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Non-WIMP dark matter

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IFT2019
future collider program
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Mass scale of dark matter

(not to scale)

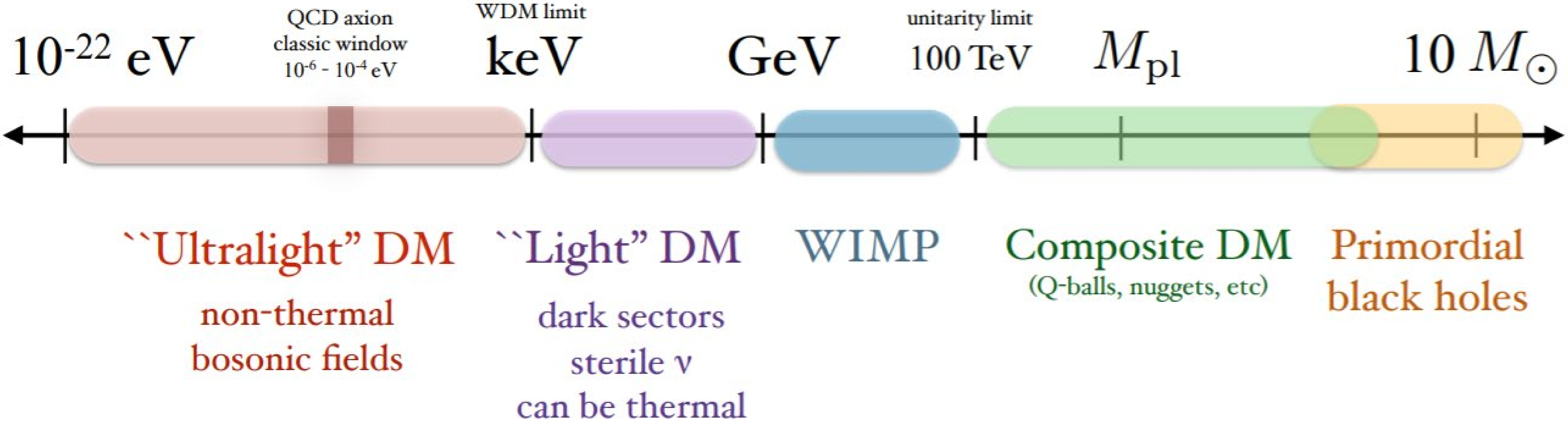
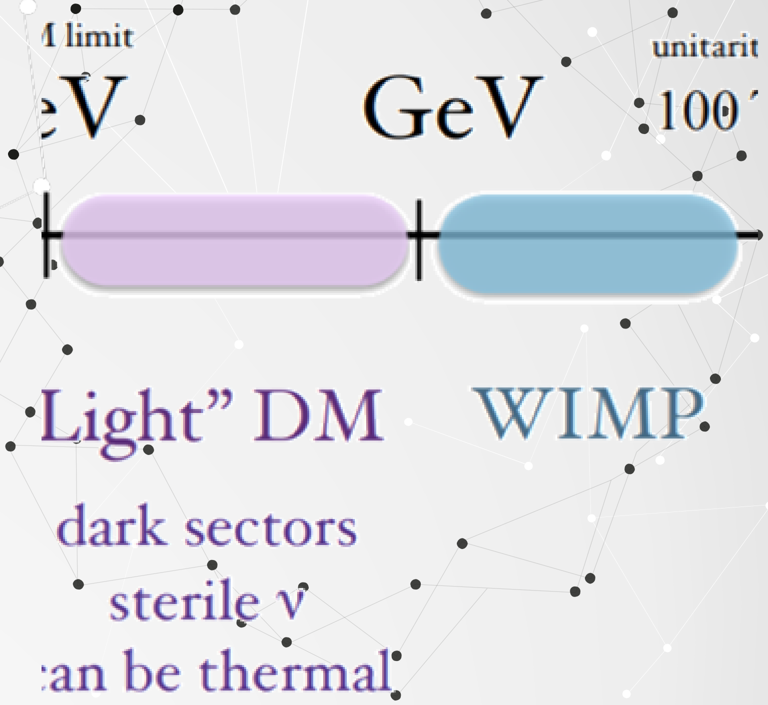


Fig. credit: Tongyan Lin 1904.07915

Light Dark Matter

Moving beyond WIMPs, the <u>broad</u> vicinity of the weak scale is still an excellent place to focus on:

- **An important scale!**
- **Familiar stable matter resides here!**
- **Thermal DM works well here!**



Many light DM overview discussion from G. Krnjaic

Q: What's so great about equilibrium?

A: Generic and easy to achieve

Compare interaction rate to Hubble expansion

$$\mathcal{L}_{\rm eff} = \frac{g^2}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f)$$

$$H \sim n\sigma v \quad \Longrightarrow \quad \frac{T^2}{m_{Pl}} \sim \frac{g^2 T^5}{\Lambda^4}\bigg|_{T=m_\chi}$$

Equilibrium is reached in the early universe if

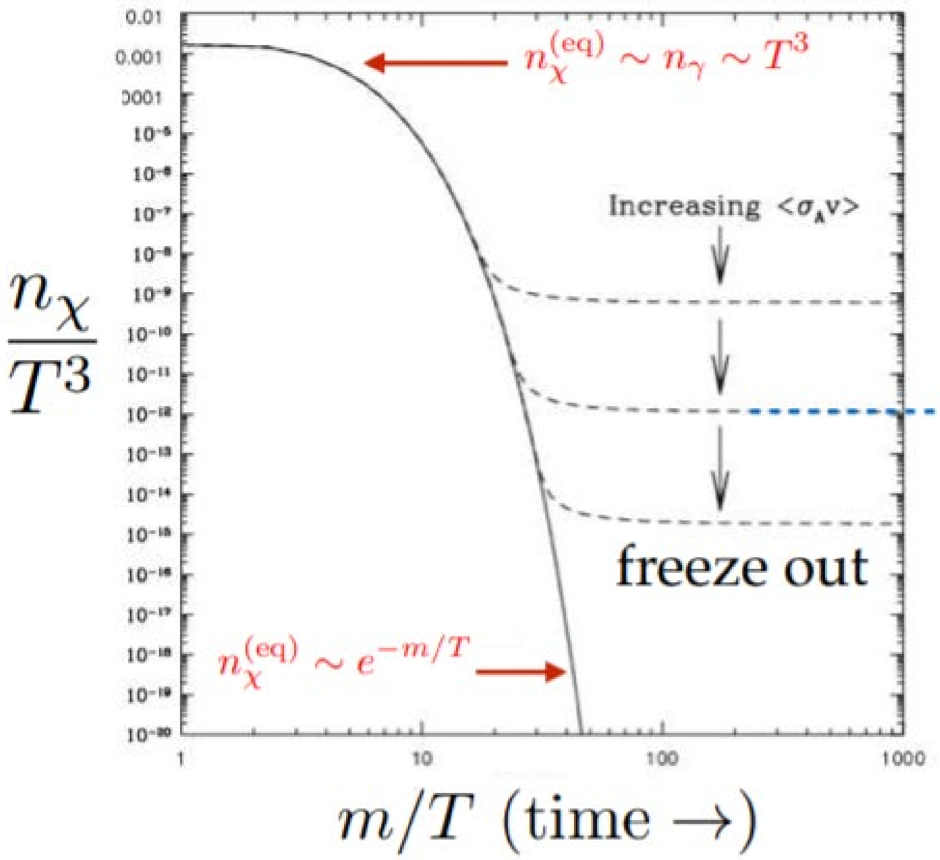
$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}$$

Nearly all testable models feature equilibrium at early times

Q: What's so great about equilibrium?

A: Minimum annihilation rate

$$n_\chi^{(\mathrm{eq})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \propto \begin{cases} T^3 & (T \gg m) \\ e^{-m/T} & (T \ll m) \end{cases}$$



Observed density requires

$$\sigma v > 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

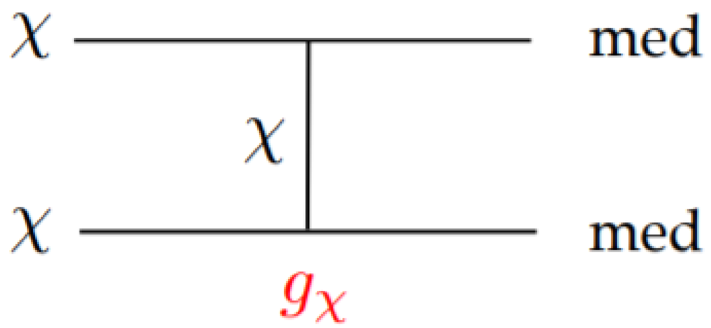
However, minimum target in all equilibrium scenarios

… asymmetric DM
… coannihilating DM

Who's Heavier: DM or Mediator?

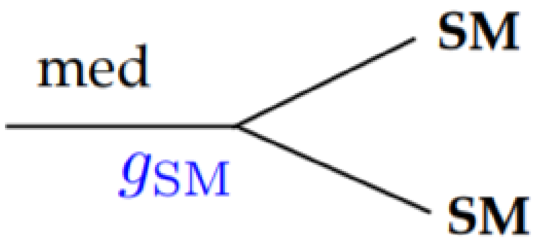
Secluded Annihilation

$m_\chi > m_{\rm med}$



No clear experimental target

Abundance set by g_χ

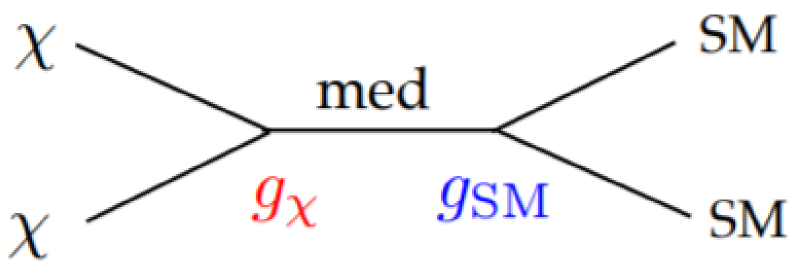


Mediator decays **visibly**

Motivates hidden force searches

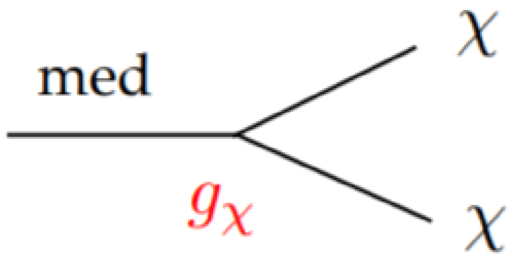
Direct Annihilation

$m_\chi < m_{\rm med}$



Predictive thermal targets

Abundance depends on $g_{\rm SM}$



Mediator decays **invisibly***

Motivates missing energy probes

Neutrality and Renormalizability require "portal" interactions

$\epsilon\,\phi H^\dagger H$ → **Scalar ϕ mixes with Higgs after EWSB**

Couples to SM **masses** $\epsilon\phi\frac{m_f}{v}\bar{f}f$

$\epsilon\,F'_{\mu\nu}F^{\mu\nu}$ → **Dark photon A' mixes with SM photon**

Couples to **EM** current $\epsilon A'_\mu J^\mu_{\rm EM}$

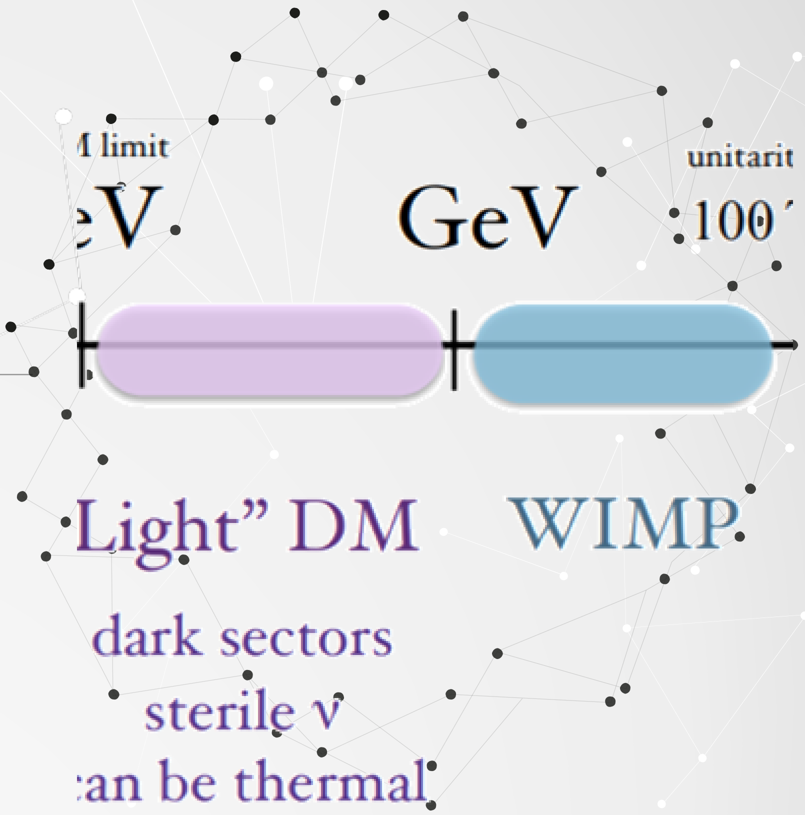
$\epsilon\,V_\mu J^\mu_{\rm SM}$ → **Vector V directly couples to DM & SM**

Couples to **different** current $J^\mu_{\rm SM}$

Anomaly free options $B-L\ ,\ L_i-L_j\ ,\ B-3L_i$

Vector models all similar, but also couple to neutrinos

Kinetic mixing portal

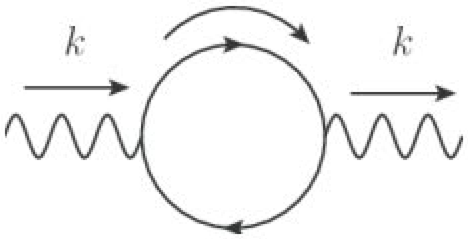


Holdom
Galison, Manohar

Millicharged particles (motivation)

$\mathcal{L} =$ a particle with charge ε.

heavy particles charged under both.



$\varepsilon F_{\mu\nu} F'^{\mu\nu}$

Our $U(1)_{EM}$ + our matter

another massless $U(1)'$ + matter'

Holdom
Galison, Manohar

Millicharged particles (motivation)

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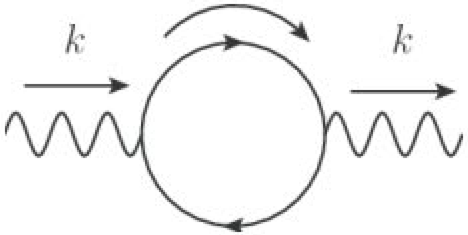


$\varepsilon F_{\mu\nu} F'^{\mu\nu}$

Our $U(1)_{EM}$

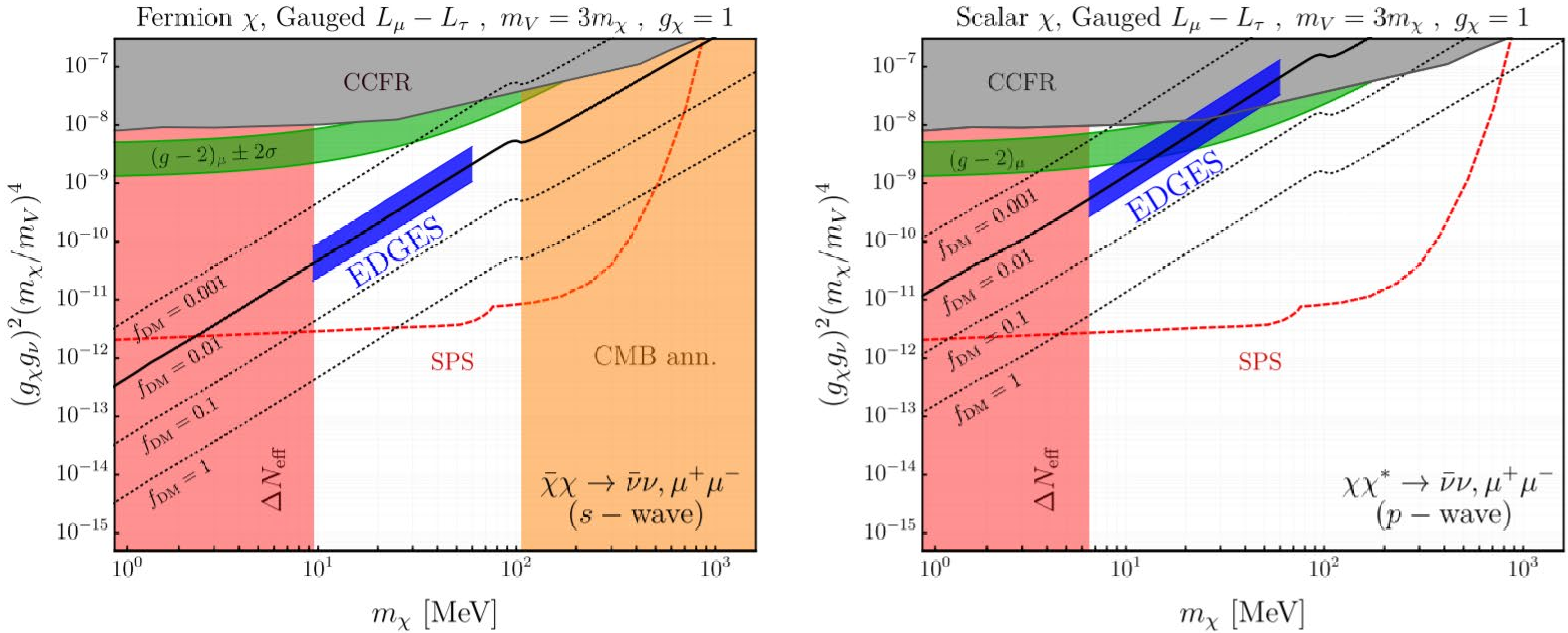
+ our matter

After we diagonalized everything, matter ' picks up a charge of ε under our EM.

