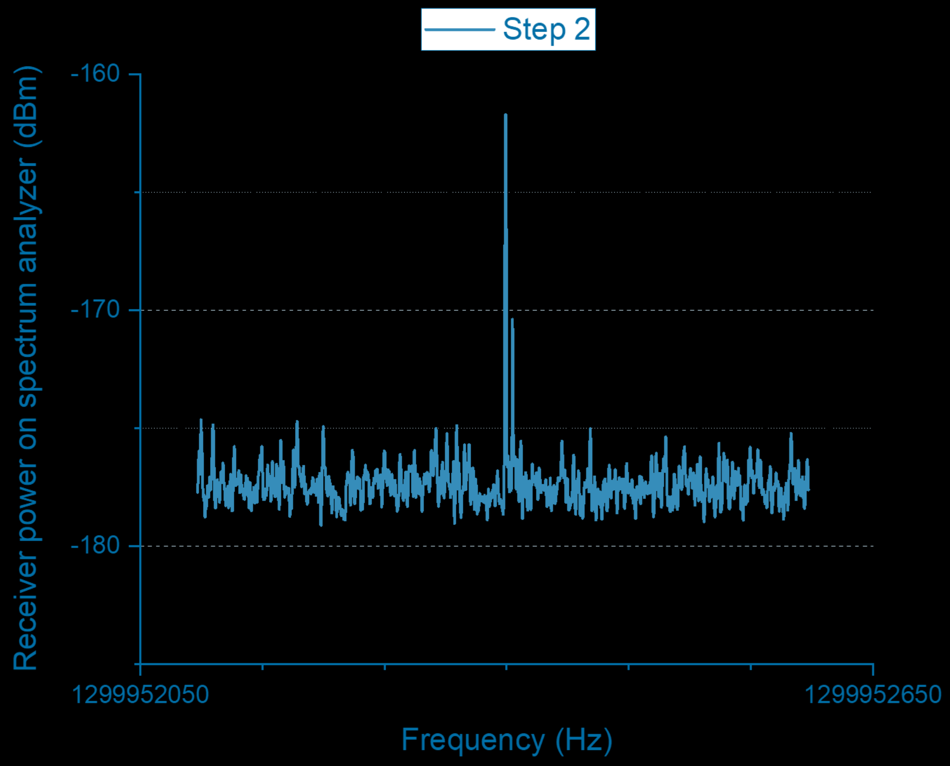
From now on, most measurement are shown in dBm (dB 10log(x), dBm=10log(x/mW).) Note that we are always in dB-space, 3dB = factor of 2 in linear space.



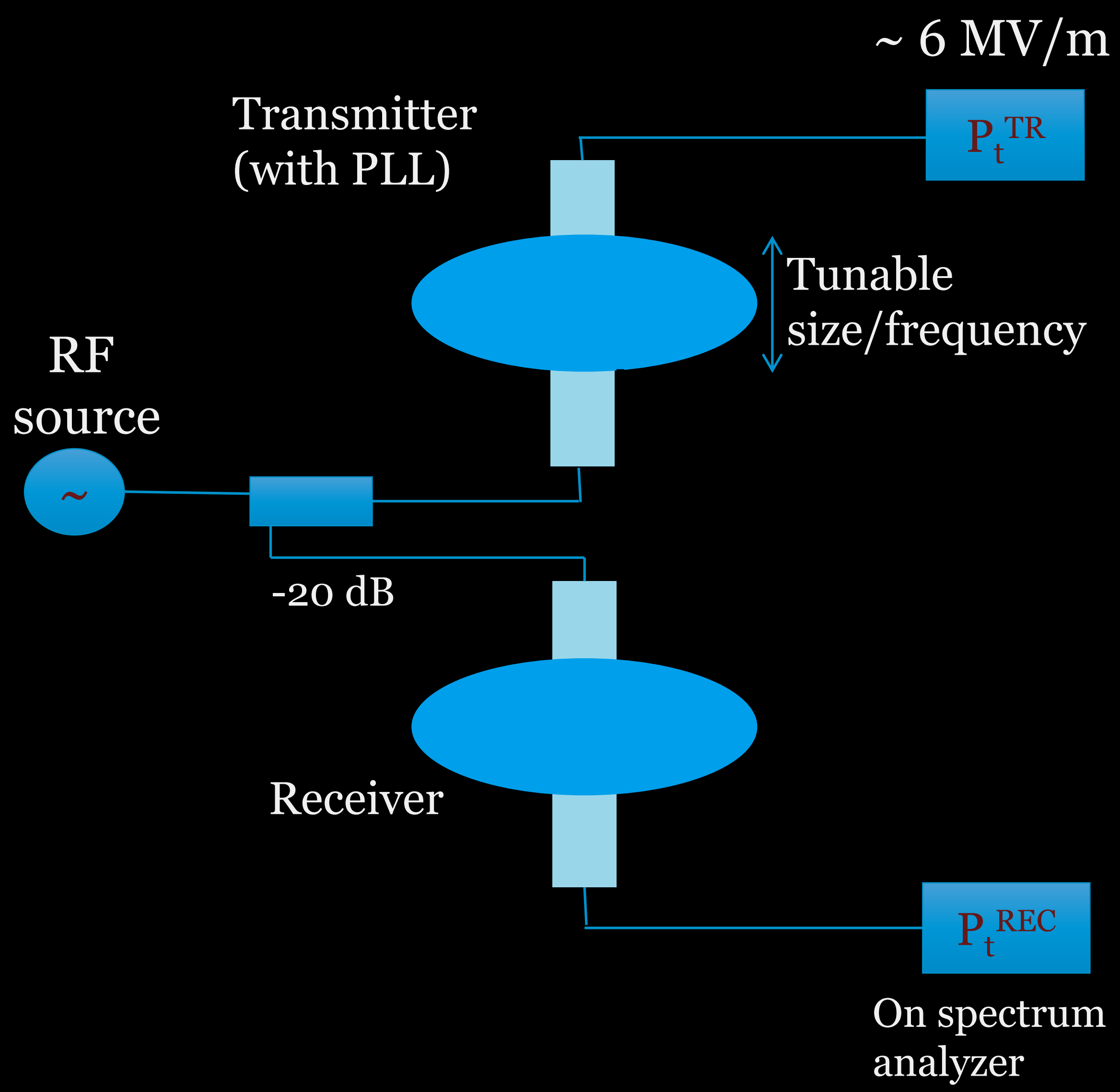
PLL (phase lock loop)