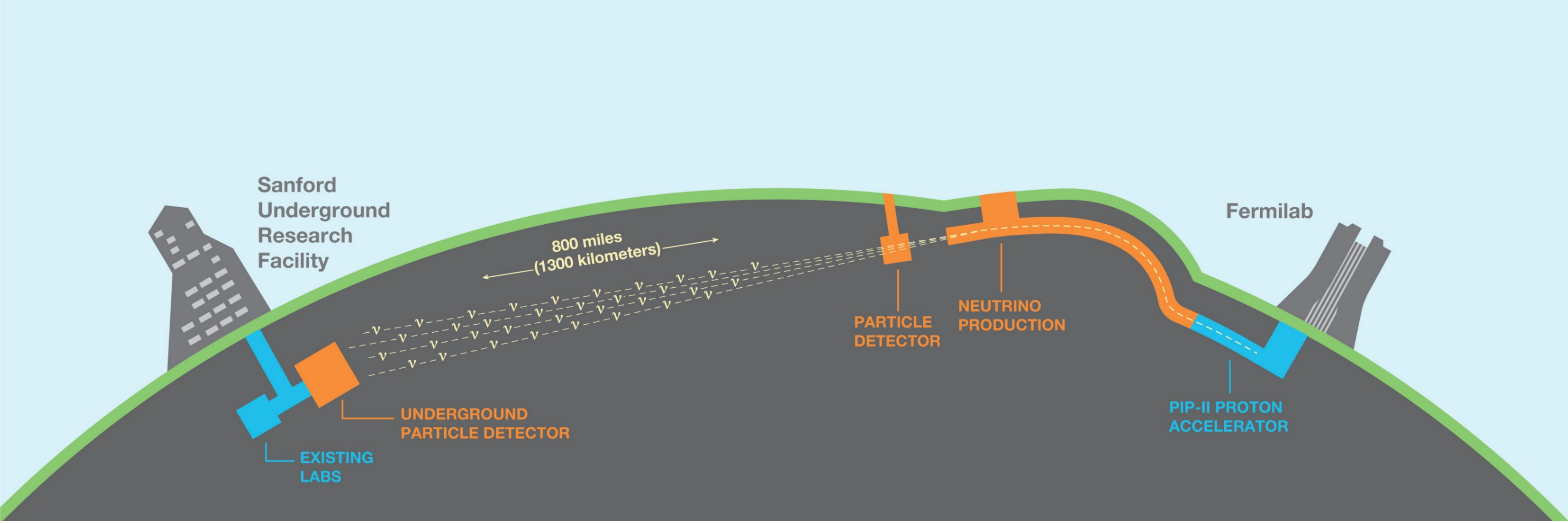
Holdom
Galison, Manohar

Millicharged particles (motivation)

$\mathcal{L} =$ a particle with charge ε.



Neutrino experiments→ High quality beamdump experiments
E.g., NuMI beam: good source for Millicharged particles



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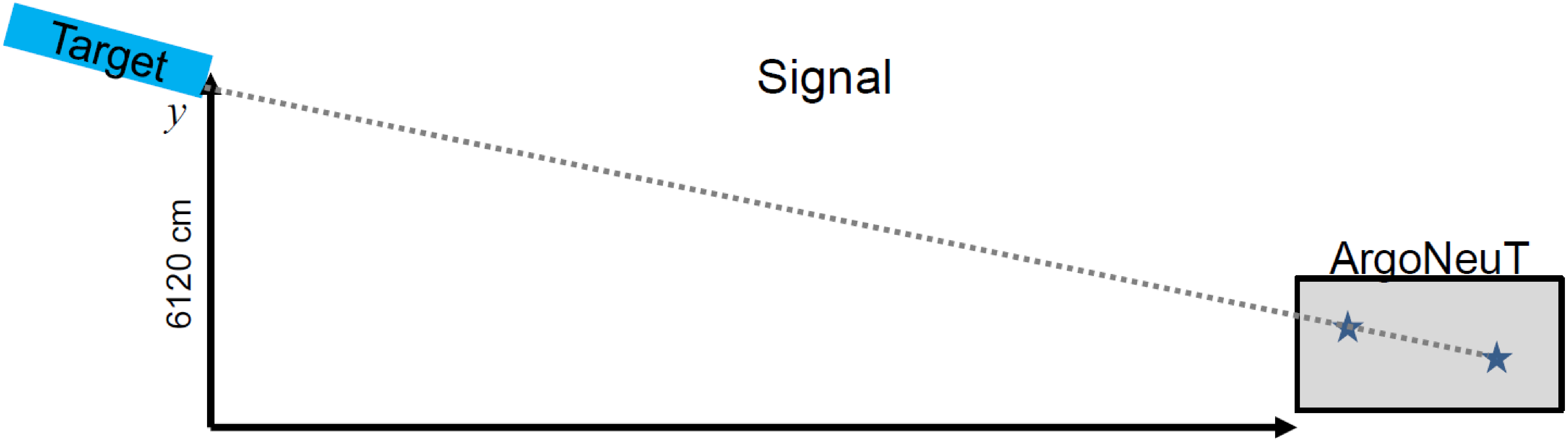
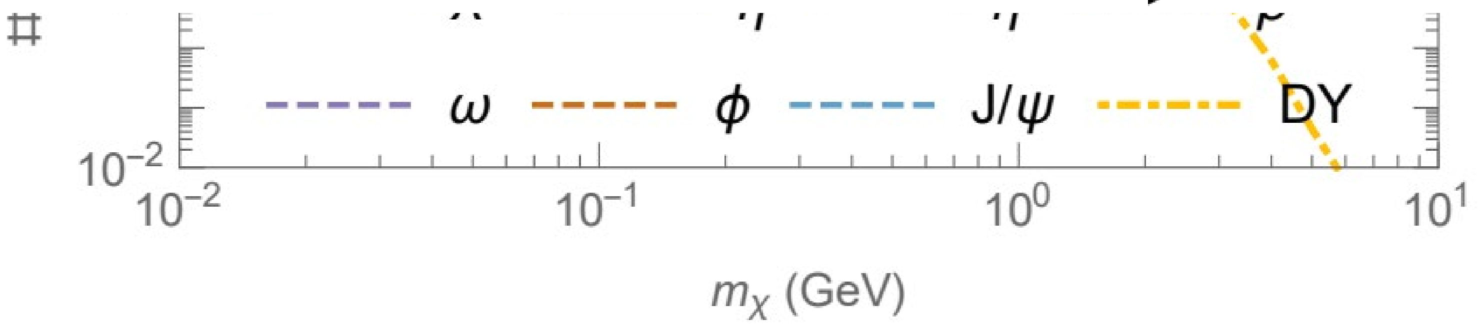
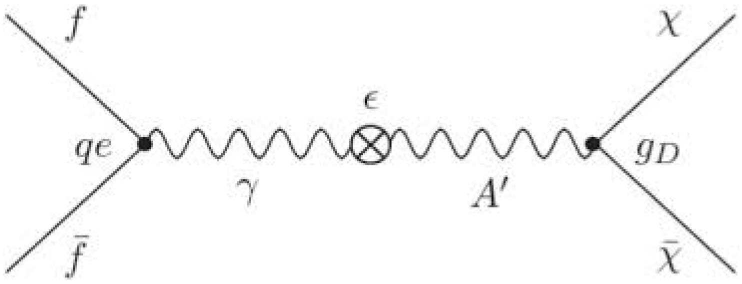


acceptance: $10^{-5\sim6}$

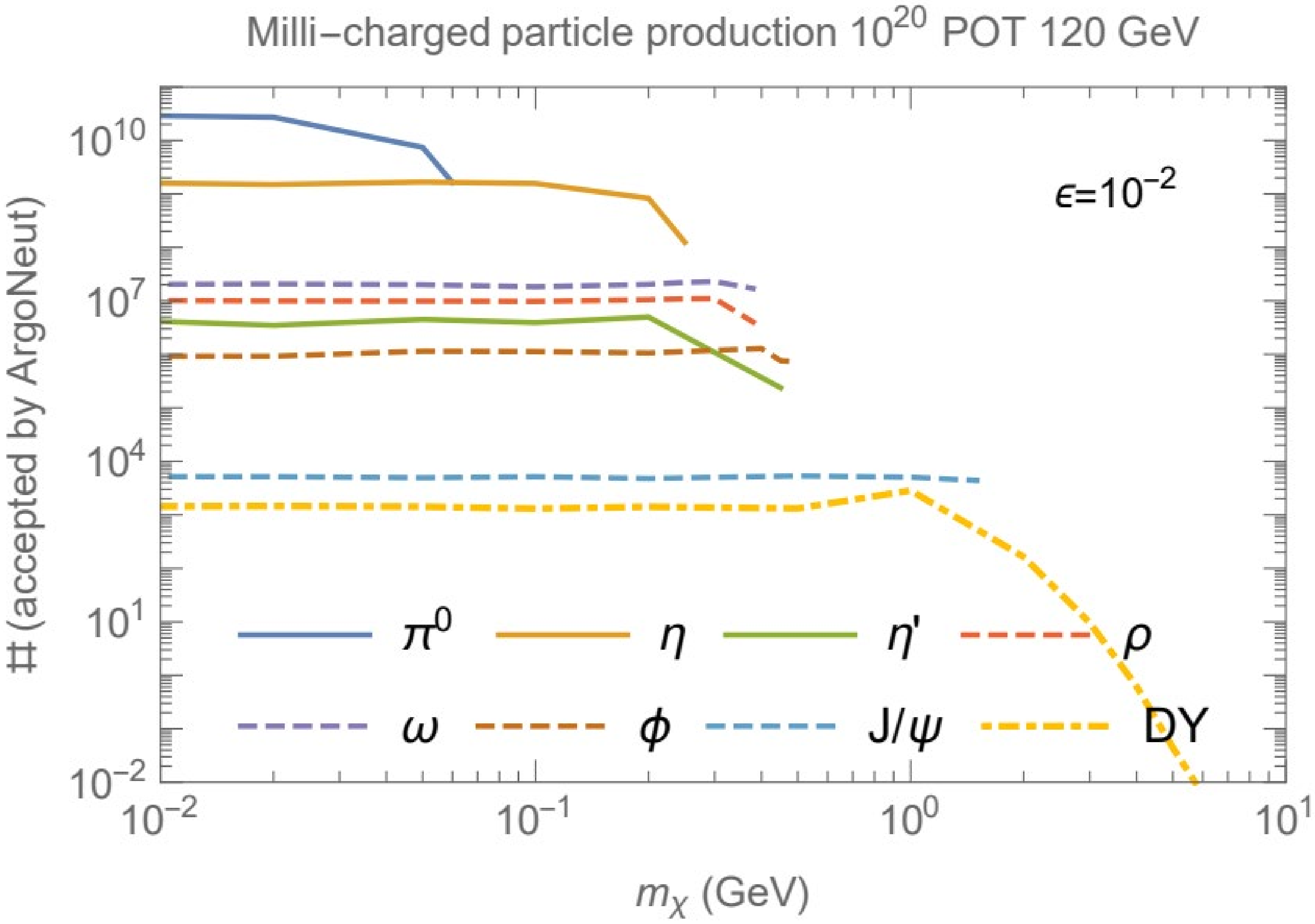


Neutrino experiments→ High quality beamdump experiments
E.g., NuMI beam: good source for Millicharged particles

High beam energy
High POT



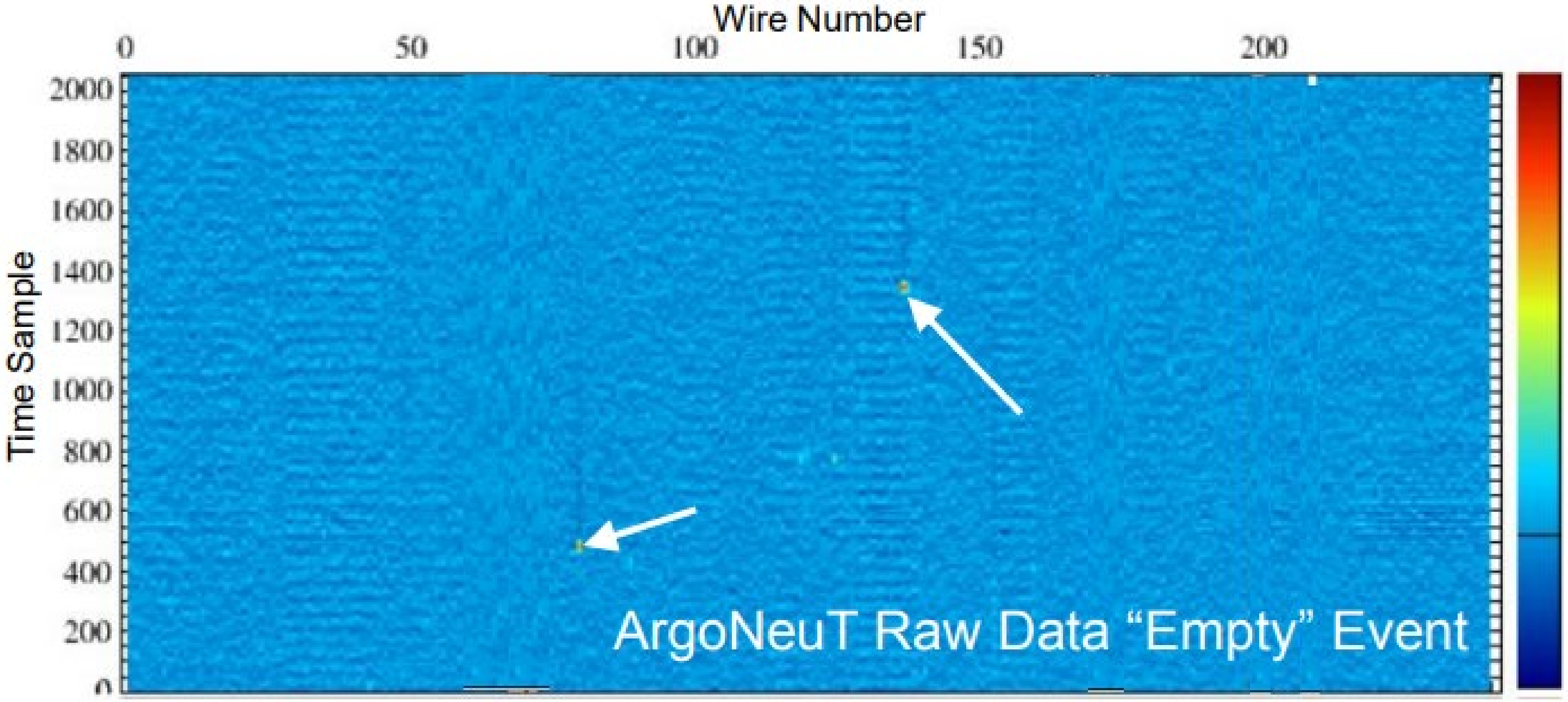
Typical geometric acceptance: $10^{-5\sim 6}$



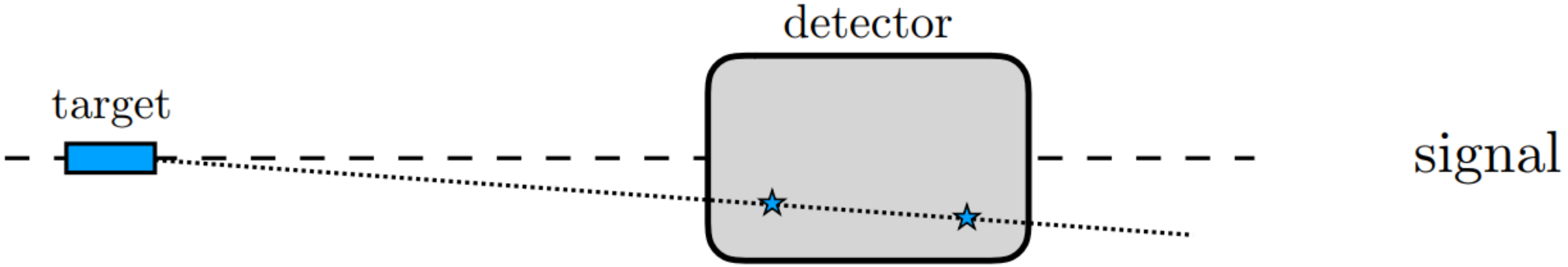
ArgoNeuT detector: low threshold & high resolution

Look for energy depositions (“clusters”) above threshold (~300 keV).
Obtain 3D positions of these depositions.