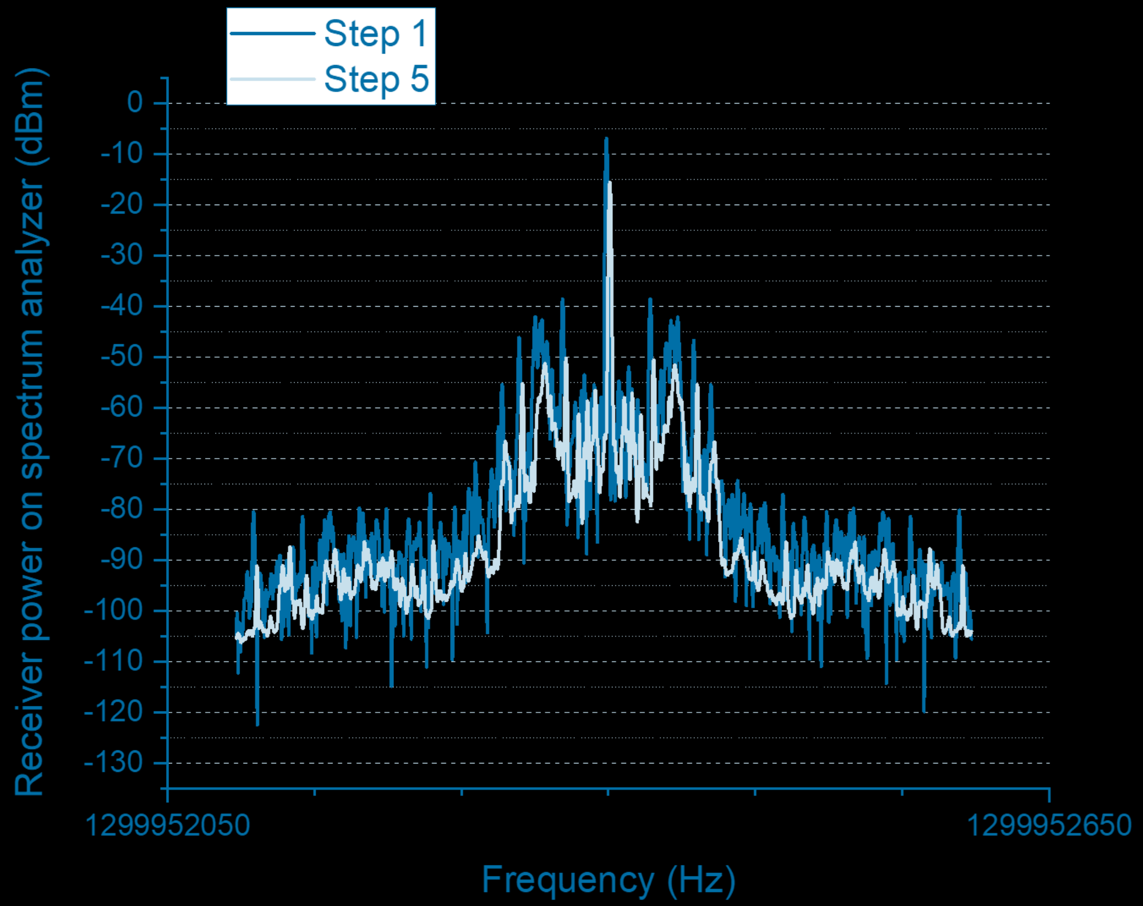
Dark Photon search! – (Step 2)





Back to Step 5 = Step 1 – all in tune



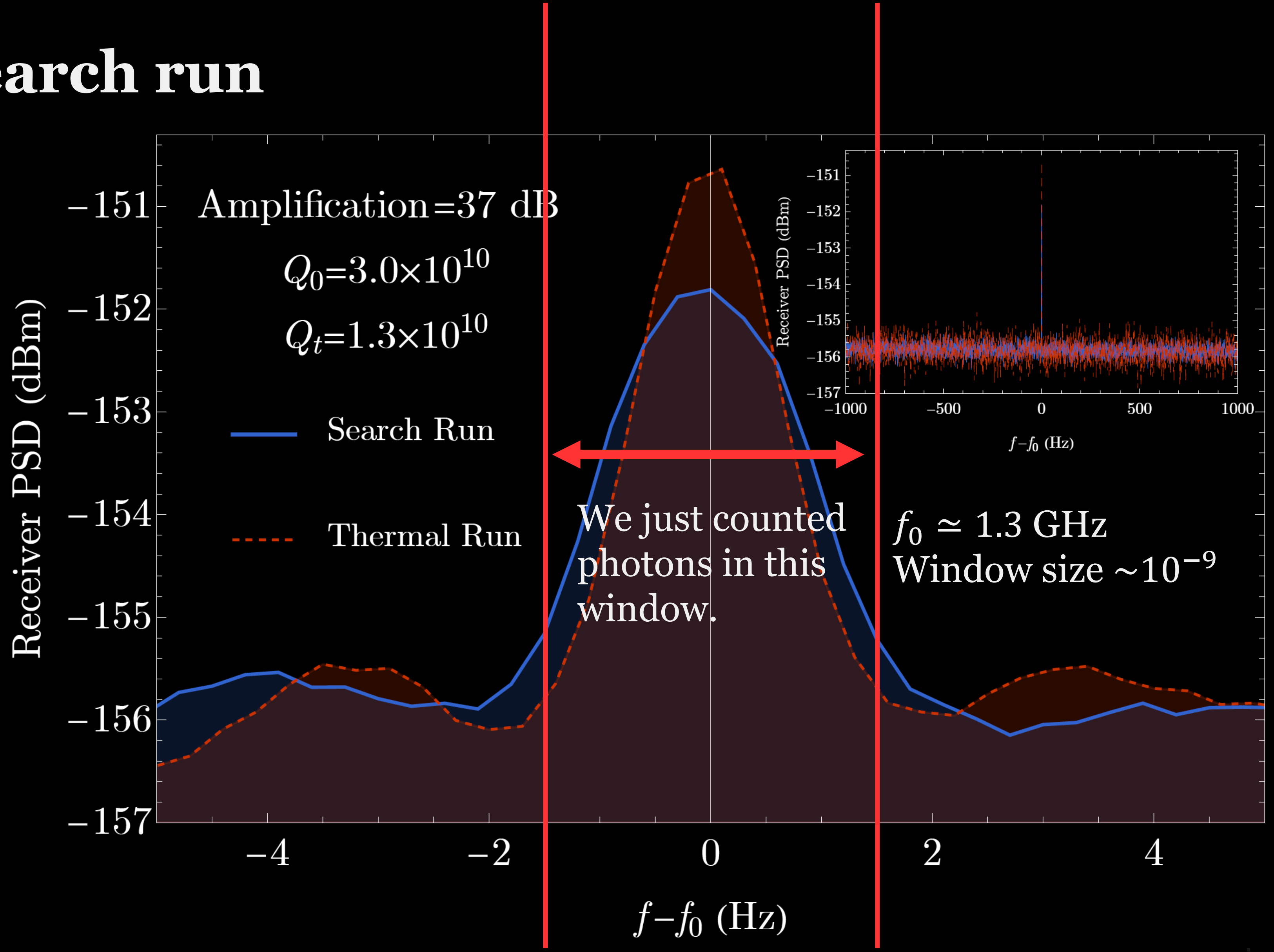


Measurements and Results

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

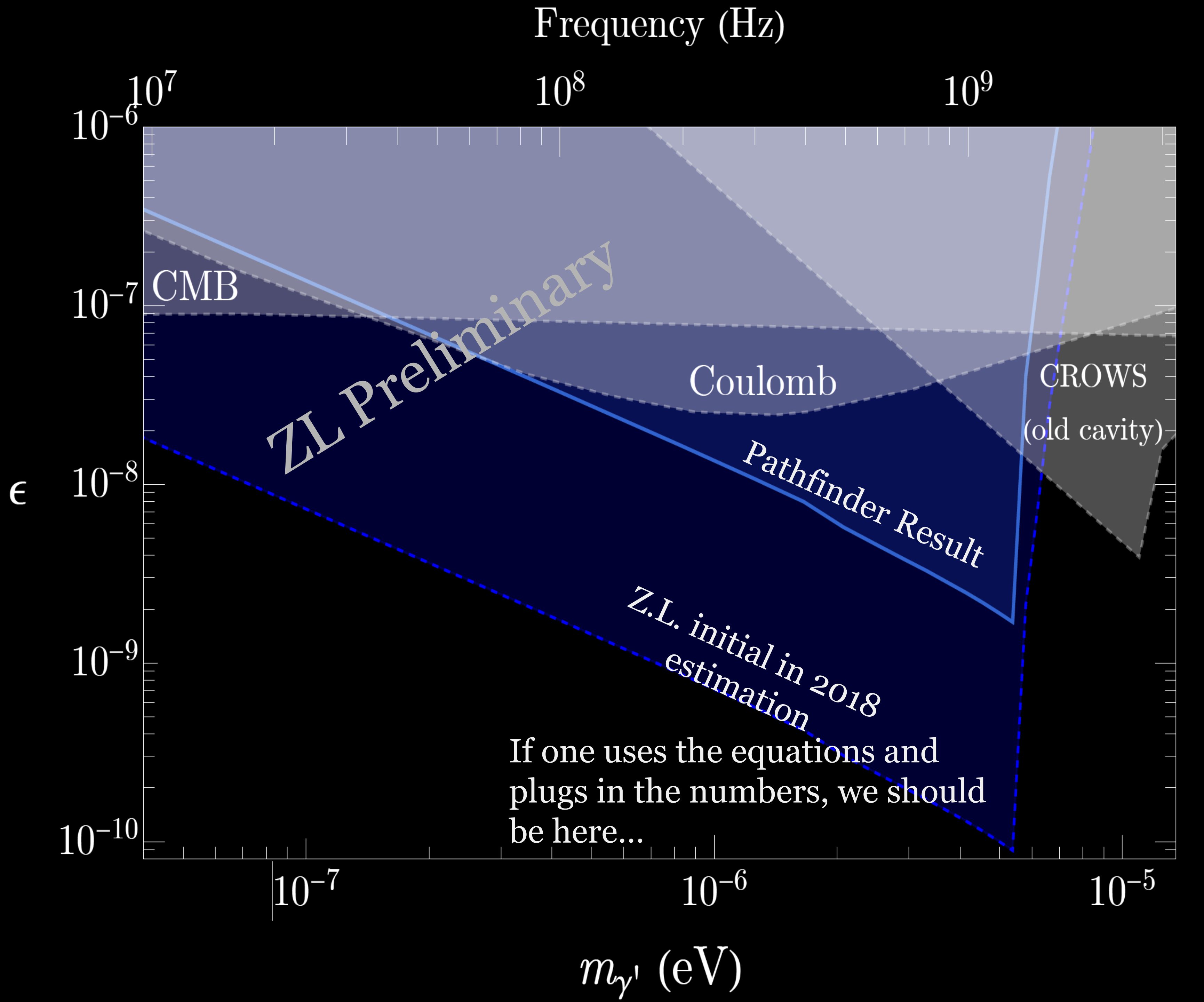
(uncertainty driven by the integration time)



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:

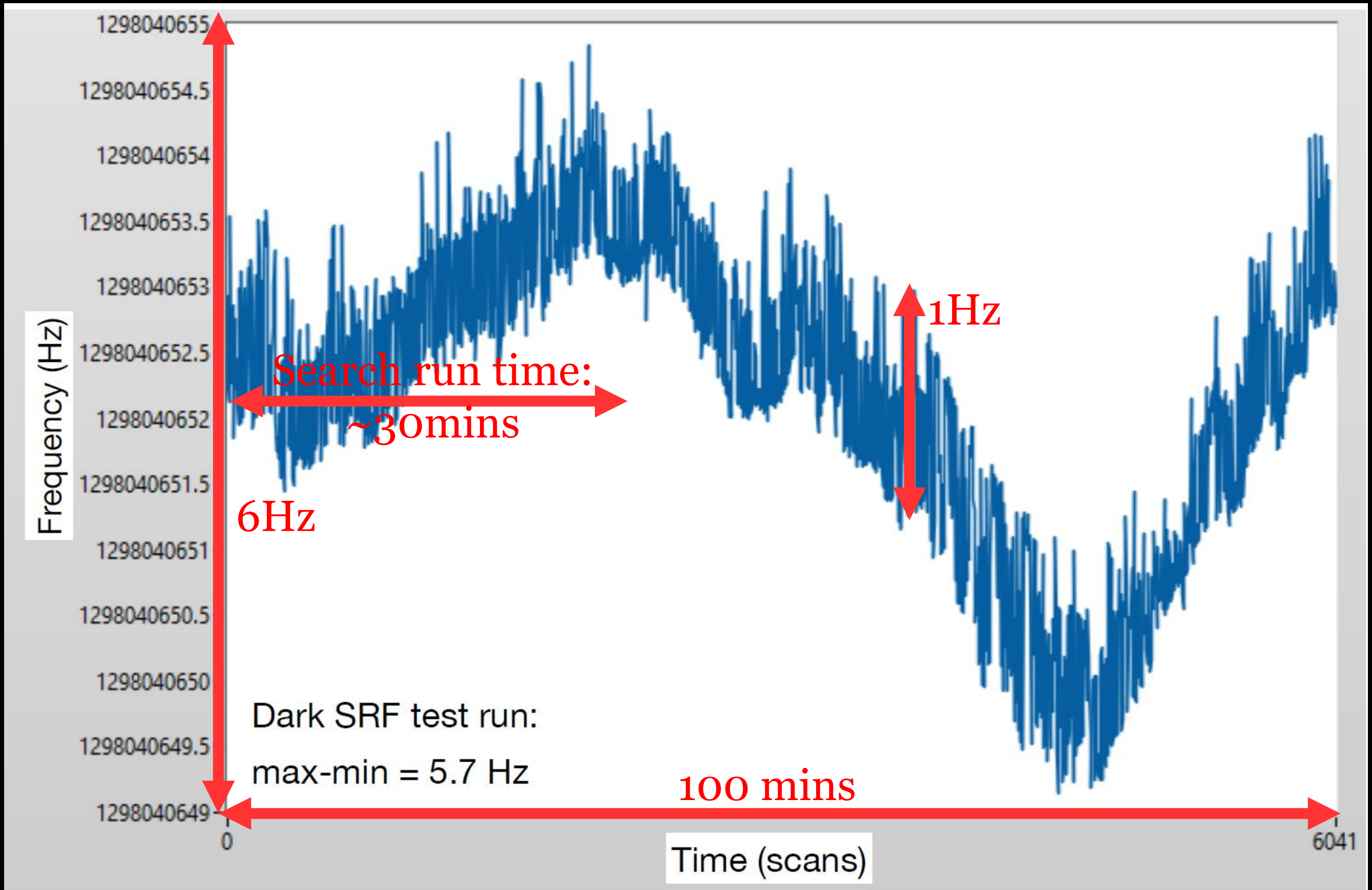
- High-Q is a double-sided sword
- Our pathfinder result did not benefit as Q^2 that we initially wanted
  - We are in a different limit that has not been explored before: $\frac{\omega}{Q} \ll \delta\omega$ (the sources I will highlight soon)
  - Post the end-of-2019 pathfinder search run, we had to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