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

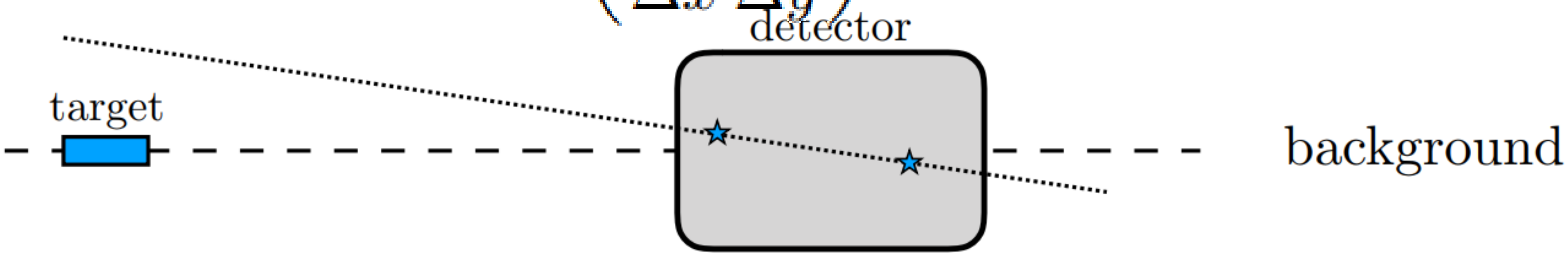


Signature



Dominated by low recoil energy scattering

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

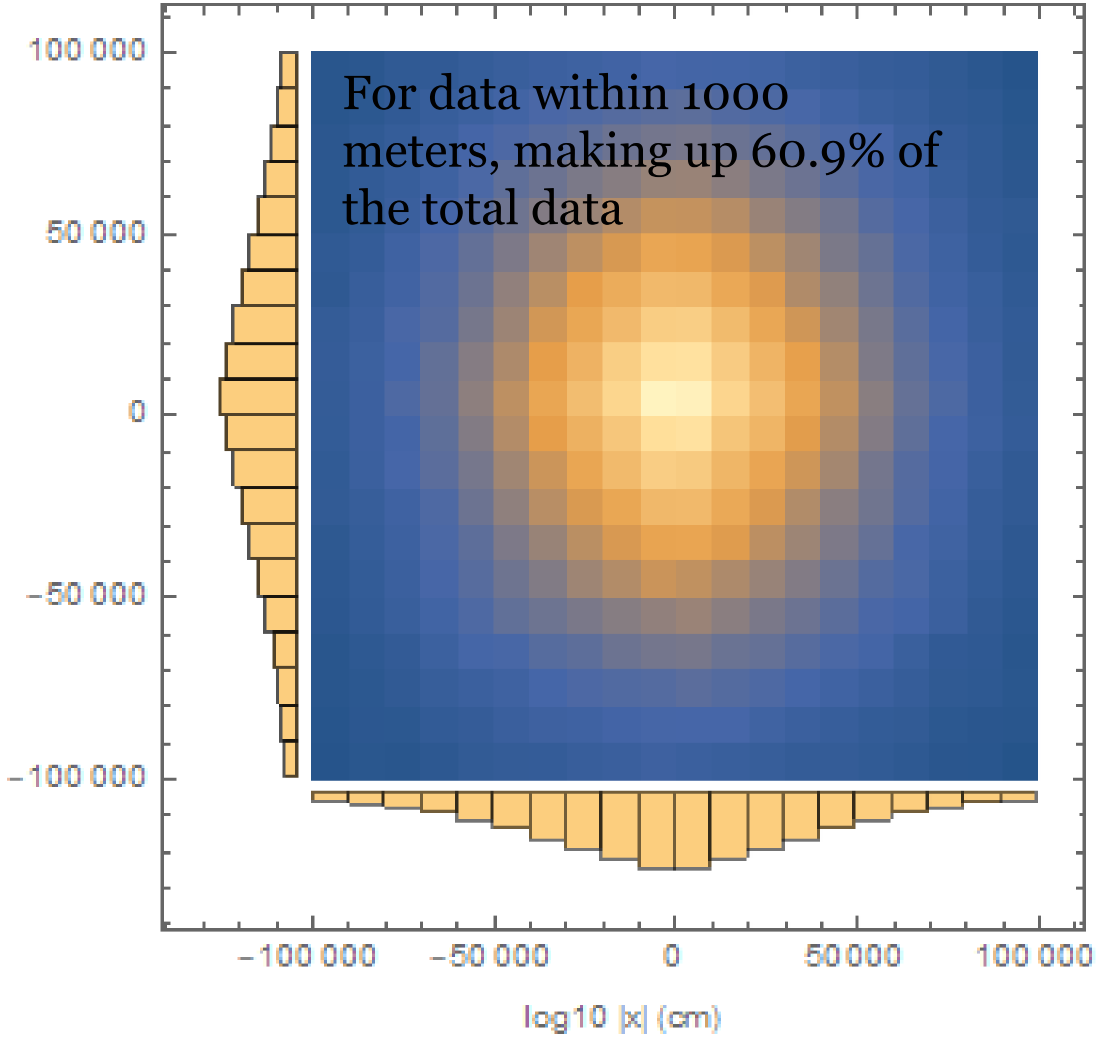


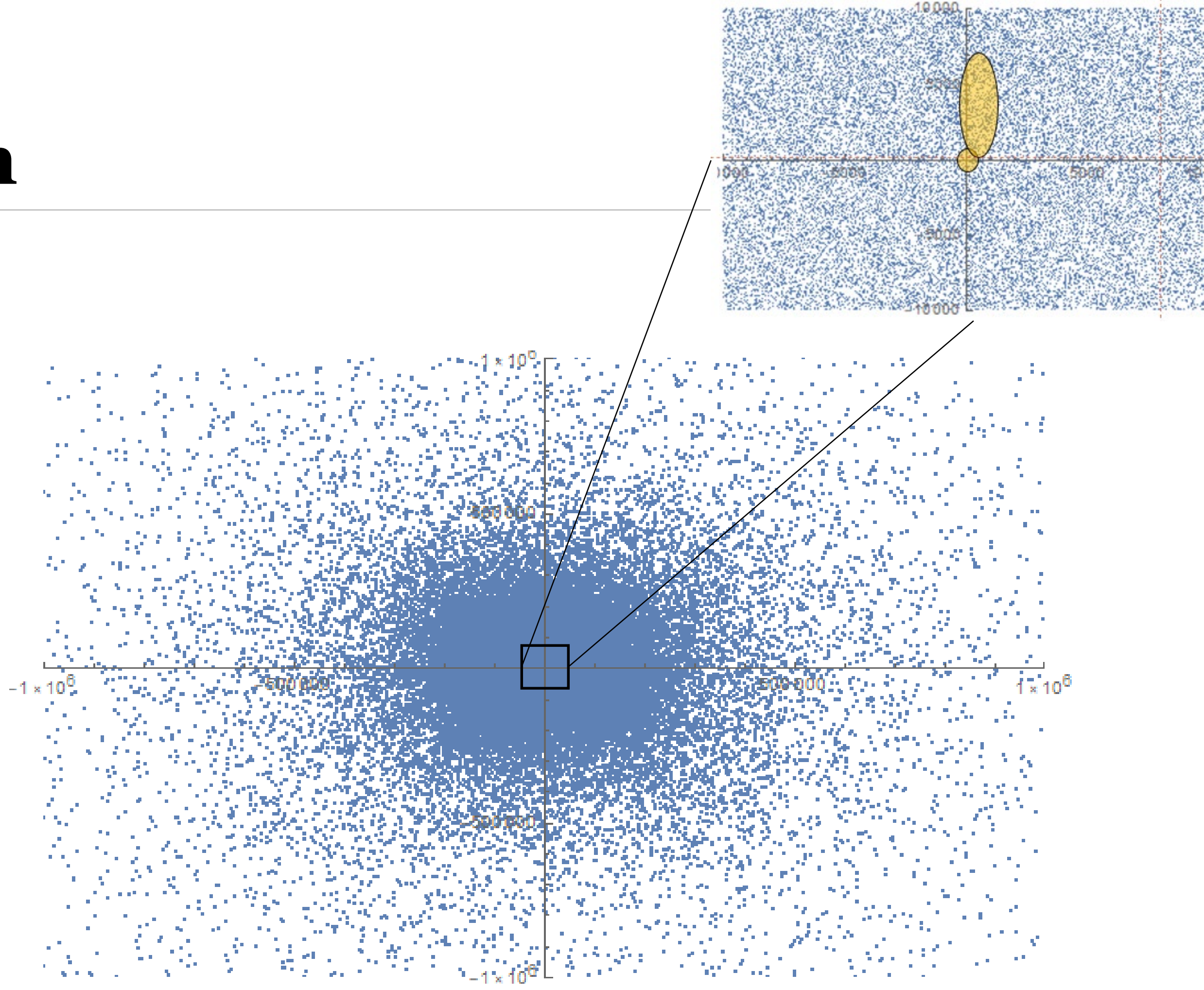
Signal scattering probability and mean free path

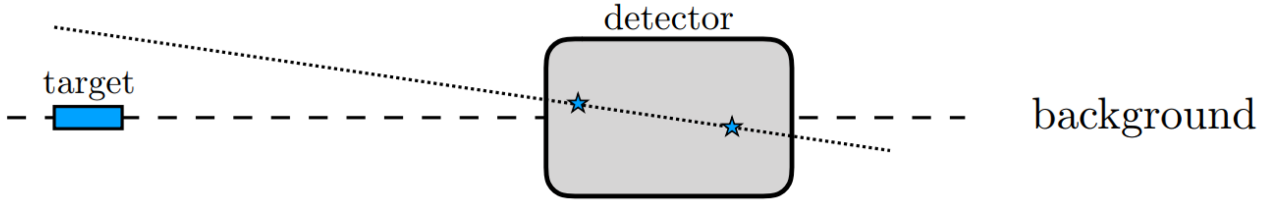
$$\left.\frac{d\sigma}{dE_r}\right|_{E_\chi \gg m_\chi, m_e, E_r} \simeq \frac{2\pi\alpha^2\epsilon^2}{E_r^2 m_e}.$$

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

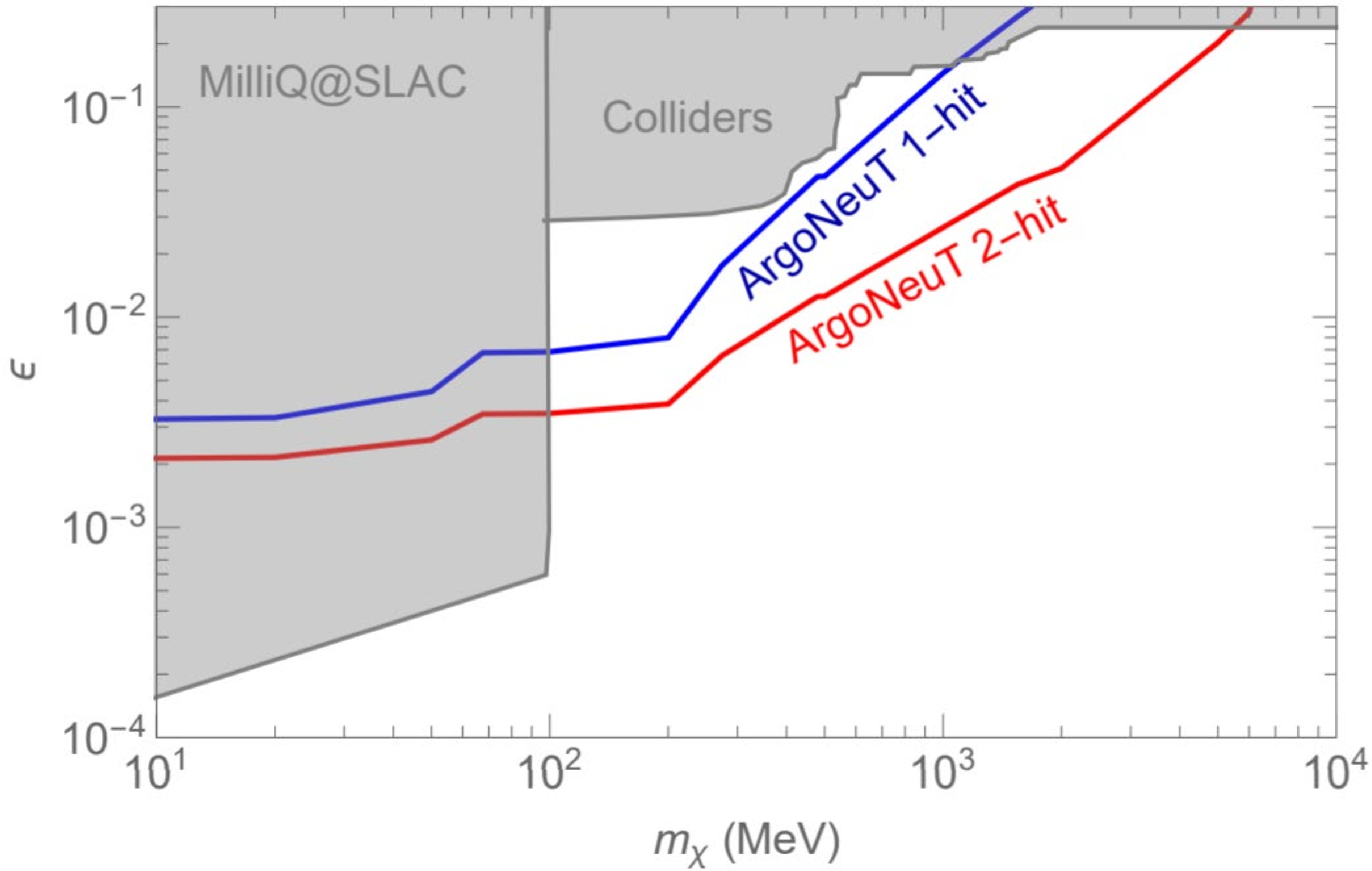
BKG target screen distribution







Expected reach

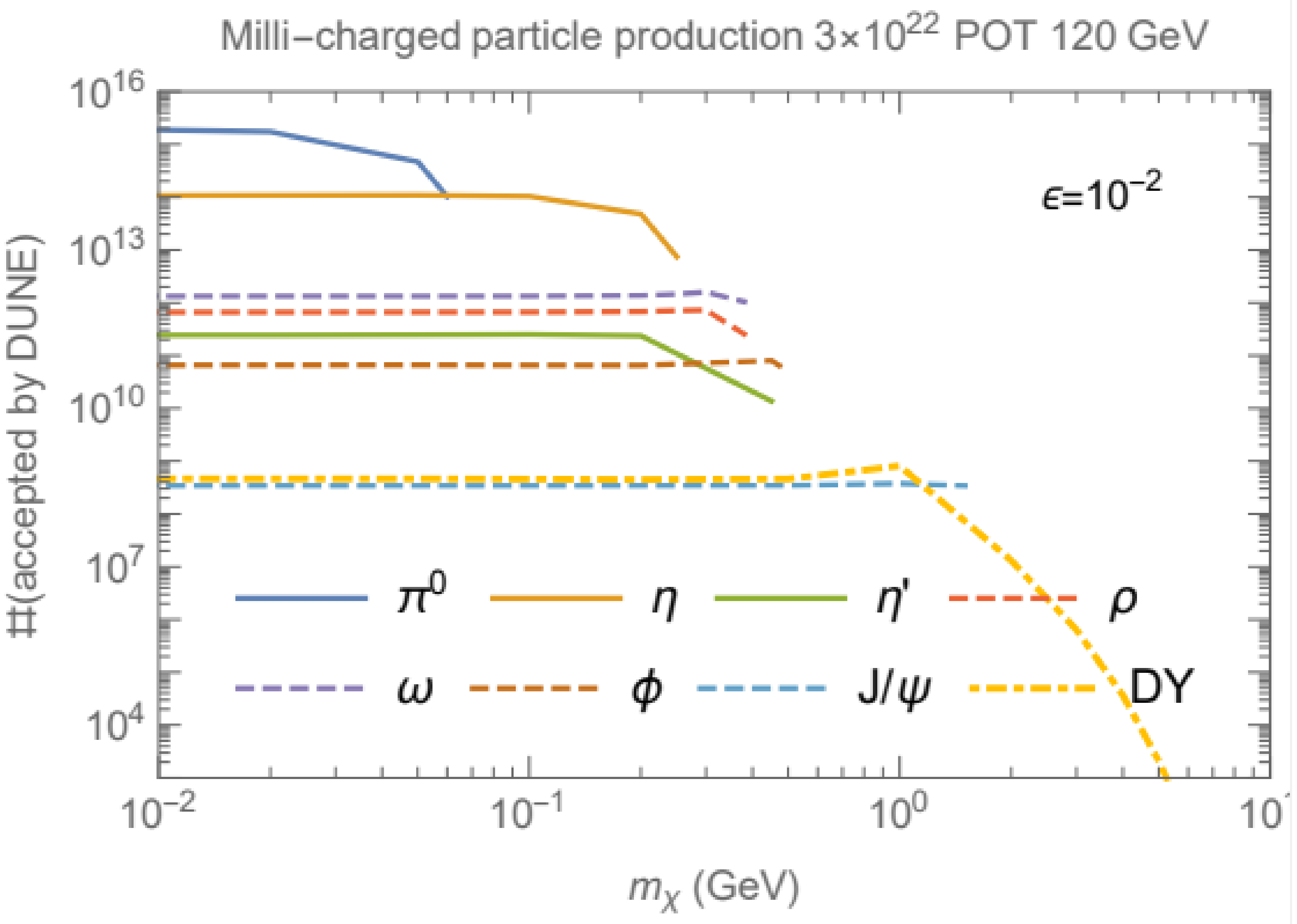


Harnik, Liu, Palamara, [1902.03246](1902.03246)

How about DUNE ND?

300 times more POT
240 times larger detector
Factor of two closer to the target

Should be very promising!

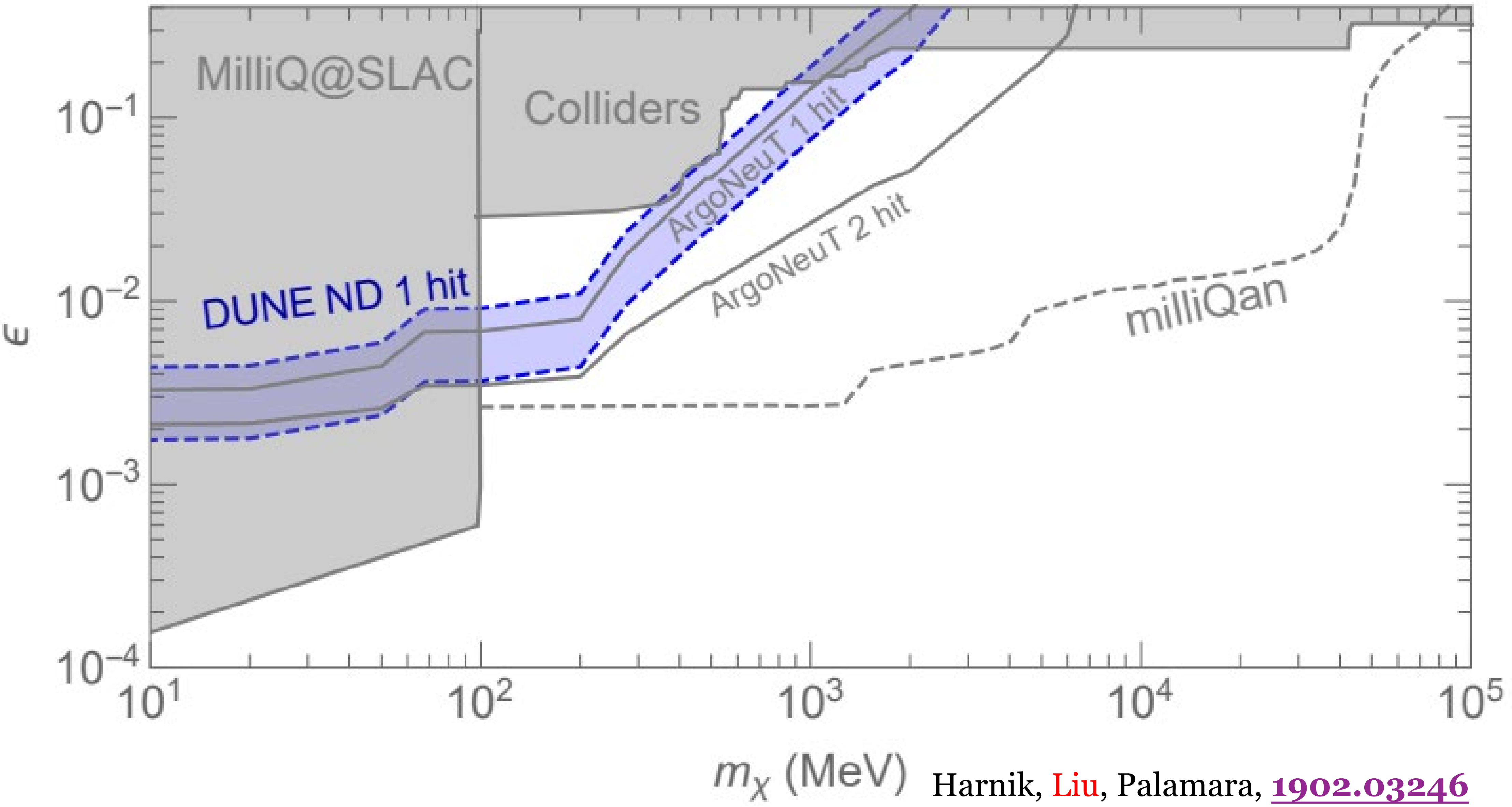


Background scale non-trivially for DUNE ND

	Bkg Scaling	Bkg reduction	# frames with ≥ 0 hit	≥ 1 hits	≥ 2 hits	# Background events 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}
DUNE ND	Volume	Systematic	1×10^8			4.5×10^9	1.0×10^{11}	1.4×10^4	1.6×10^{12}	0.030
		Statistic						$\sqrt{1.4 \times 10^4}$		0.030
		Timed	1×10^{10}	3.6×10^9	7.6×10^8		1.0×10^9	$\sqrt{1.4 \times 10^2}$	1.6×10^8	3.0×10^{-6}
	Vol.$\times$Int.	Systematic	1×10^8			1.8×10^{11}	1.6×10^{14}	2.2×10^7	9.3×10^{16}	1.8×10^3
		Statistic						$\sqrt{2.2 \times 10^7}$		$\sqrt{1.8 \times 10^3}$
		Timed	1×10^{10}				1.6×10^{12}	$\sqrt{2.2 \times 10^5}$	9.3×10^{12}	0.18