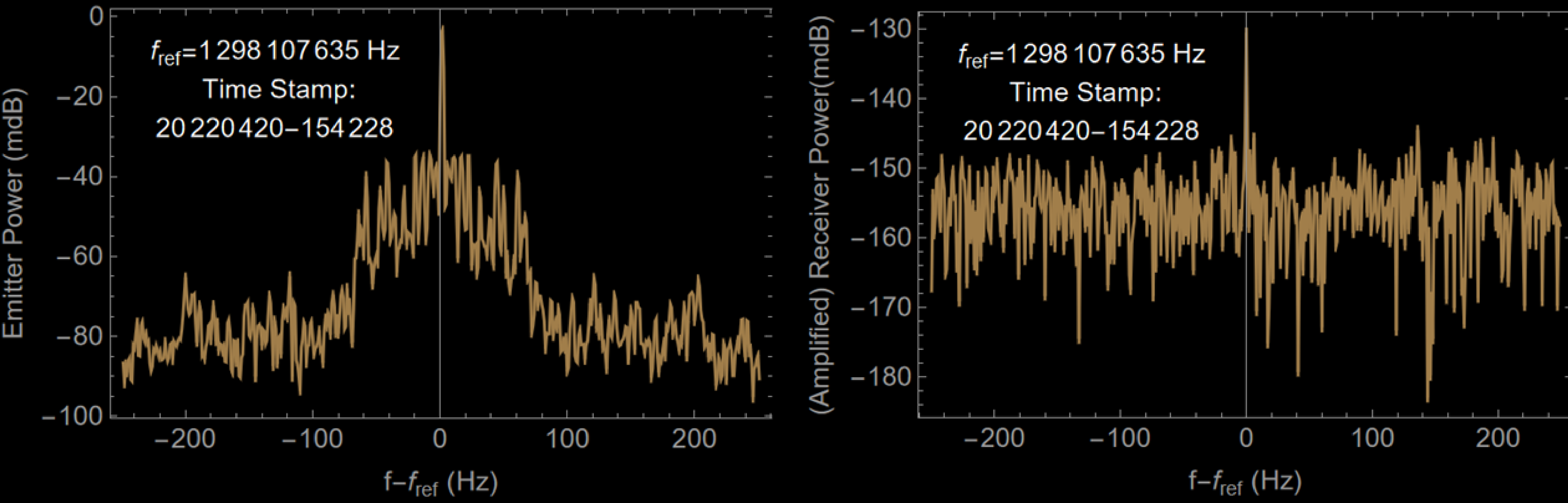


Dedicated frequency stability runs, two effects:

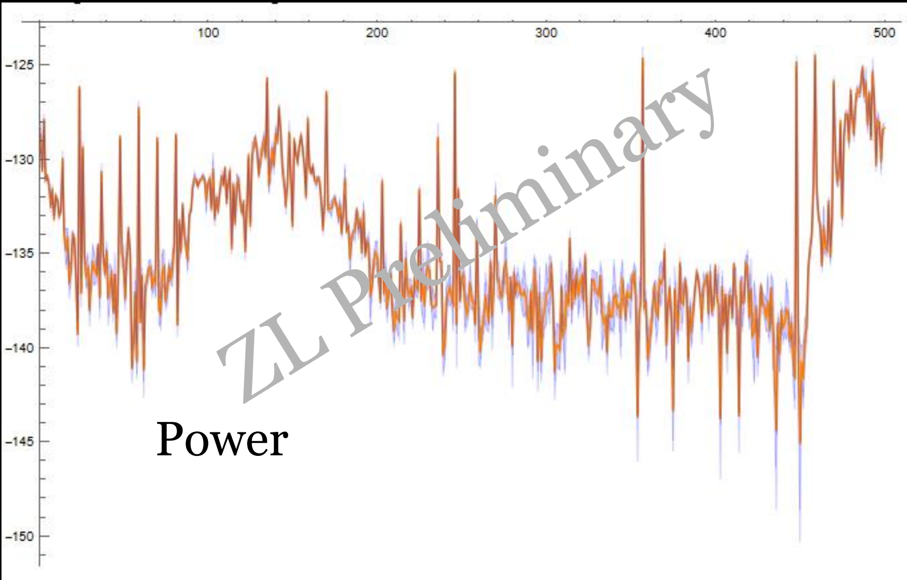
- Frequency drift
- Microphonics

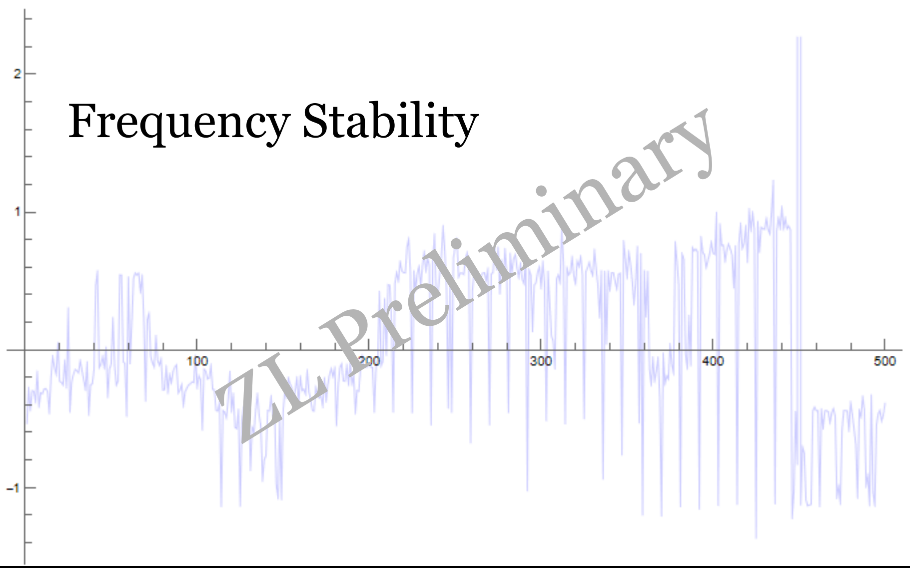
Parameter	Emitter	Receiver
Q_0	4.5×10^{10}	3.0×10^{10}
Q_{in}	1.8×10^{9}	4.5×10^{11}
Q_{t}	2.9×10^{11}	1.3×10^{10}
freq. drift	5.7 Hz	3.0 Hz
microphonics	3.1 Hz	3.1 Hz

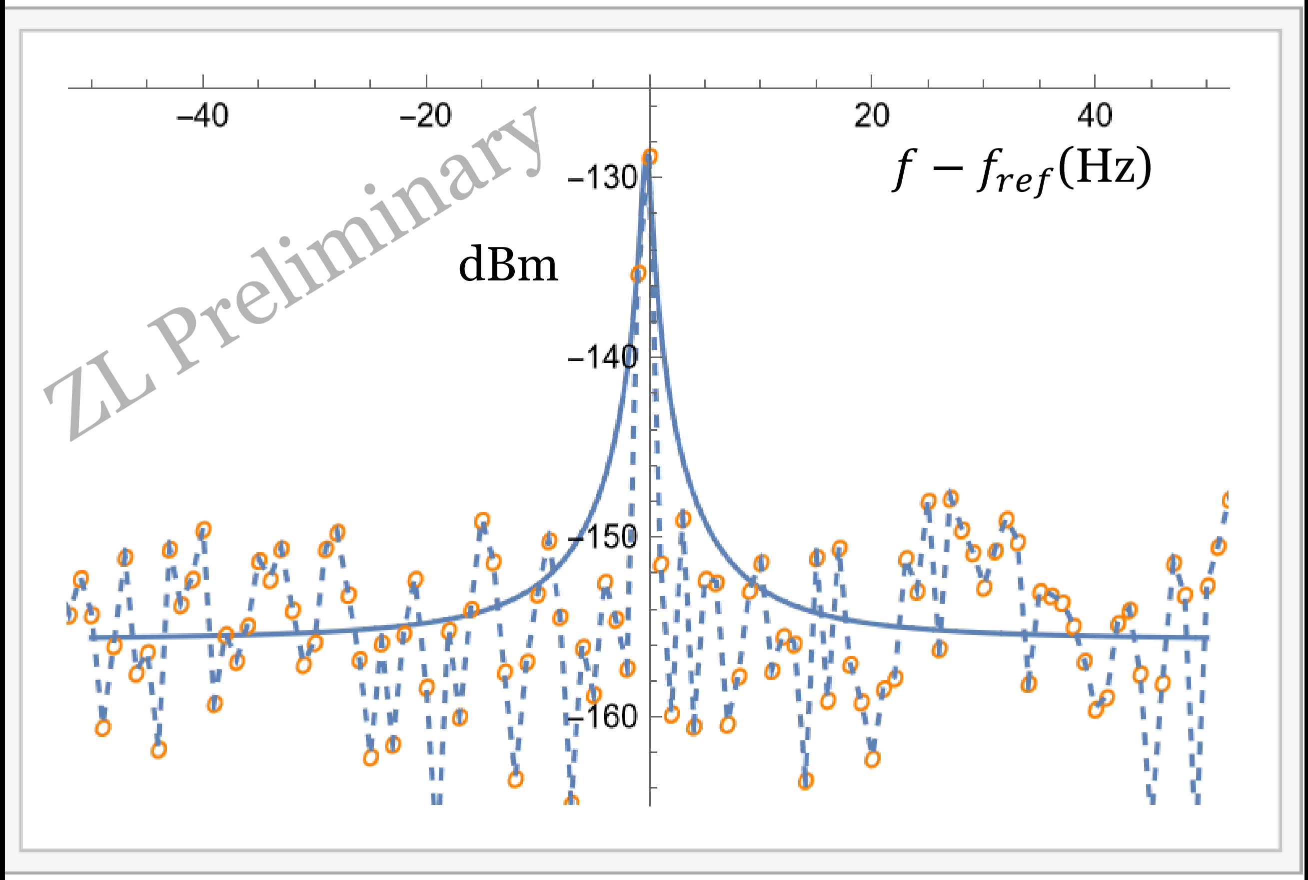
The PSD of the Emitter and Receiver at a given moment



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





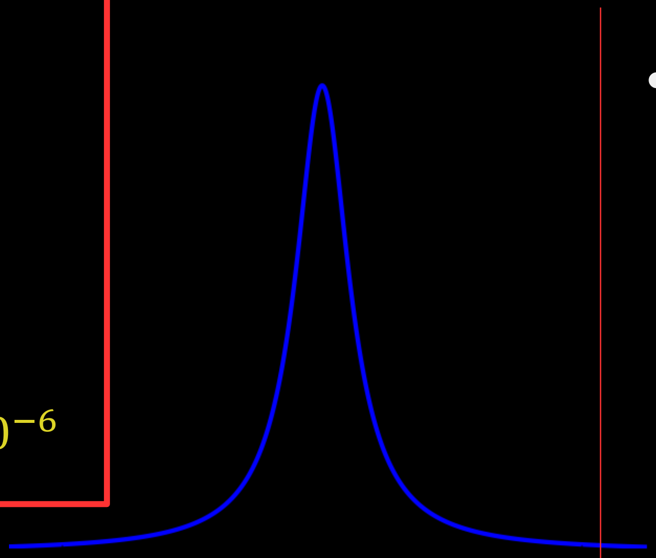


We presented a very conservative limit

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

$$|G|^2 \to \frac{\omega^2}{\omega^2 + 4\delta_\omega^2 Q_{\rm rec}^2}|G|^2$$

$$\frac{\omega^2}{\omega^2 + 4\delta_\omega^2 Q_{rec}^2} \to \frac{\left(\frac{\omega}{Q_{rec}}\right)^2}{\left(\frac{\omega}{Q_{rec}}\right)^2 + 4\delta_\omega^2} \to \frac{(\sim 0.04\ Hz)^2}{(\sim 16\ Hz)^2} \to 7 \times 10^{-6}$$

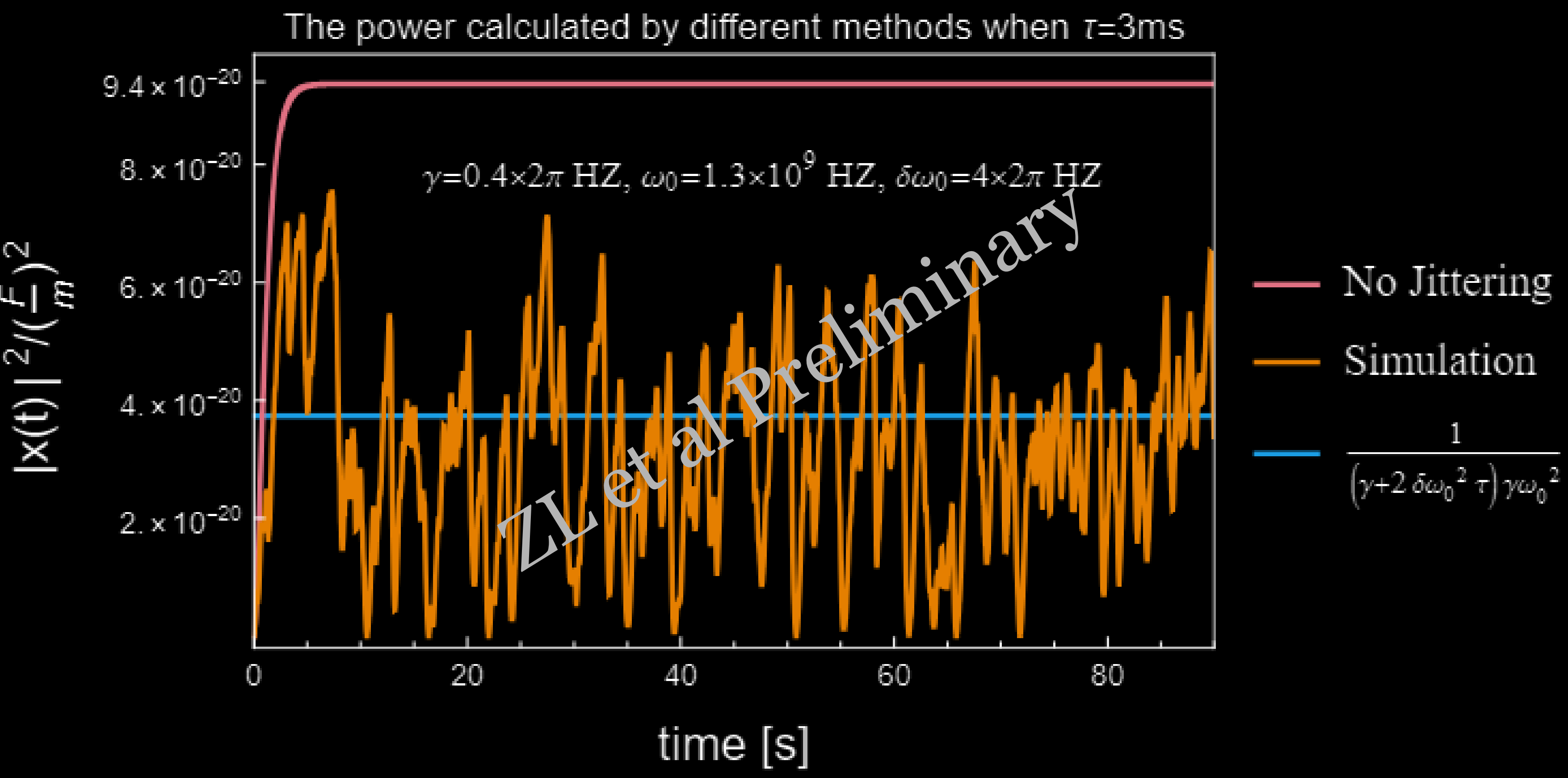


Essentially, modeled as searching off-resonance.