Average occupation number per frame:
ArgoNeuT: 0.13
DUNE ND: 45—1800

DUNE ND 1-hit projections



Harnik, Liu, Palamara, 1902.03246

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Average occupation number per frame:
ArgoNeuT: 0.13
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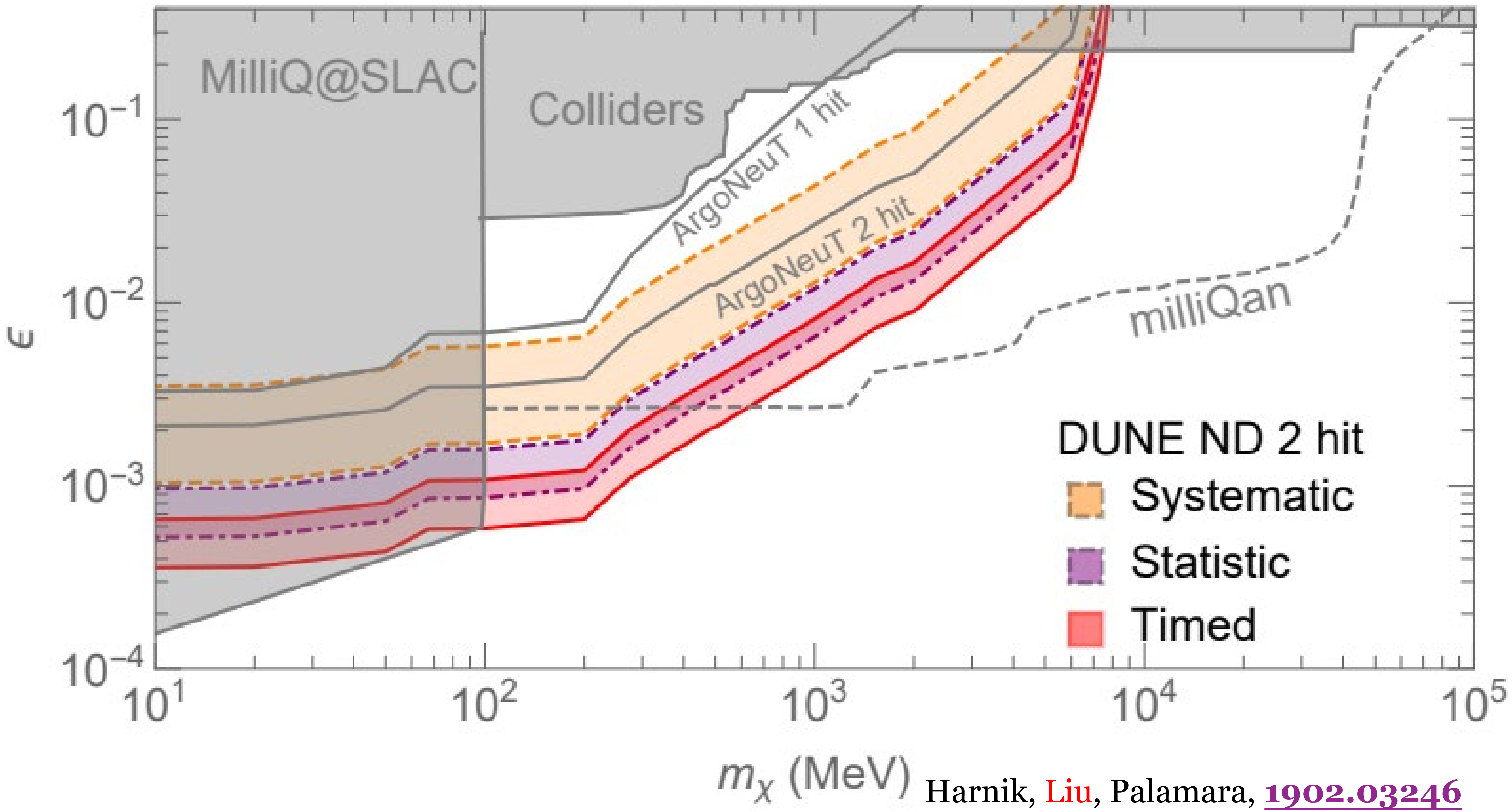
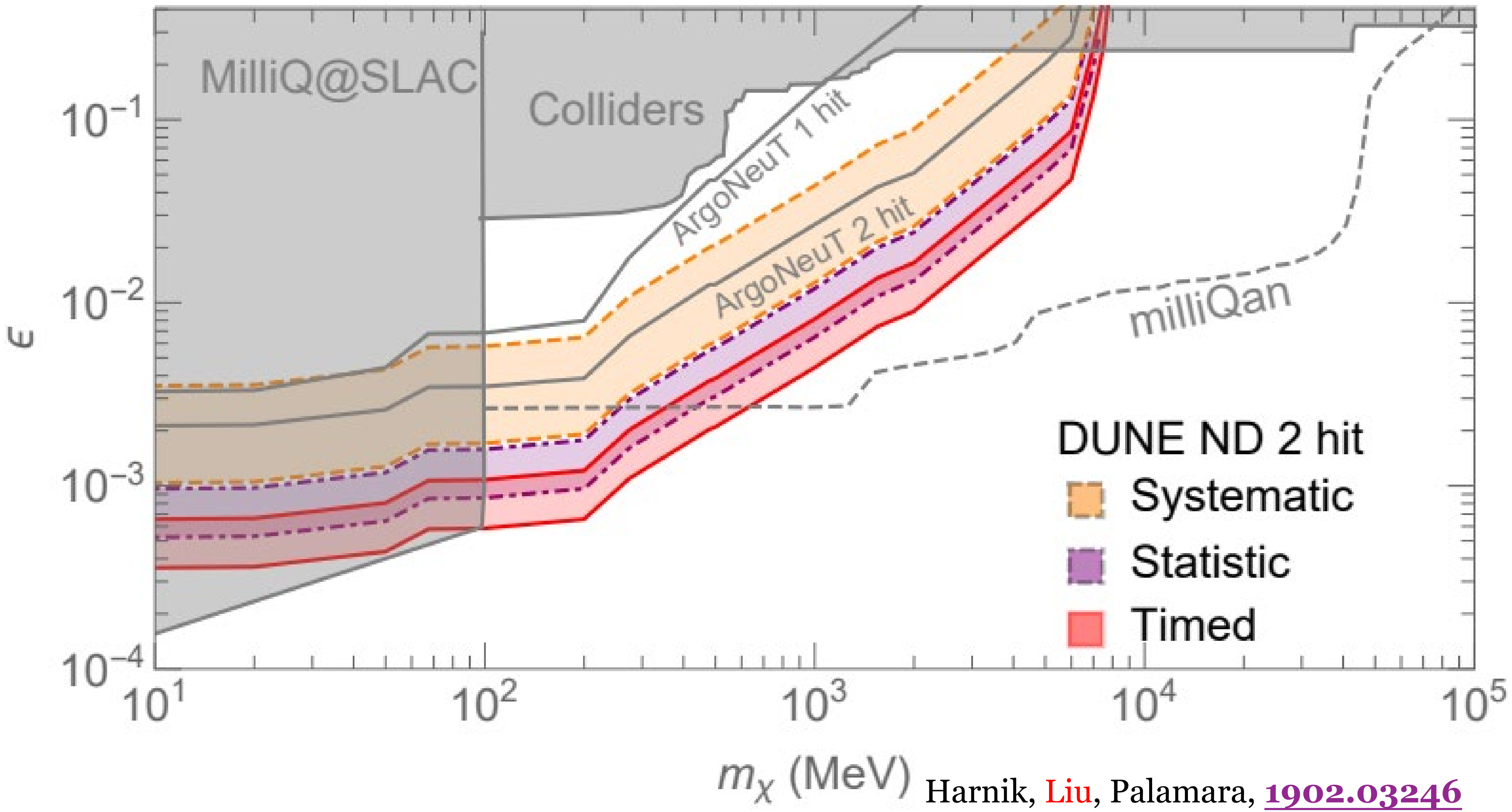
DUNE ND double hit coverage



Harnik, Liu, Palamara, 1902.03246

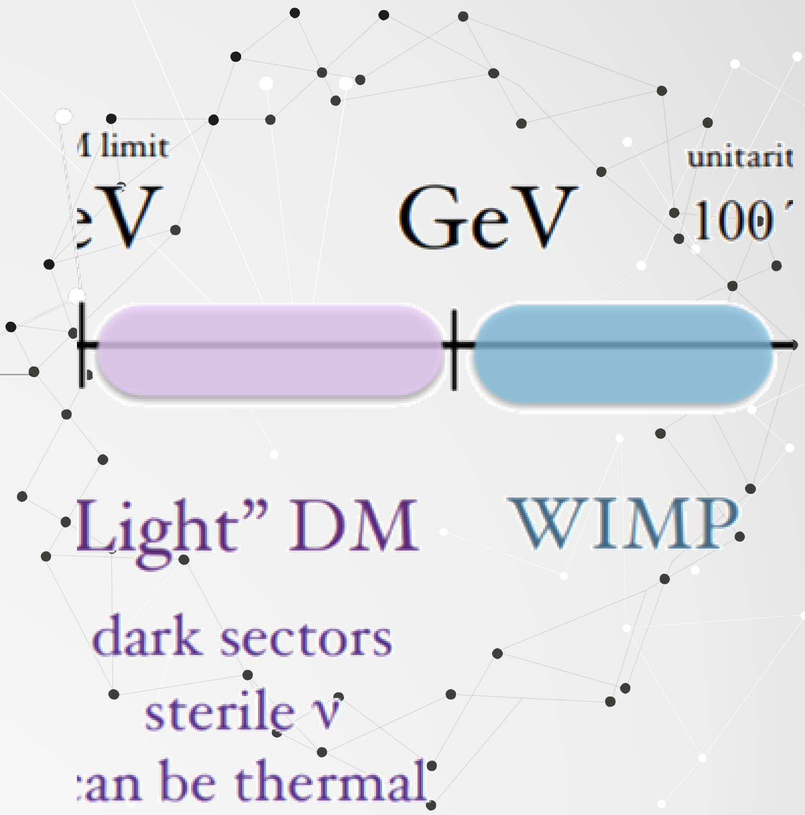
Active research field, see new works
ArgoNeuT result coming, I. Lepetic

DUNE ND double hit coverage



Harnik, Liu, Palamara, 1902.03246

Heavy Neutral Lepton Portal

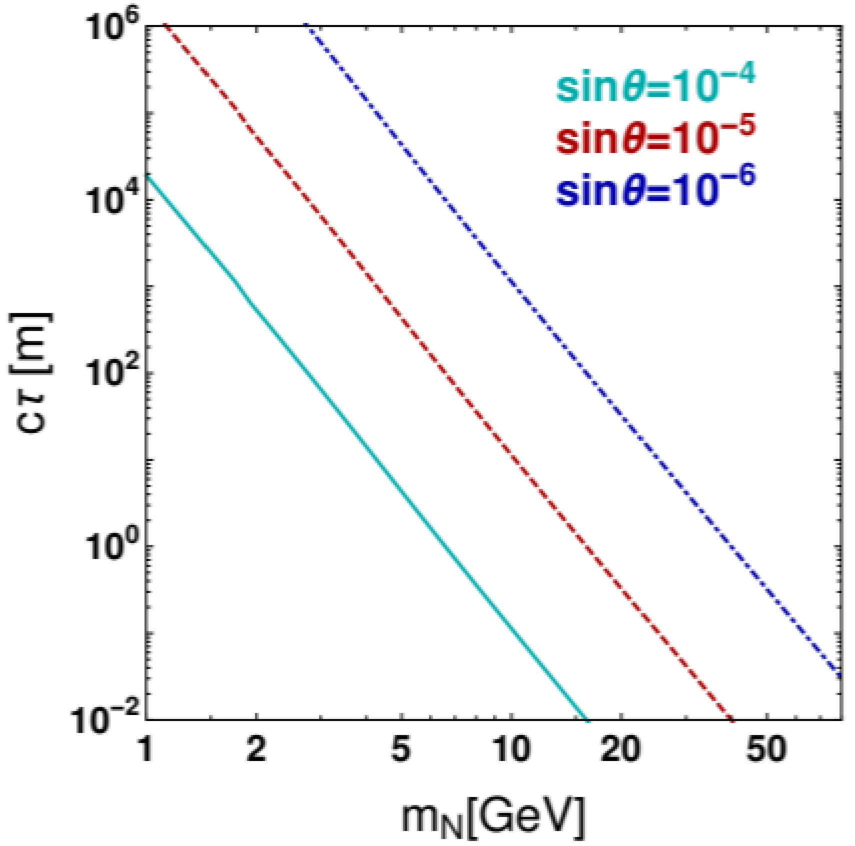


HNL a unique Physics case & LLP benchmark

HNL are a well-motivated prototype LLP
they have to be studied as thoroughly as possible!

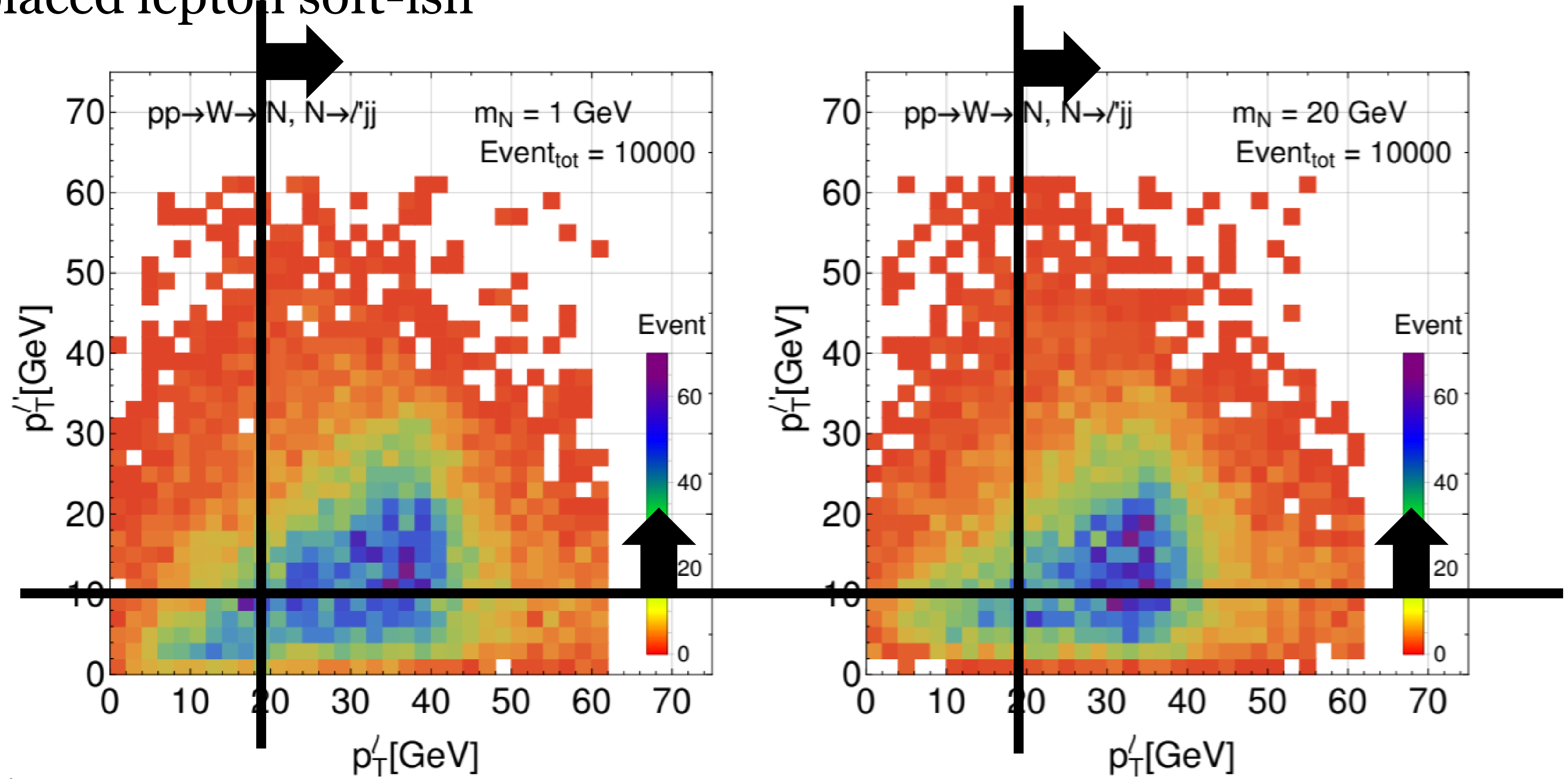
- Singly produced LLP
- Low mass LLP
- Prompt lepton trigger highly efficient
- Boosted low mass LLPs “fails” “traditional” hard & slow displaced vertex searches

$$\Delta\mathcal{L}_\nu = -\lambda_\nu \bar{L}\tilde{H}N - \frac{m_N}{2}\bar{N}^c N + h.c.$$



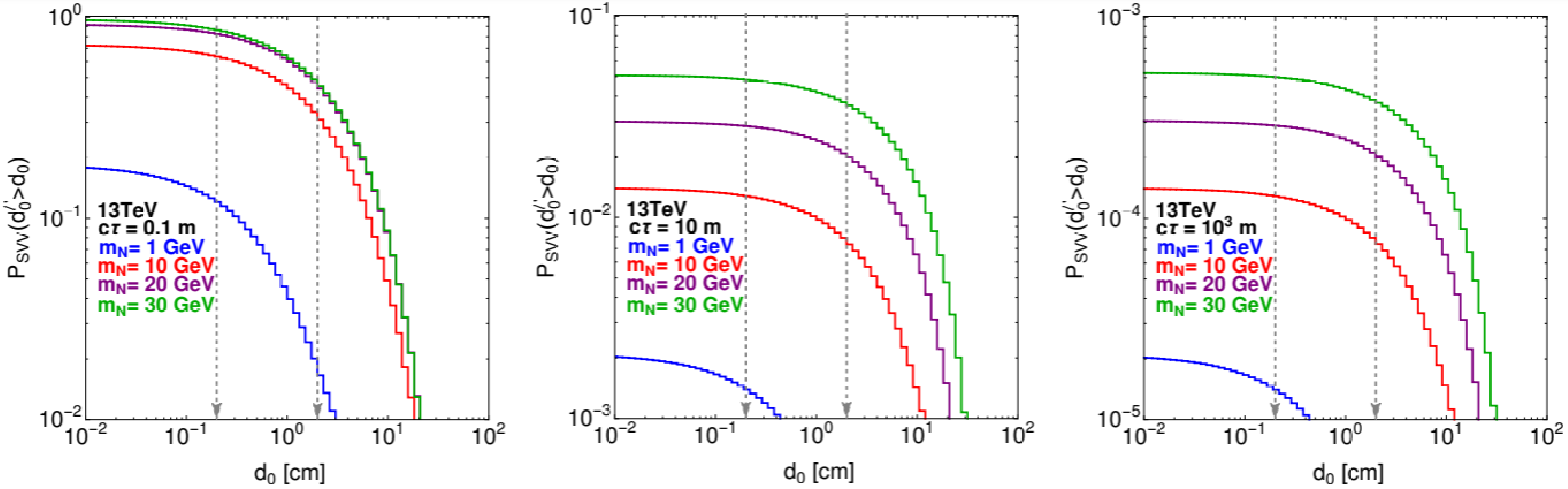
The lepton behaviors

- Prompt lepton hard-ish
- Displaced lepton soft-ish



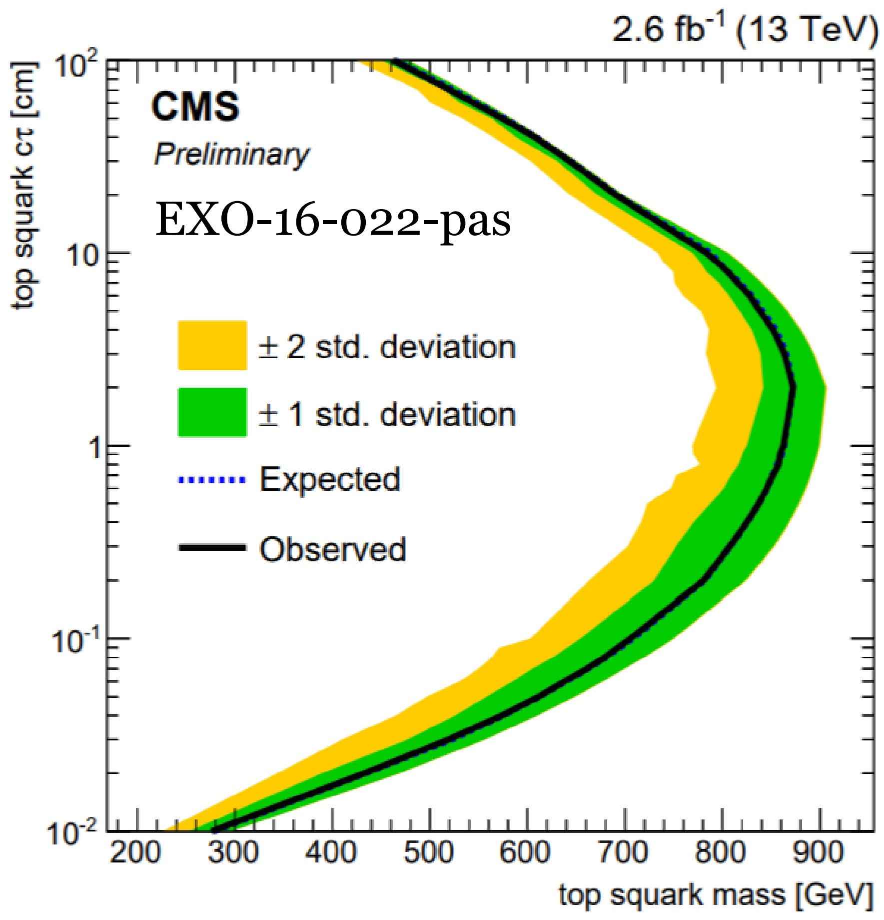
The lepton behaviors

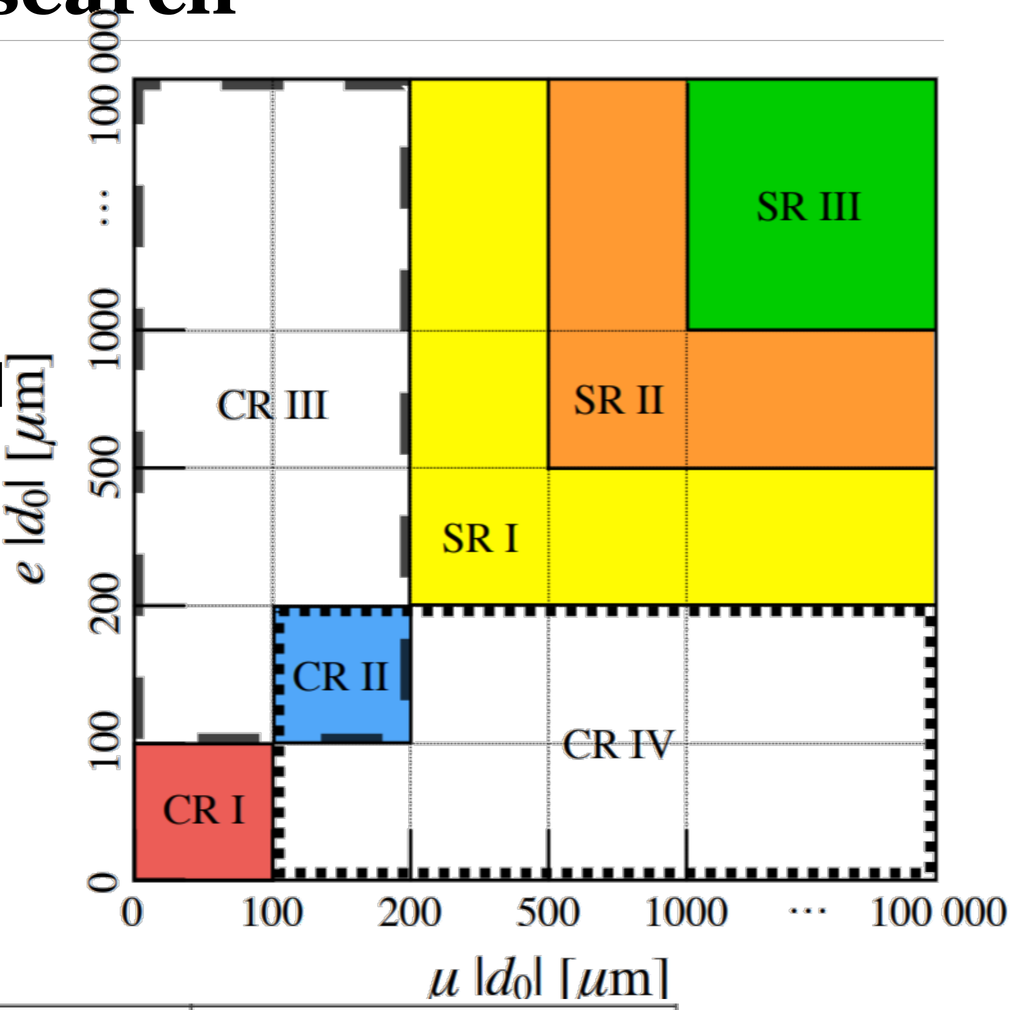
Required decay within R=0.5m
to have good tracks



- Large d0 cut, smaller signal efficiency;
- For short lifetime, >10 GeV sterile neutrinos behave similarly;
- For long lifetime, heavier sterile neutrinos are slower and hence higher decay probability within the tracker;
- For mN=1 GeV, decay product too collimated, suffering low d0;

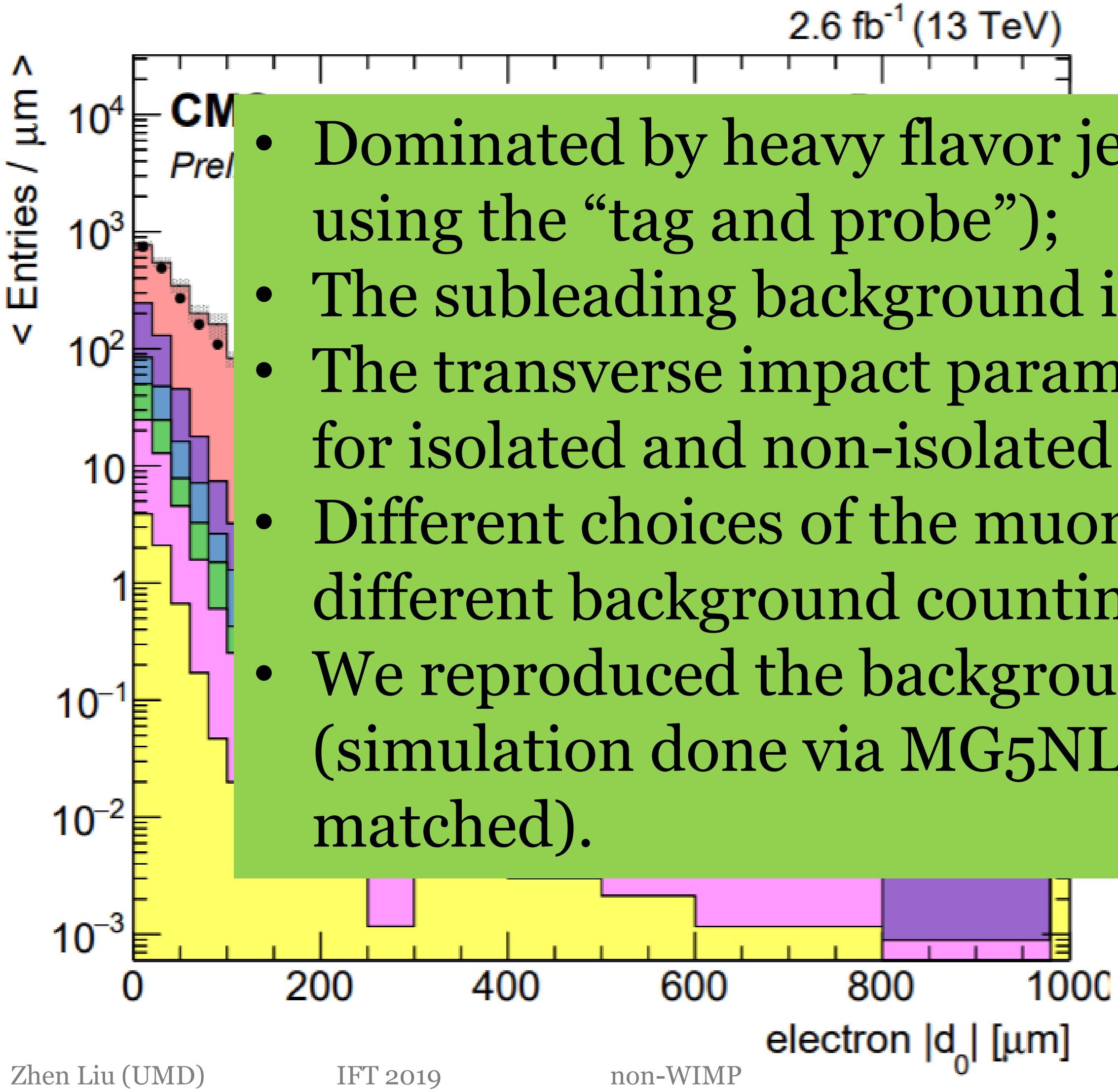
Valuable knowledge from a SUSY search

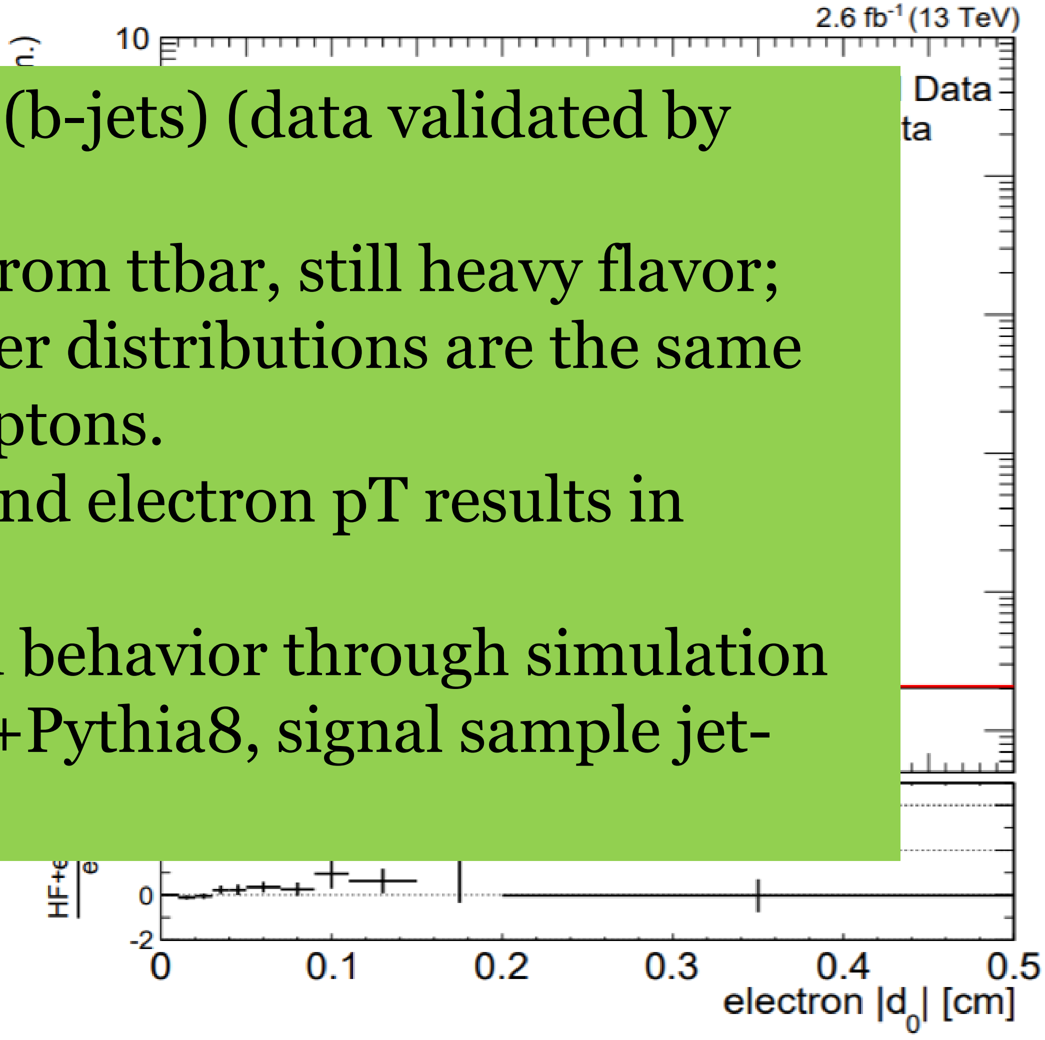




Displaced Electron Region (CR III)	Validation of HF Estimation	$\lvert d_0\rvert_e > 100\ \mu m$ $\lvert d_0\rvert_\mu < 200\ \mu m$
Displaced Muon Region (CR IV)	Validation of HF Estimation	$\lvert d_0\rvert_\mu > 100\ \mu m$ $\lvert d_0\rvert_e < 200\ \mu m$

Valuable knowledge from a SUSY search



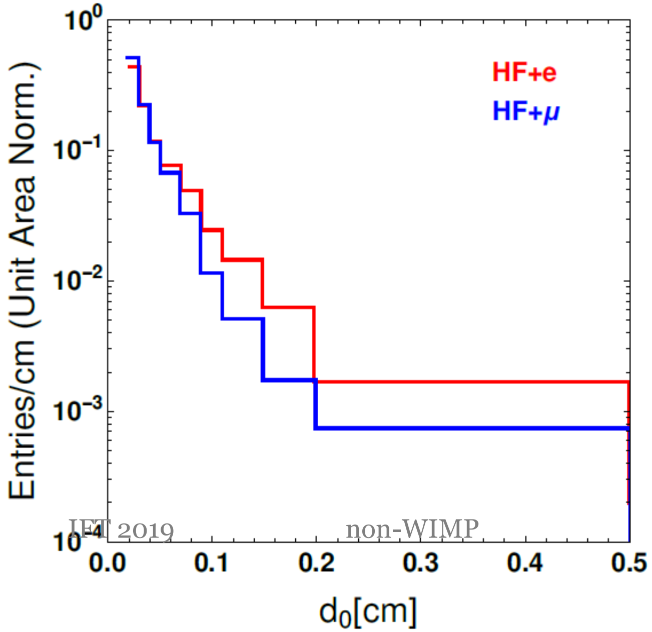


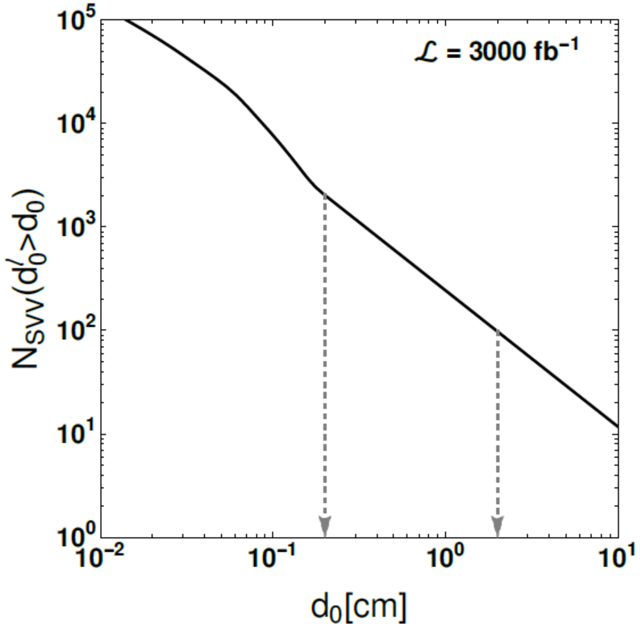
- Dominated by heavy flavor jets (b-jets) (data validated by using the "tag and probe");
- The subleading background is from ttbar, still heavy flavor;
- The transverse impact parameter distributions are the same for isolated and non-isolated leptons.
- Different choices of the muon and electron pT results in different background counting
- We reproduced the background behavior through simulation (simulation done via MG5NLO+Pythia8, signal sample jet-matched).