- 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.)

Modeling Microphonics

H. Cui, S. Henrich, S. Kalia, ZL, finalizing.

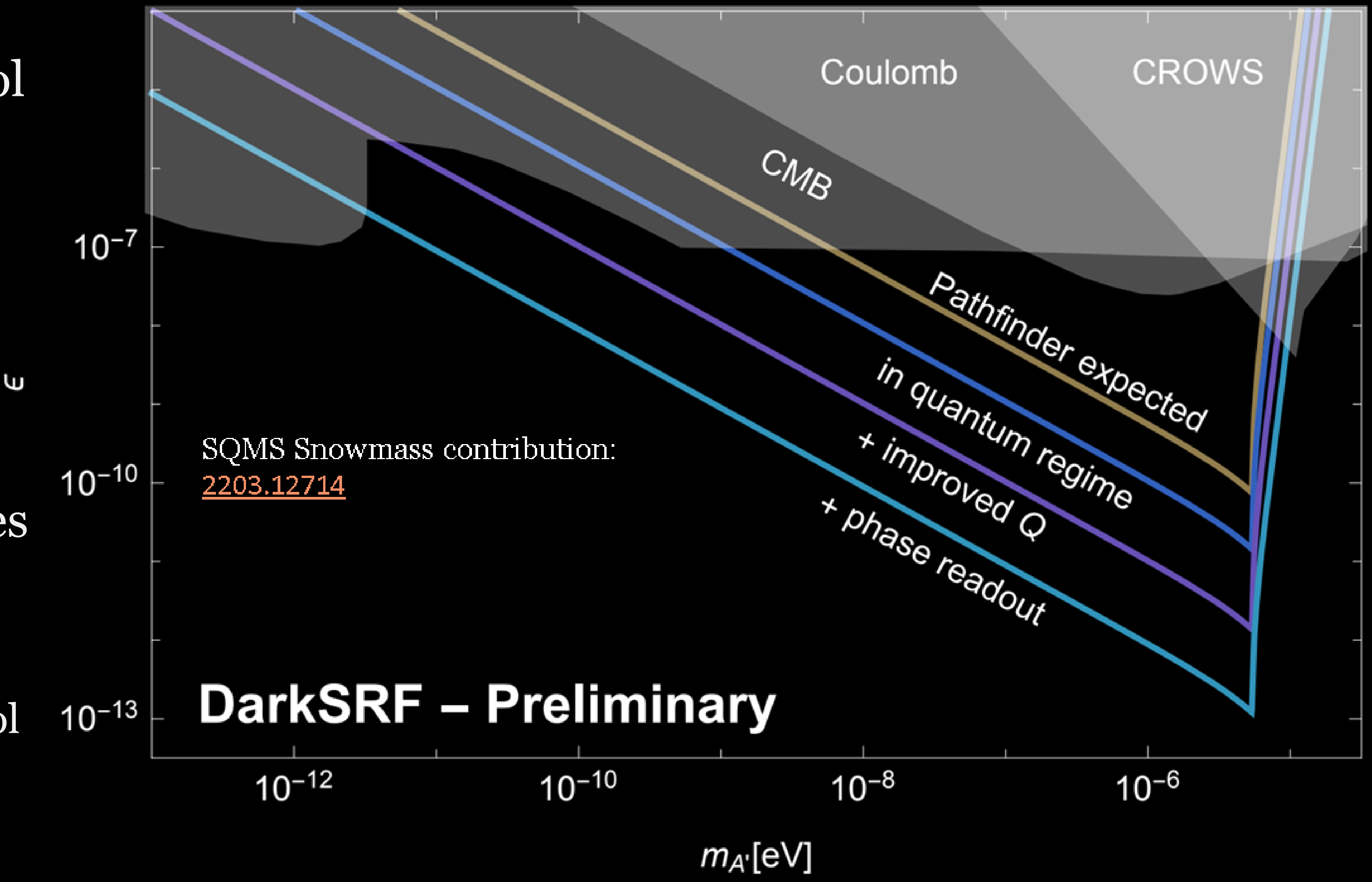


When one controls the drifting effect (either use stiffer receiver cavity or realign the frequency every few mins), the dominant effect is microphonics.

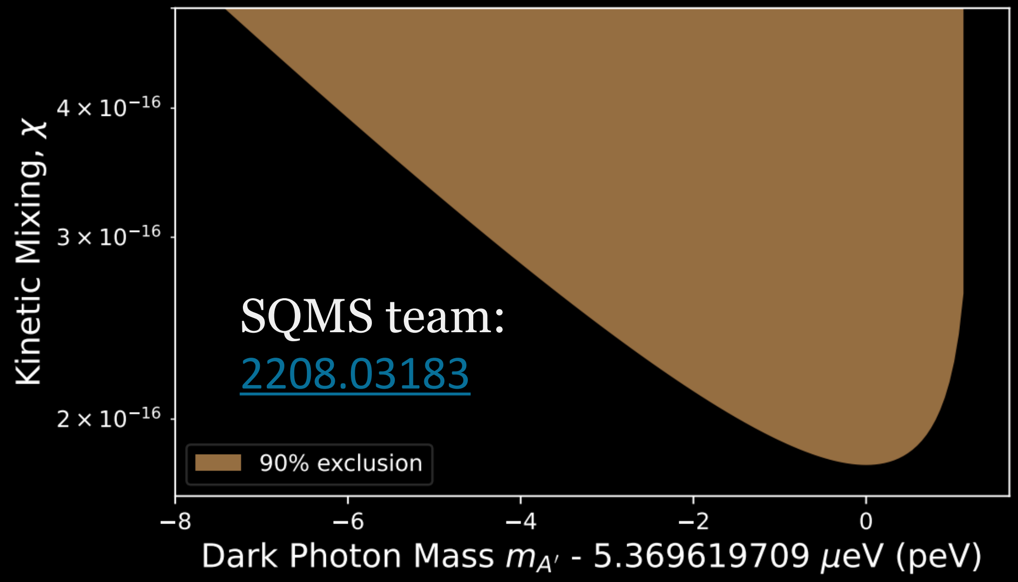
Our proper modeling show that it impact on SNR is about 40% suppression instead of 10^-5 suppression, restoring my original estimation but with needed search protocol updates.