Our search and projected sensitivity

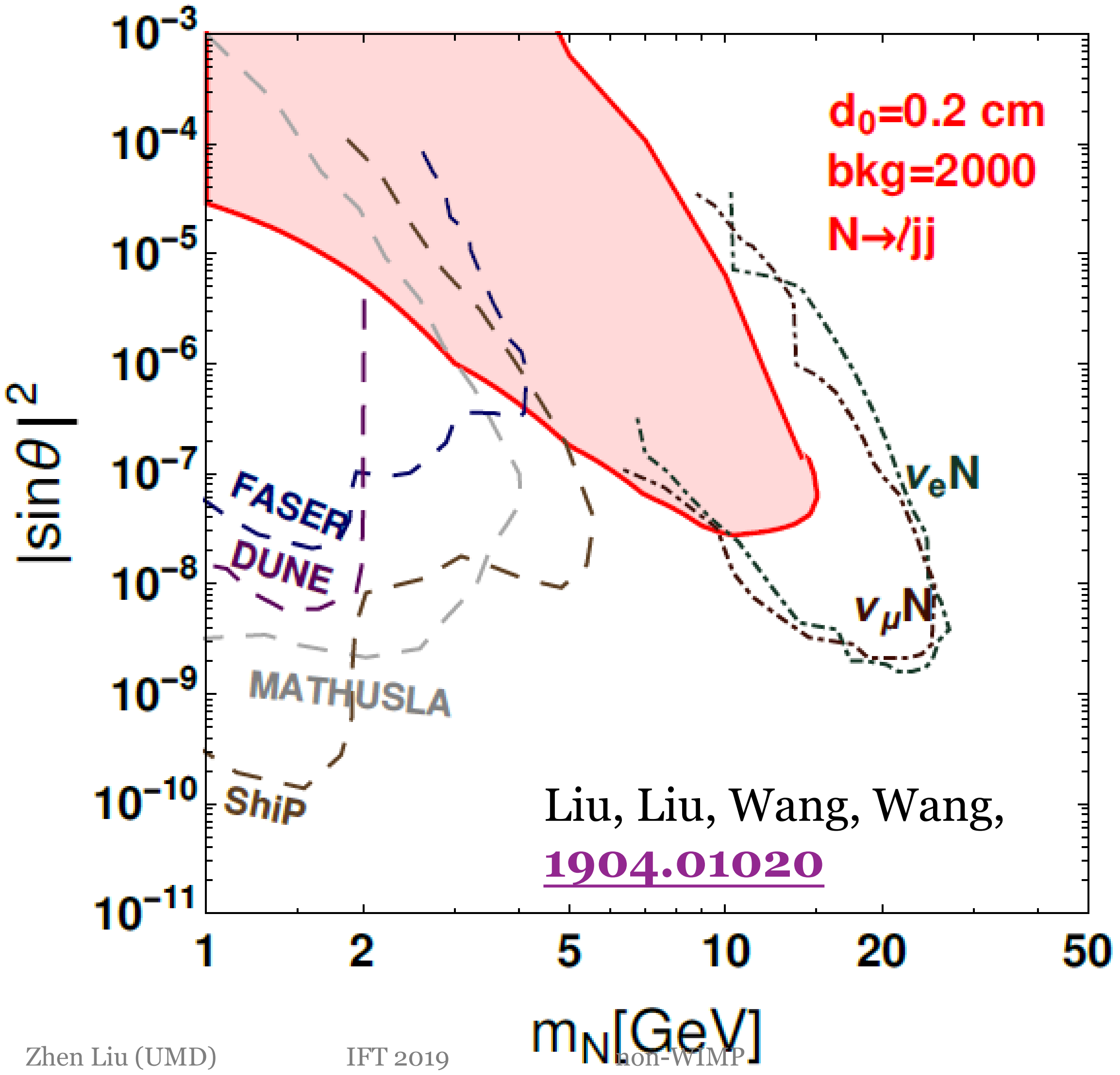
Efficiency	$\sigma^{\rm ncut}$ (pb)	$N_b^{30}=0$	$N_j^{20}<2$	$N_j^{50}=0$	$H_T^{\rm vis}<100$ GeV	$p_T^{\ell_1}>19$GeV	$p_T^{\ell_2}>10.5$GeV	$\epsilon_{\rm opt}$
$t\bar{t}\to b\bar{b}+\ell+X$	136	0.25	0.08	0.62	0.43	0.055	0.42	1.2×10^{-4}
$W+b\bar{b}, W\to\ell\nu$	3.8	0.40	0.60	0.76	0.40	0.27	0.29	5.7×10^{-3}

$$N_{\rm bkg}=\frac{\sigma^{\rm CMS}_{{\rm HF}+e}+\sigma^{\rm CMS}_{{\rm HF}+\mu}}{\sigma^{\rm icut}_{b\bar{b}(e)}+\sigma^{\rm icut}_{b\bar{b}(\mu)}}\left(\sigma^{\rm ncut}_{W+b\bar{b},W\to\ell\nu}\times\epsilon^{W+b\bar{b}}_{\rm opt}+\sigma^{\rm ncut}_{t\bar{t}\to b\bar{b}+\ell+X}\times\epsilon^{t\bar{t}}_{\rm opt}\right)\times\mathcal{L}_{\rm HL-LHC}$$



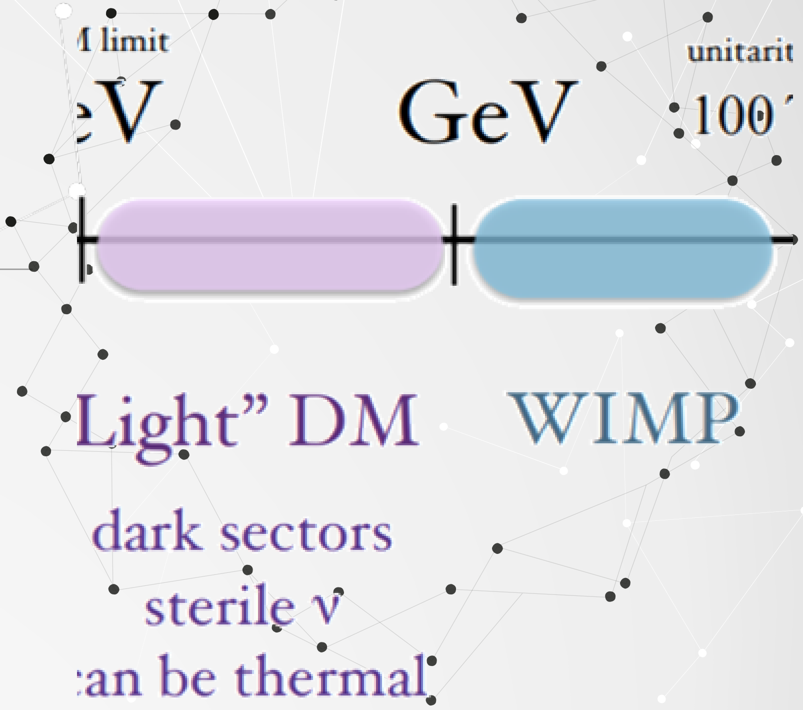


Results



- Non-zero background at HL-LHC: ~ 2K
- Interesting expansion of the LHC coverage to lower masses (< 5 GeV) by taking the heavy flavor background directly;
- A example of "serious" pheno new search studies on LLPs can be done at the LHC;

Axion-like particle portal



Strong CP puzzle can lead to long-lived axions

$$L \supset \frac{\alpha_s}{4\pi}\theta \tilde{G}G + y_u \bar{Q}_L \tilde{H} u_R + y_d \bar{Q}_L H d_R$$

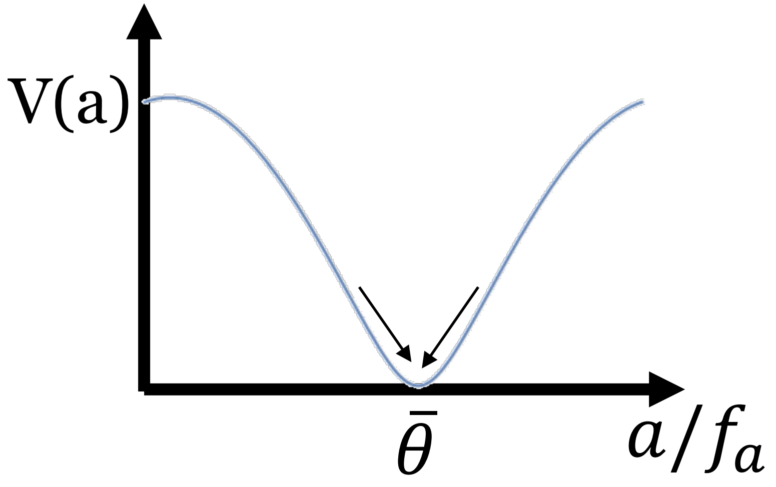
$$\bar{\theta} \equiv \theta + \mathrm{ArgDet}[Y_u Y_d] \leq 10^{-10}$$

While $\mathrm{ArgDet}[Y_u Y_d]$ anticipated around $\delta_{CKM} \sim O(1)$

Strong CP puzzle of QCD

Dynamical solution:
QCD Axion a as a pseudo Nambu-Goldstone boson

$$\frac{\alpha_s}{4\pi}\left(\theta - \frac{a}{f_a}\right)\tilde{G}G$$



Peccei, Quinn, 77'

Strong CP puzzle can lead to long-lived axions

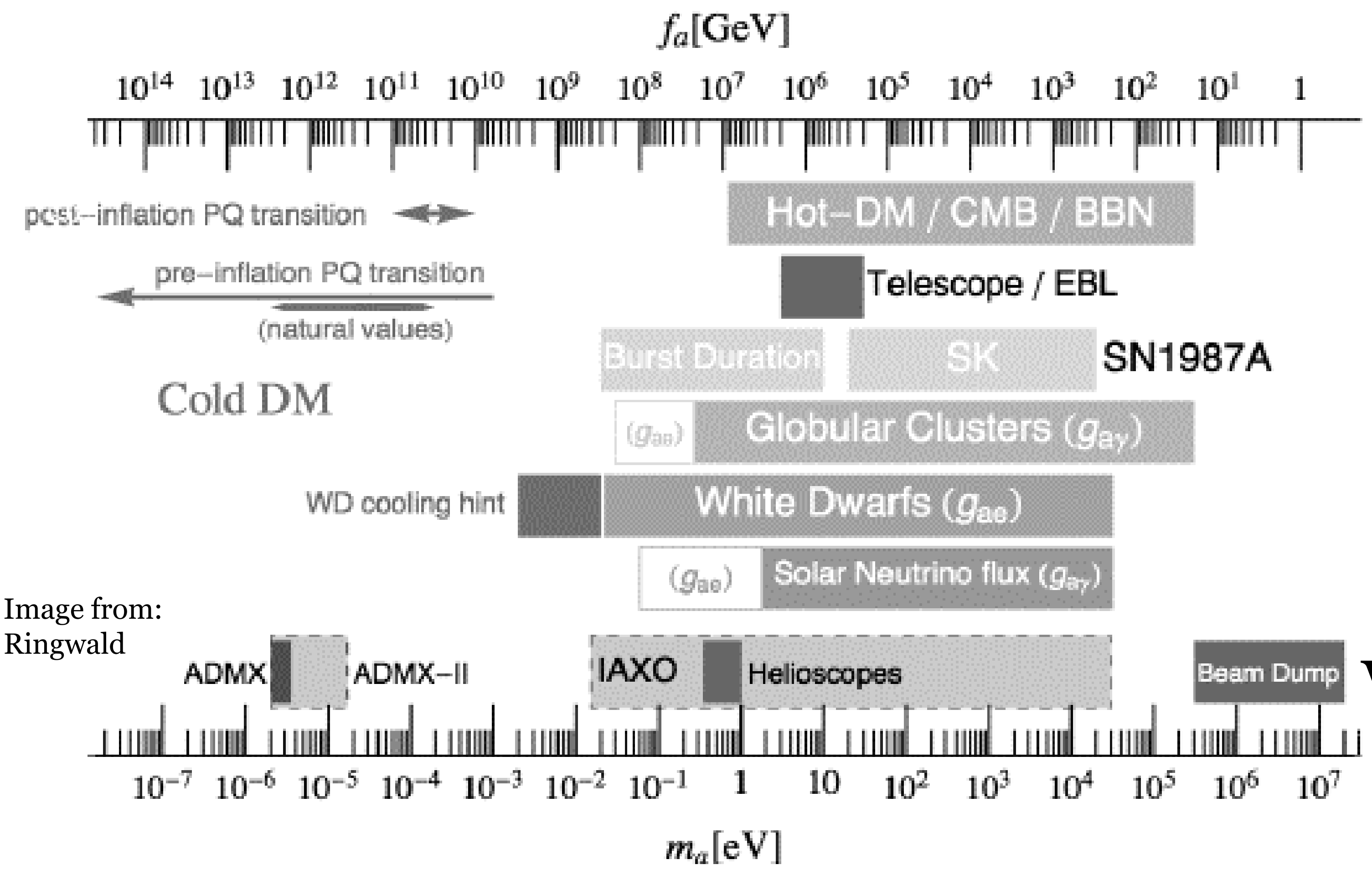
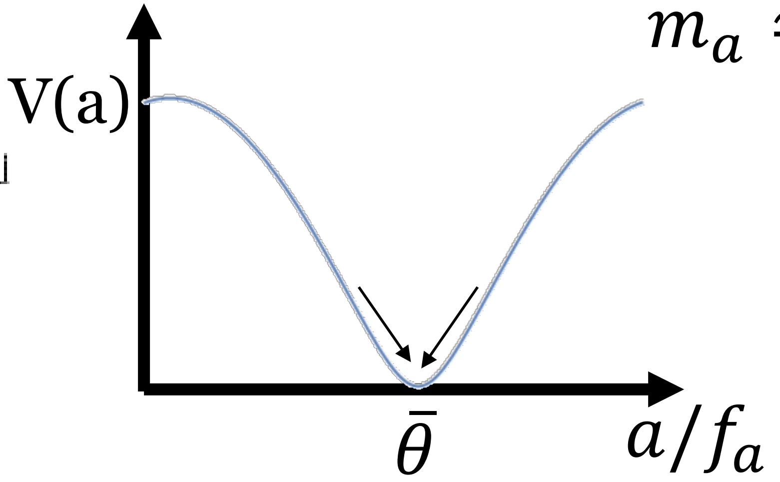


Image from:
Ringwald

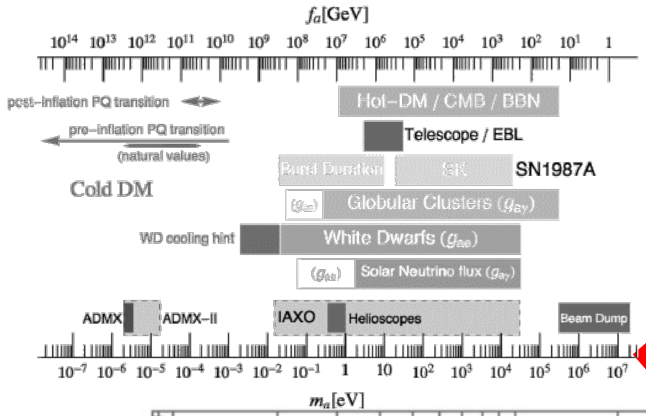
Dynamical solution:
QCD Axion a as a pseudo Nambu-Goldstone boson

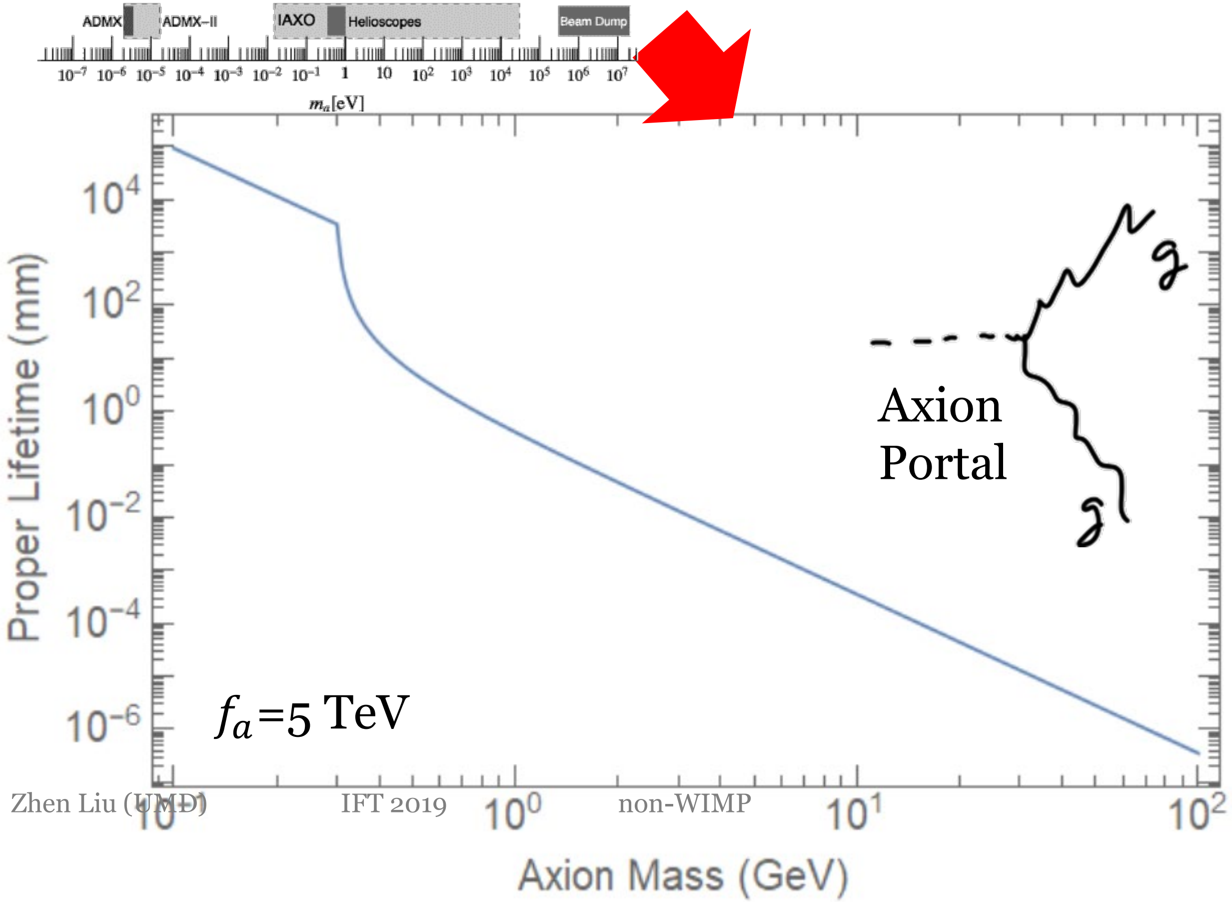
$$\frac{\alpha_s}{4\pi}\left(\theta - \frac{a}{f_a}\right)\tilde{G}G + \frac{\alpha}{4\pi}\frac{a}{f_a^{\gamma\gamma}}\tilde{\boldsymbol{F}}\boldsymbol{F}$$

$$m_a \simeq \frac{\Lambda_{QCD}^2}{f_a}$$



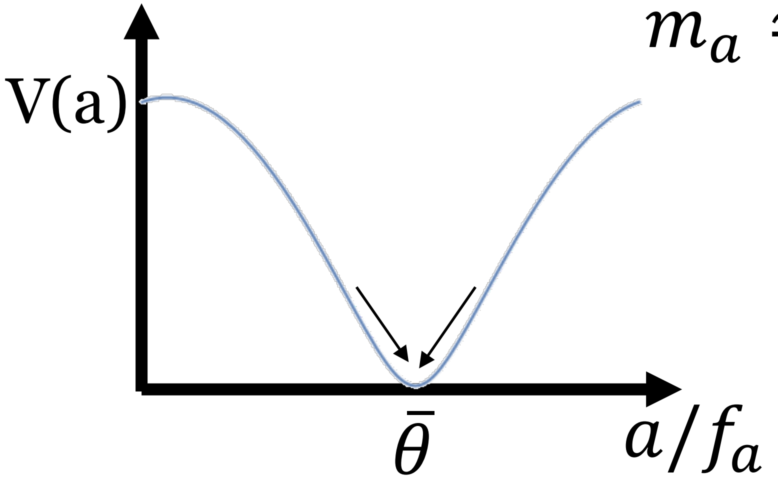
Strong CP puzzle can lead to long-lived axions !





Dynamical solution:
QCD Axion a as a pseudo Nambu-Goldstone boson

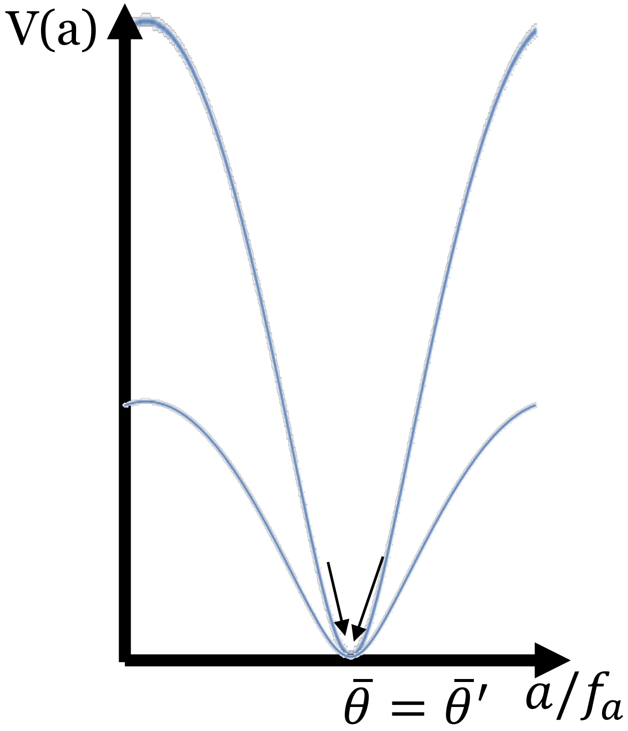
$$\frac{\alpha_s}{4\pi}\left(\theta - \frac{a}{f_a}\right)\tilde{G}G + \frac{\alpha}{4\pi}\frac{a}{f_a^{\gamma\gamma}}\tilde{F}F$$



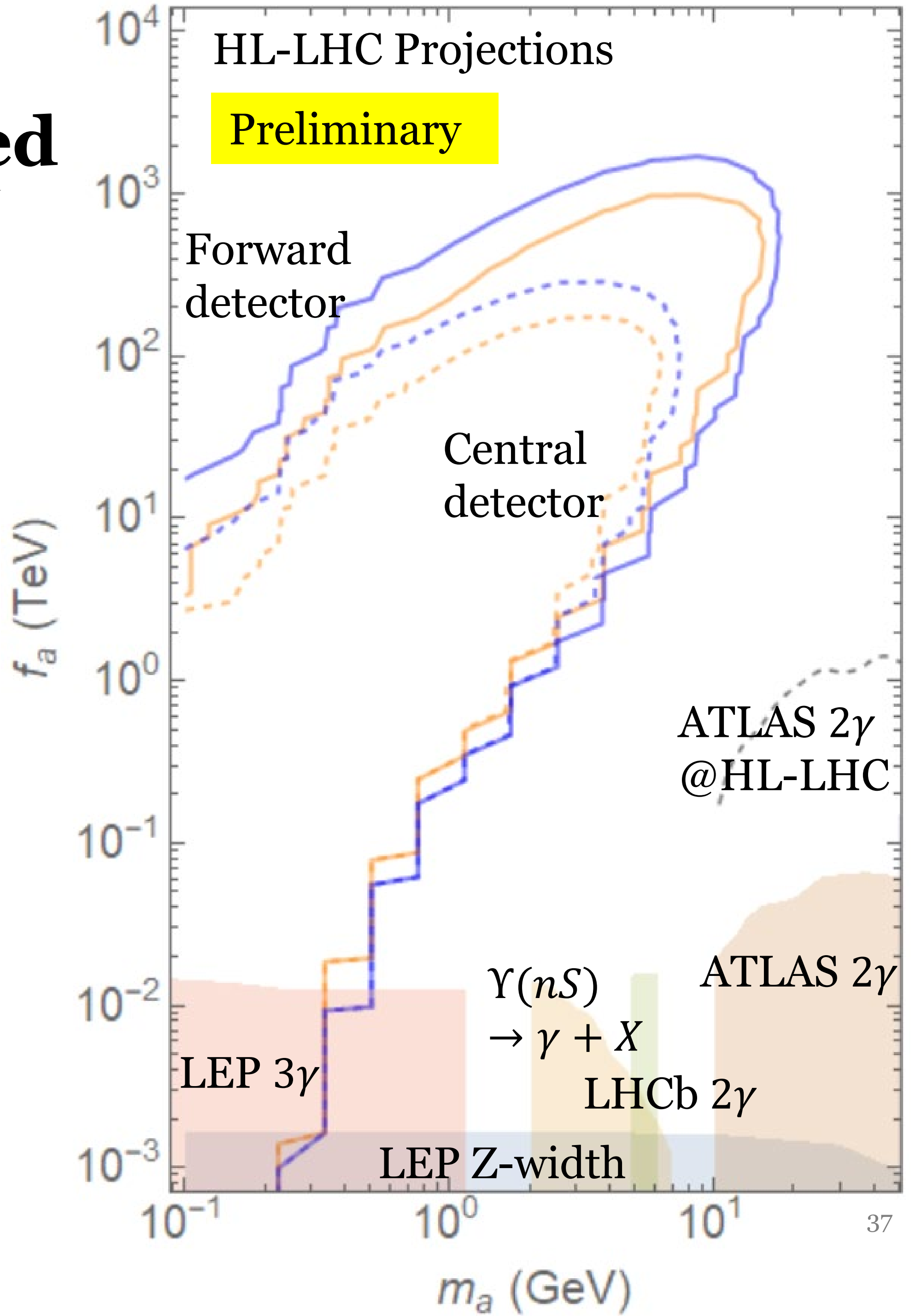
$$m_a \simeq \frac{\Lambda_{\rm QCD}^2}{f_a}$$

A high-quality axion can be probed

- Gluon factory➔ Rate high
- LLPs➔ background low
- Novel trigger and selection proposed focusing on displaced tracks

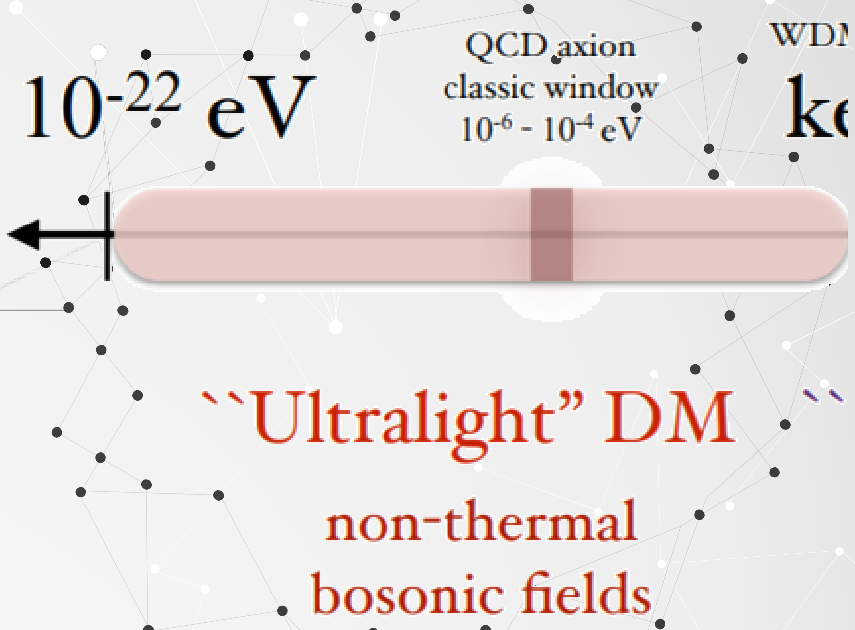


$$\frac{\alpha_s}{4\pi}\left(\theta - \frac{a}{f_a}\right)\tilde{G}G$$



Hook, Kumar, Liu, Sundrum, in progress

Ultralight DM: dark photon & ALP



Well motivated theories:

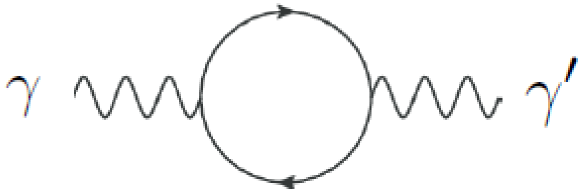
- Dark Photons
- Axions and ALPs

Well motivated searches:

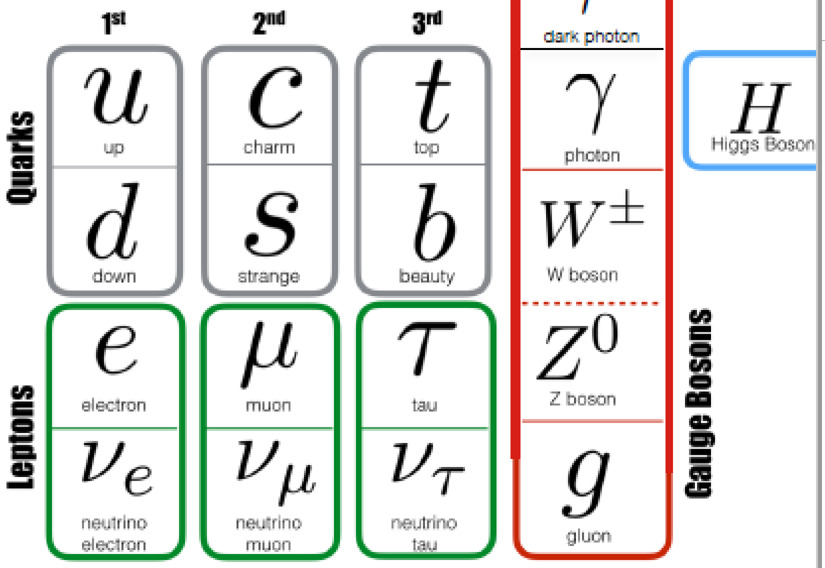
- Light mediators
- Dark matter

Dark Photons

- Imagine another photon, with a different mass.
- Common in top-down frameworks.
- *Any* heavy particle that is charged both photons will generate mixing.



Nature has already ordered extra copies of fermions. Why not gauge bosons?



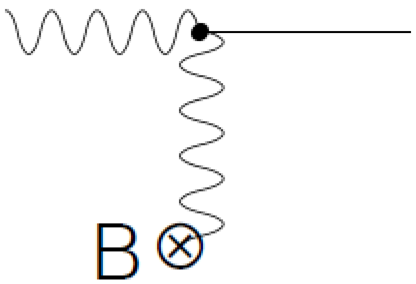
$$\mathcal{L} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu} - 2\epsilon F_{\mu\nu}F'^{\mu\nu}\right) + \ldots \supset \epsilon\left(\vec{E}\cdot\vec{E}' + \vec{B}\cdot\vec{B}'\right)$$

An oscillating EM field is a source of dark photons, and vice versa. (reminiscent of neutrino oscillations)

Axion-like particles

- Imagine an approximate symmetry broken at a high scale f.
  → a pseudo-Goldstone Boson ≃ an axion-like particle.
- Common in top-down constructions, the axion is invoked to solve the strong CP problem.
- Loops of heavy charged particles can generate interaction:

$$\mathcal{L} = \frac{\alpha}{f} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$



Axions and photons mix in a magnetic field.

An oscillating E·B is a source of dark photons.

Longer Range Interactions and Wave-like Dark Matter

- Both axion-like particles and dark photons are well motivated as mediators of long range interactions that can be searched for.

$$\mathcal{L} \supset \quad \text{dark photons? axions?}$$

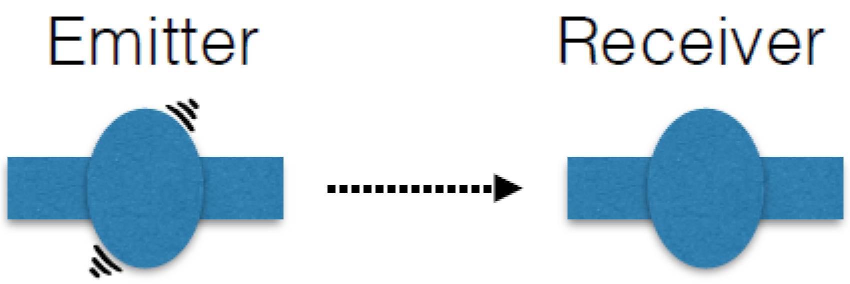
- Both axion-like particles and dark photons are dark matter candidates.
- In the Wave-like DM category. Oscillating at $\omega = m_{DM}$.

$\supset$ dark photons? axions?

Searches with SRF Cavities

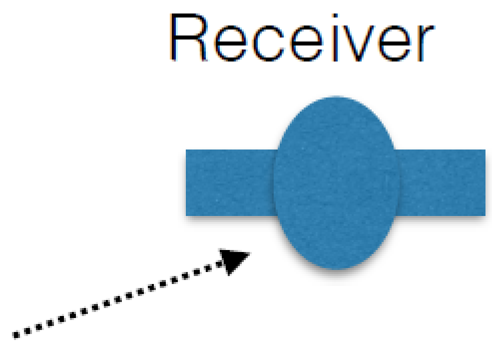
- Fermilab's SRF Cavities are world's highest quality photon resonators, with Q as high as 10^{11}:
  - Large fields when excited → can source dark fields.
  - Resonant response → can amplify a feeble signal.

Light Shining through wall:



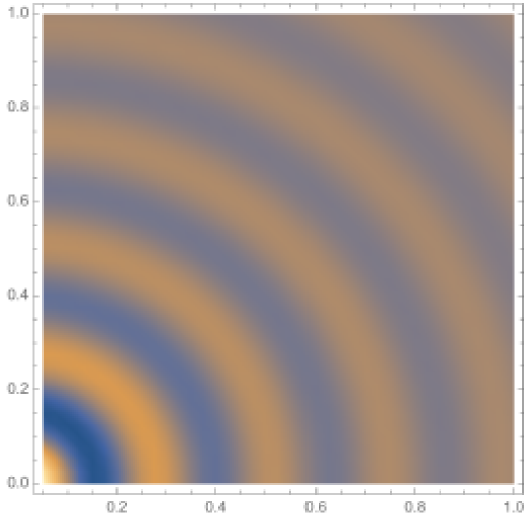
a search for a mediator.

A dark matter search:

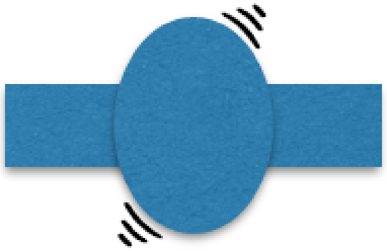


the DM filled Universe
is the emitter

Dark Photon Search

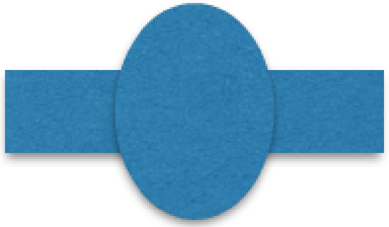


a dark photon field is radiated at 1.3 GHz.



Emitter Cavity

Frequency of 1.3 GHz, excited to ~ 35 MV/m. Thats ~ 10^{25} Photons!



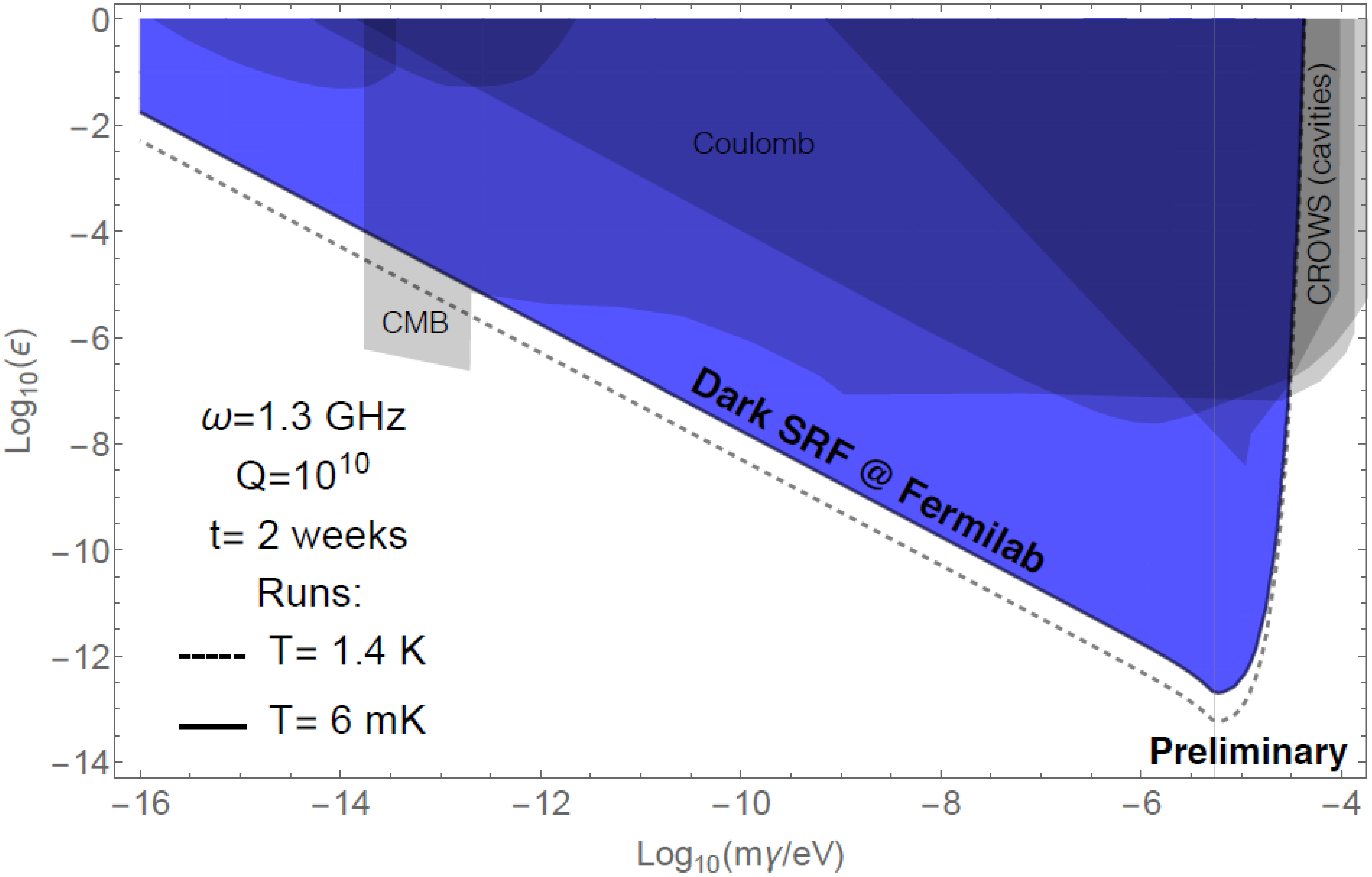
Receiver Cavity

Tuned to 1.3 GHz. Responds to dark field. Contains only thermal noise (T=1.4 K).