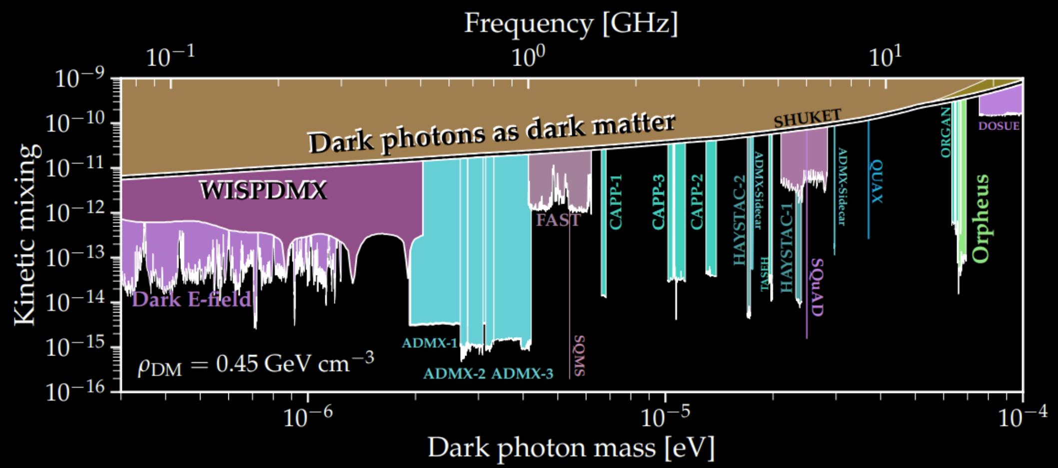
Near (or far?) Future

- 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

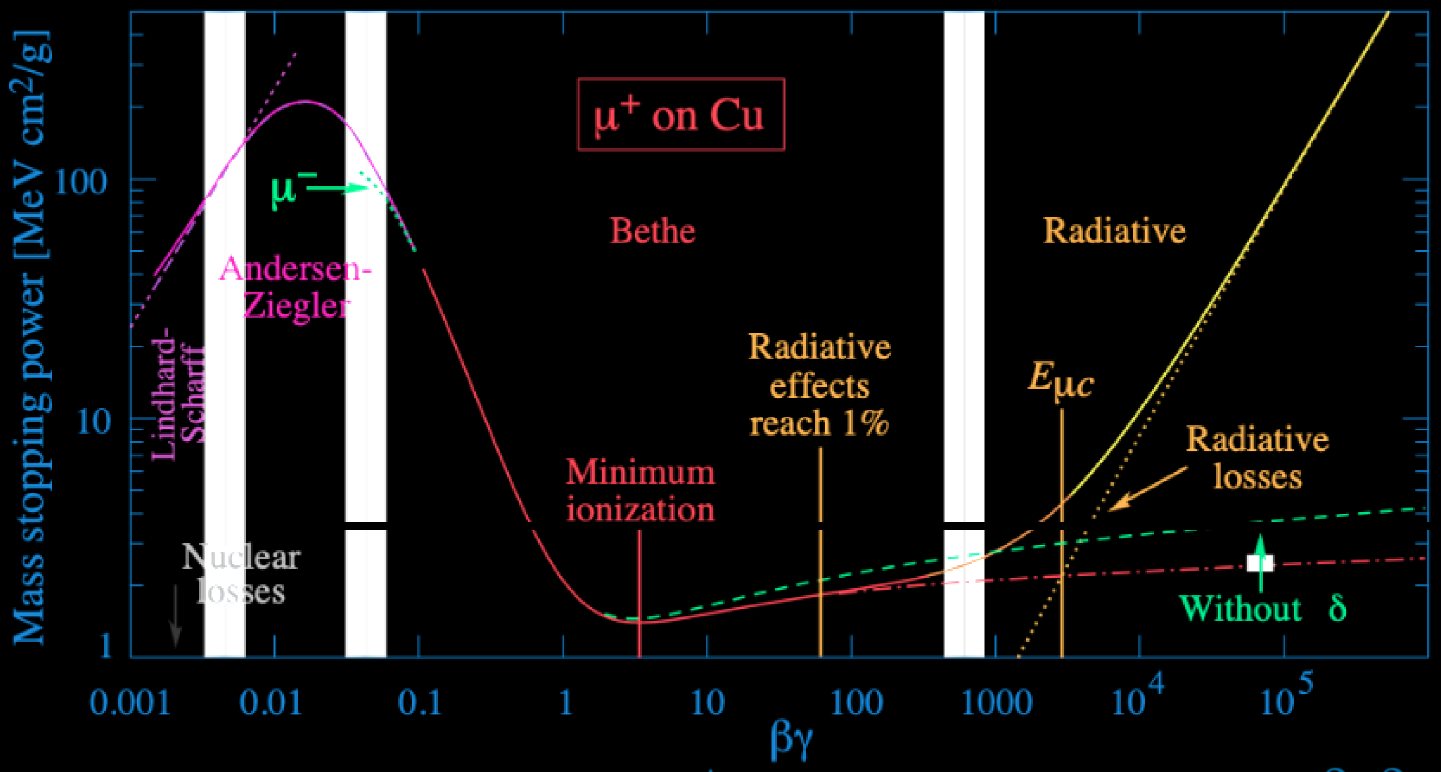
Outlook

- 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 LSW 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;

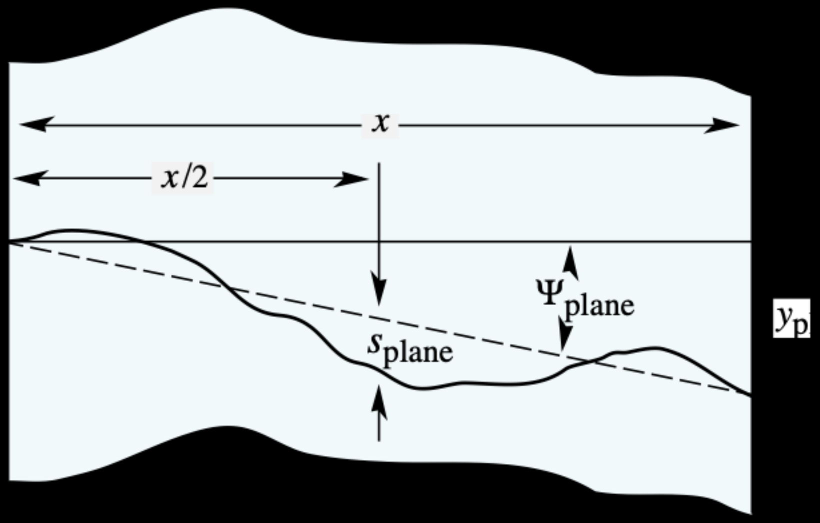
Thank you!

(Milli)Charges through Matter

average energy loss



angular deflection



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

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

Matter Effects

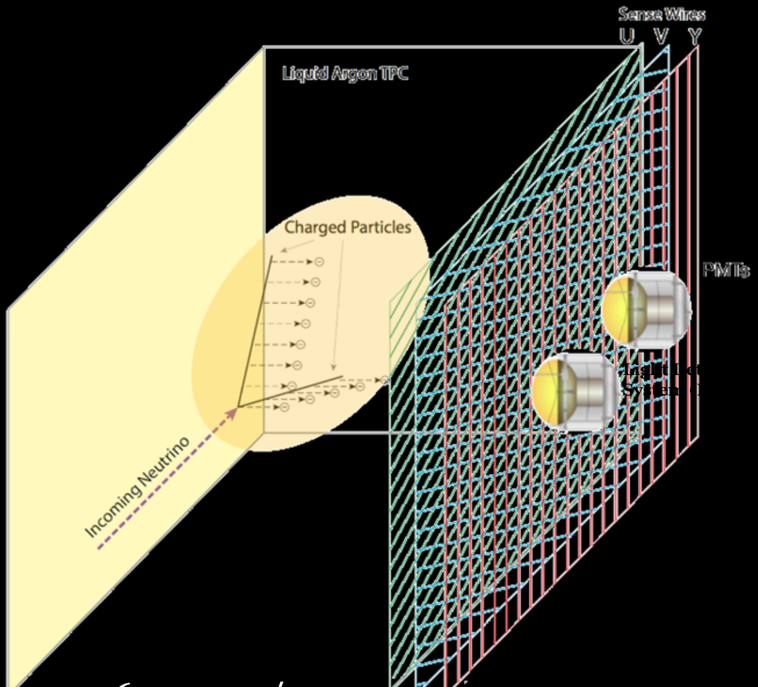
- En route to a detector, mCPs travel through ~240 meters of dirt.
- Energy loss is negligible in region of interest.
- A random walk of soft scatterings (off nuclei) leads to small **angular deflection**

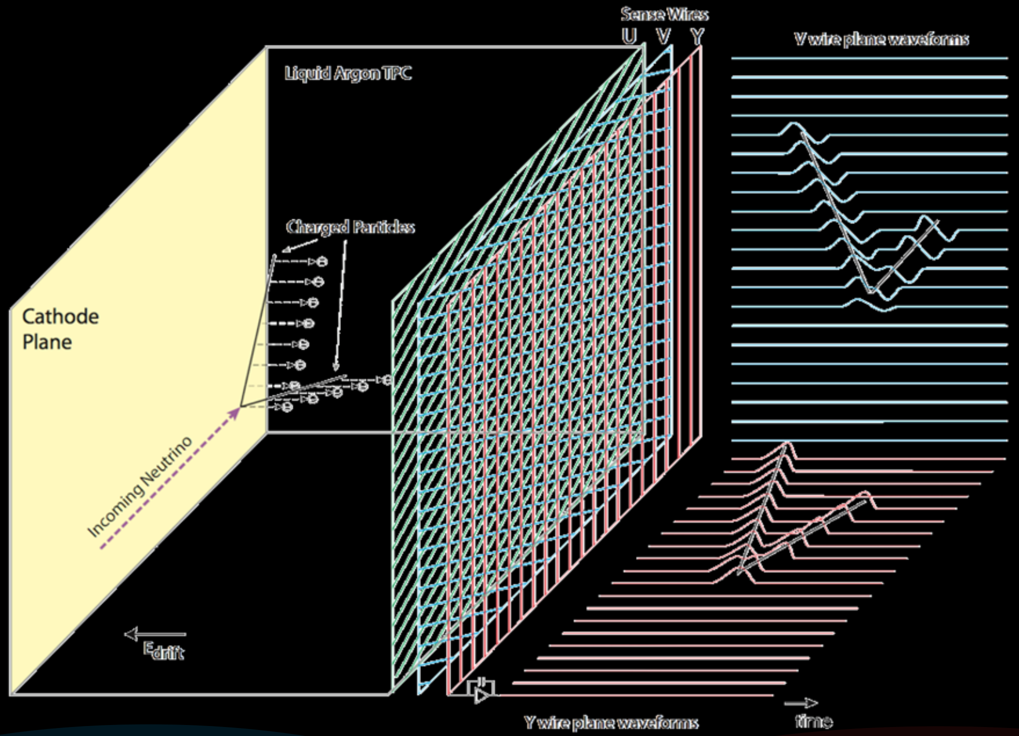
$$\Delta\theta_\chi \sim \langle\theta_\chi\rangle\sqrt{N_{\rm col}}$$ = average deflection per collision. × sqrt # of collisions.

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

The mCPs point back to the target.

LArTPC at work





m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

Charged particles in LAr produce free ionization electrons and scintillation light

Ionization charge drifts in a uniform electric field towards the readout wire-planes

Digitized signals from the wires are collected [time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge]

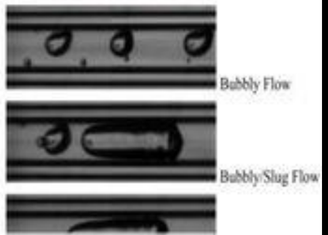
Electron drift time ~ ms

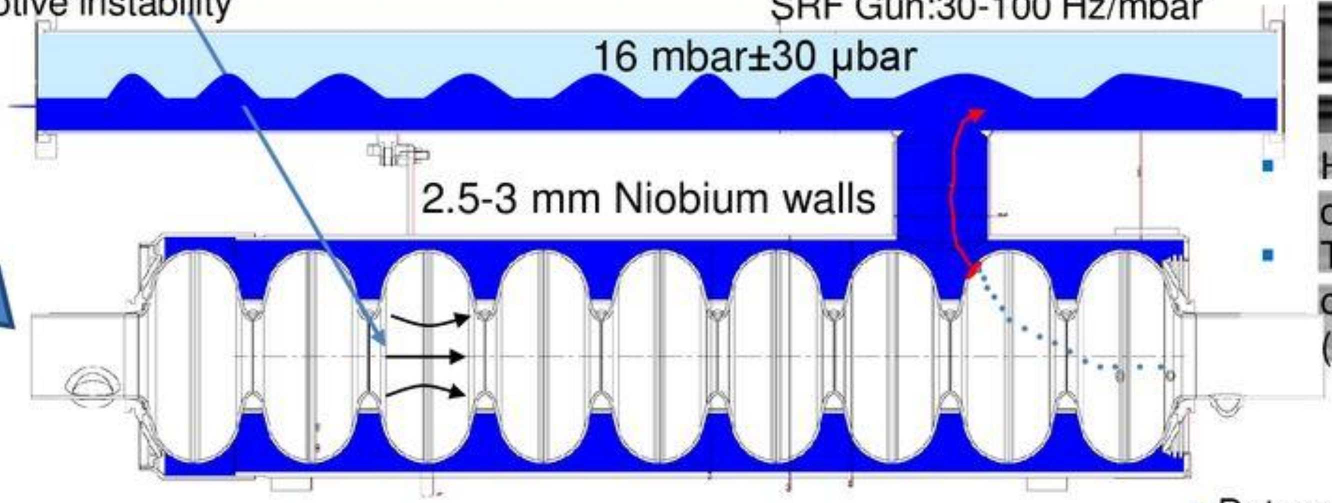
Scintillation light fast signals from LDSs give event timing

Microphonics: How does it appear?

HZB Helmholtz Zentrum Berlin

- Field amplitude variation:
  Dynamic Lorentz force, $\Delta f/\Delta E_{acc}^2 = 1 Hz/(MV/m)^2$
  → Ponderomotive instability
- Helium pressure fluctuations
  $\Delta f/\Delta p$ = 50-60 Hz/mbar,
  SRF Gun:30-100 Hz/mbar

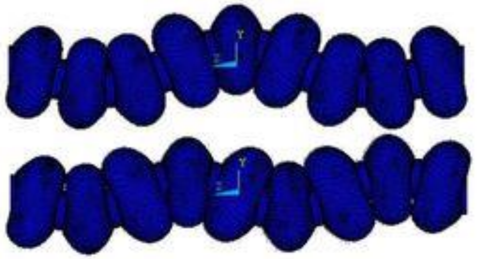




- Heat transport dynamics in LHe
- Thermo-acoustic oscillations (cryo valves…)
- Stochastic background noise
- Deterministic, narrow-band sources: Vacuum pumps

Mechanical oscillations of the Cavity: Microphonics

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



222 Hz

G. Bissofi

151 Hz

Lowest modes: Transverse

Is that the whole story?

G.P. Gelata et al. International Journal of Thermal Sciences Volume 58, August 2012, Pages 1-8

Particle Physics-Astrophysics-Cosmology Webinar (PAC Webinar-51)

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 |

PASSCOED: 001690

南京师范大学理论物理研究所
彭桓武科教合作中心
天体物理与前沿物理交叉中心