For correct cavity positioning $P_{\rm rec} \sim G^2\, \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 Q_{\rm rec} Q_{\rm em} P_{\rm em}$

[see Graham, Mardon, Rajendran, Zhao 2014]

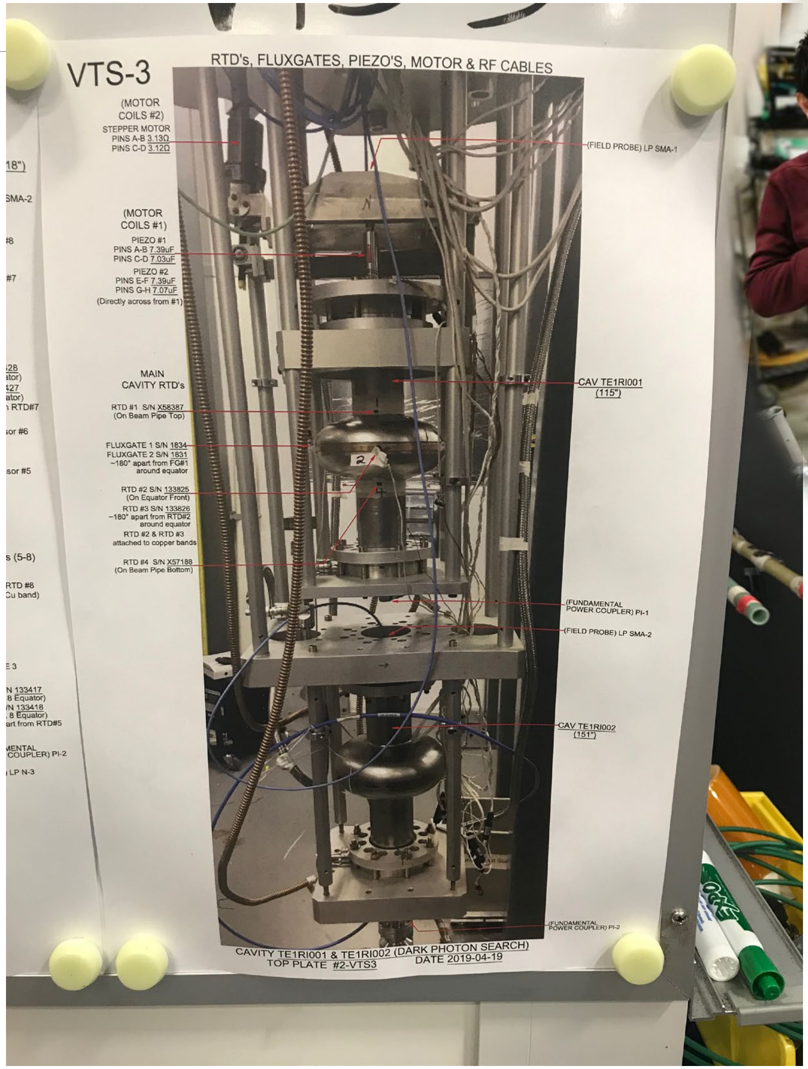
A Dark Photon Search

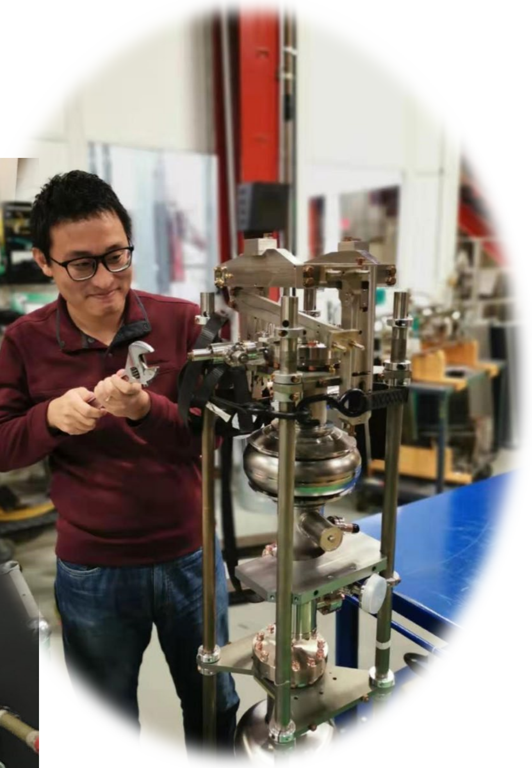


“Run 0” results summary

Everything works!

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





Dielectric haloscopes

Image from R. Lasenby

DM can Bragg-convert in medium, producing photons:

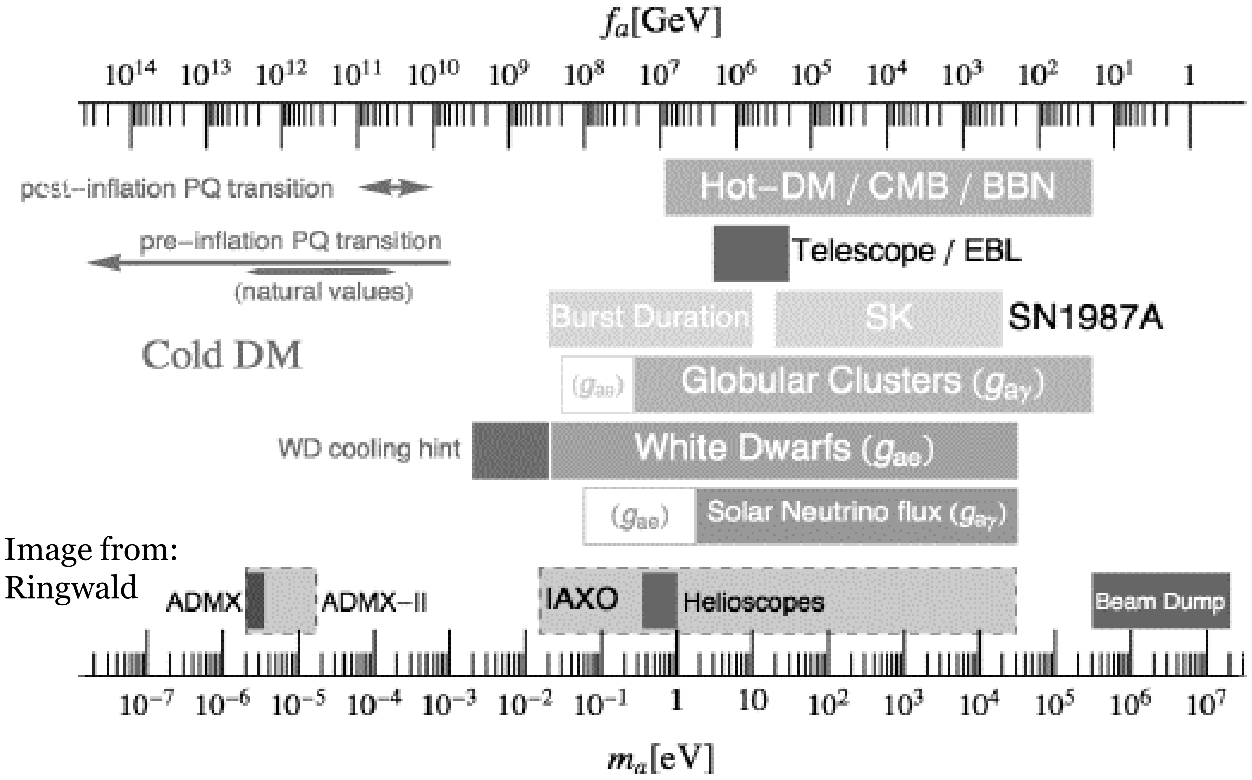
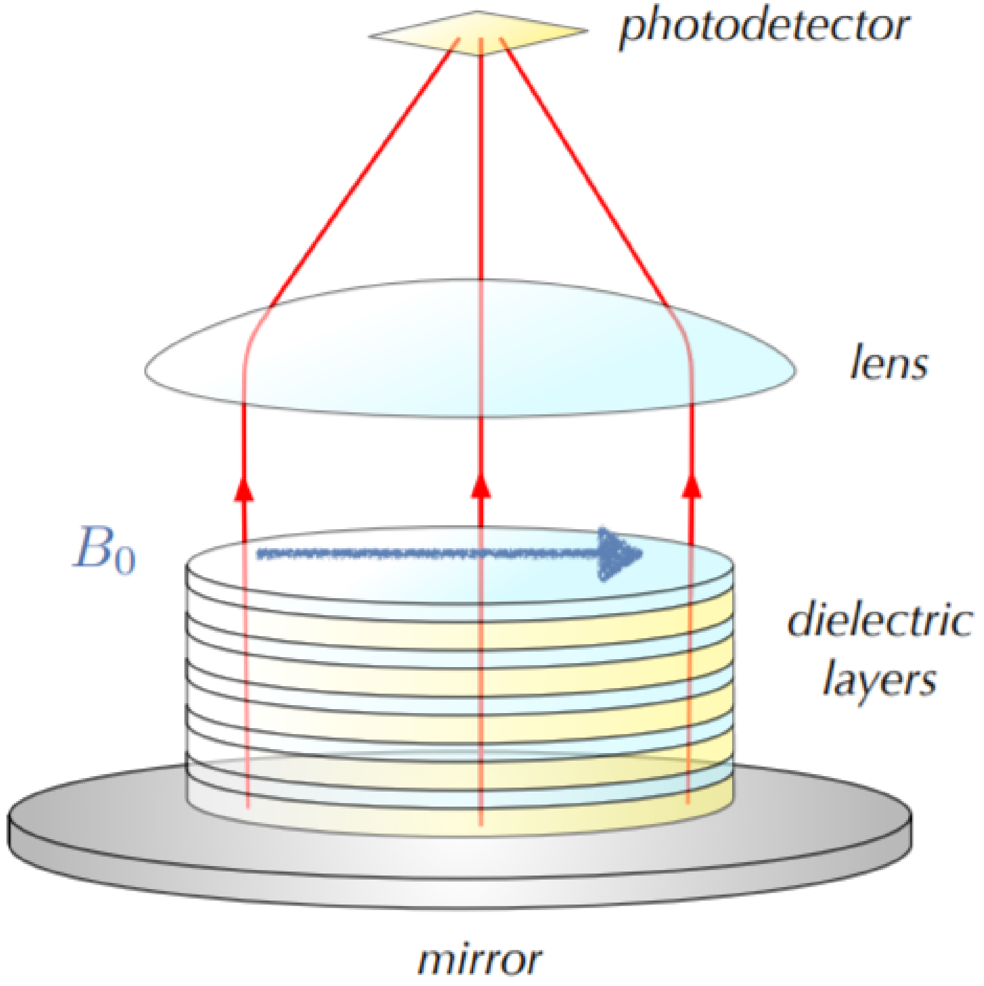
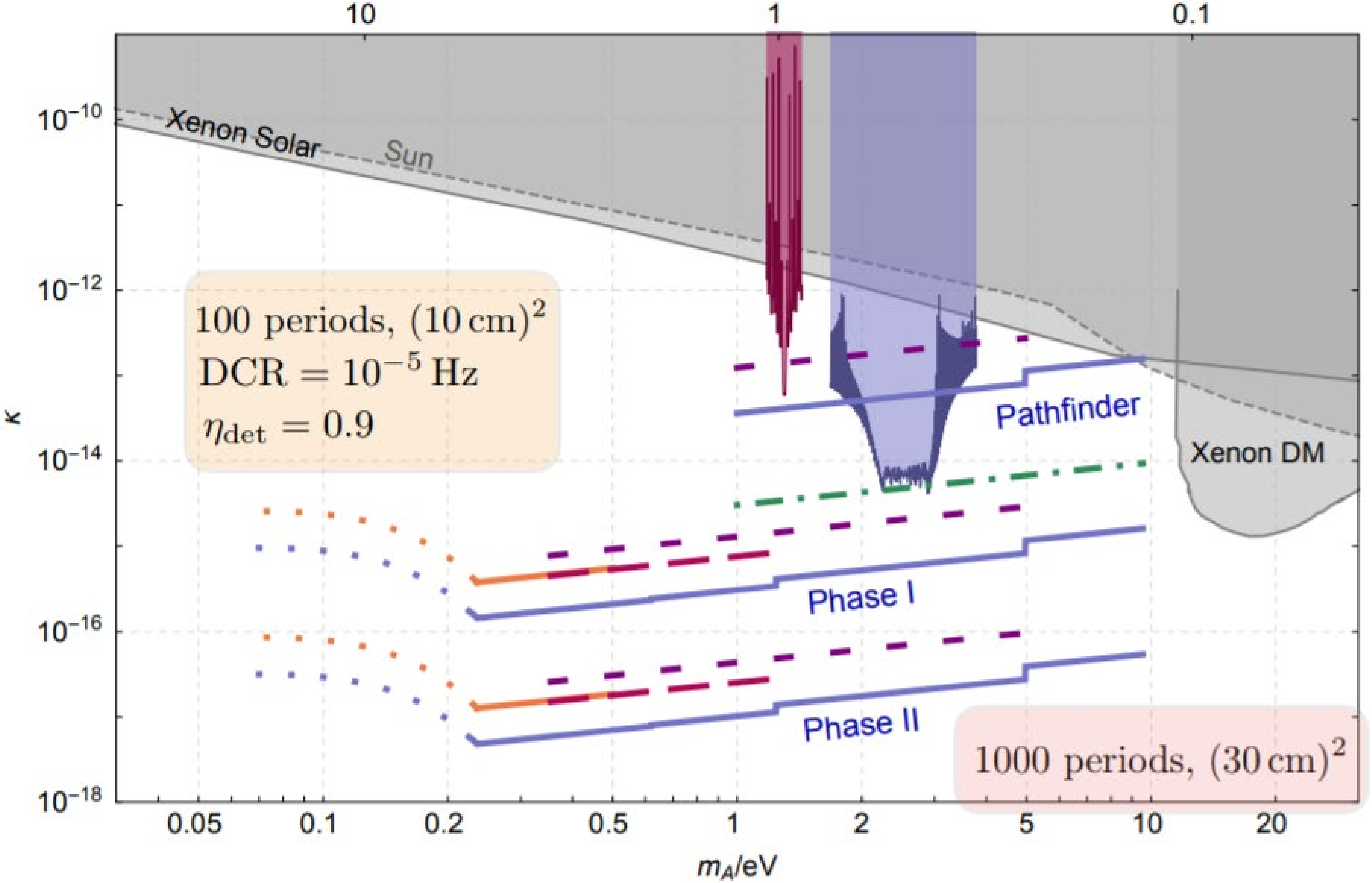


Image from:
Ringwald



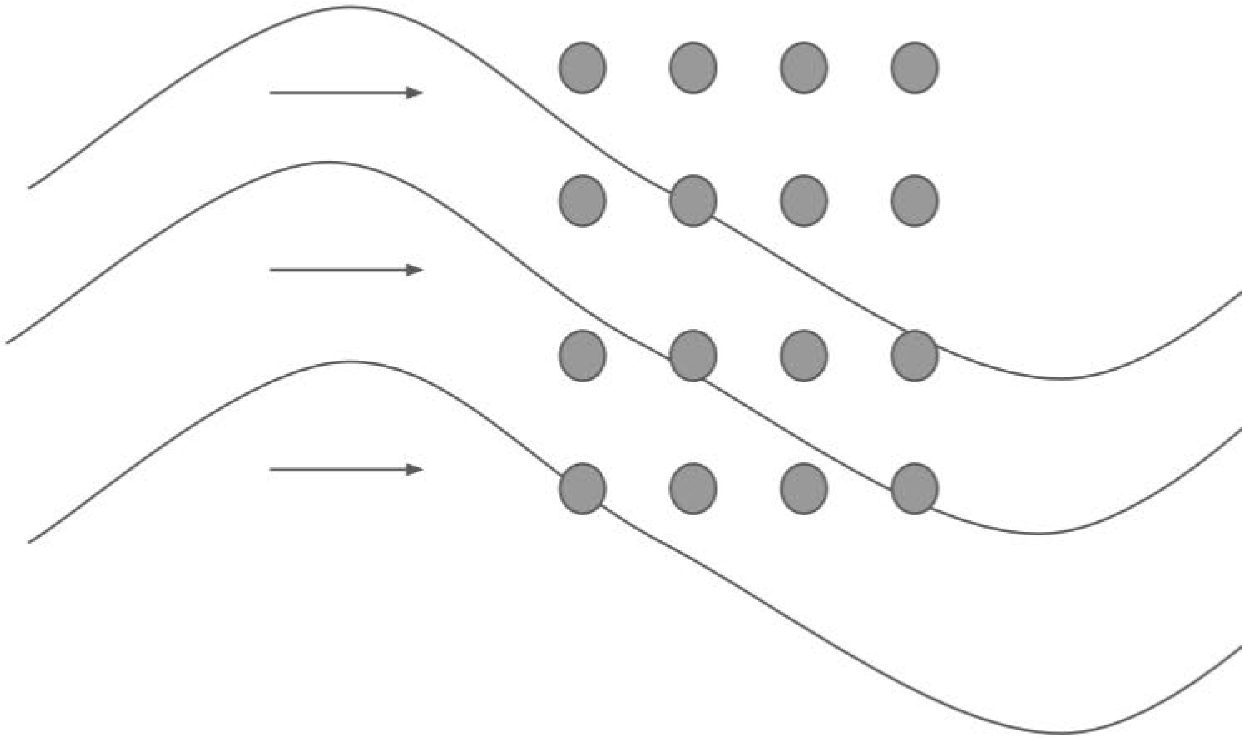
Future sensitivity

Phys.Rev. D98 (2018) no.3, 035006 (1803.11455) - M. Baryakhtar, J. Huang, RL $t_{\rm int} = 10^6\,{\rm sec}$



Ultralight DM

Suppose DM consists entirely of a single, very light field.

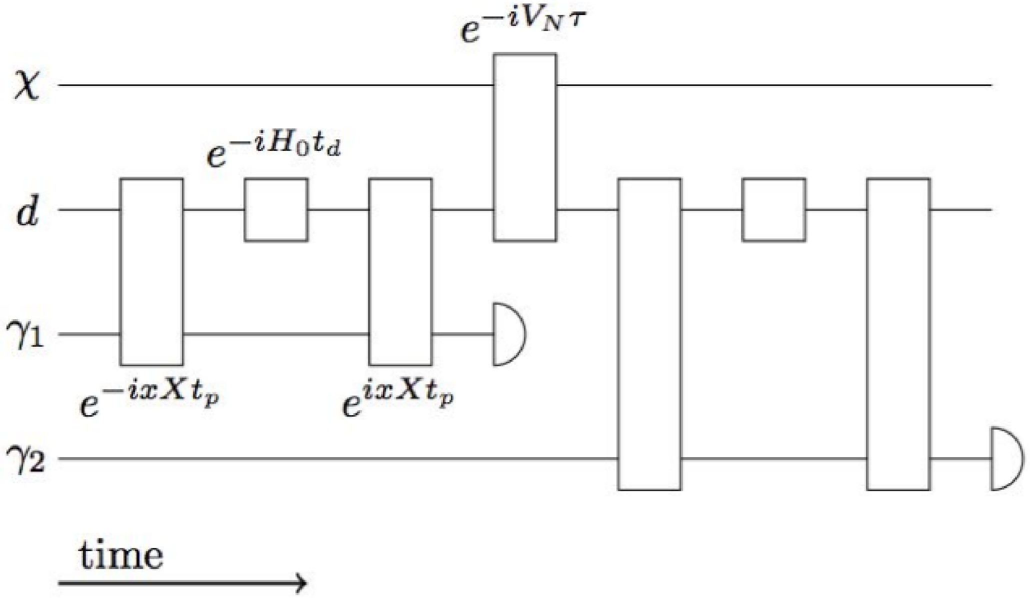


Locally, this will essentially look like a coherent wave acting across the whole array.

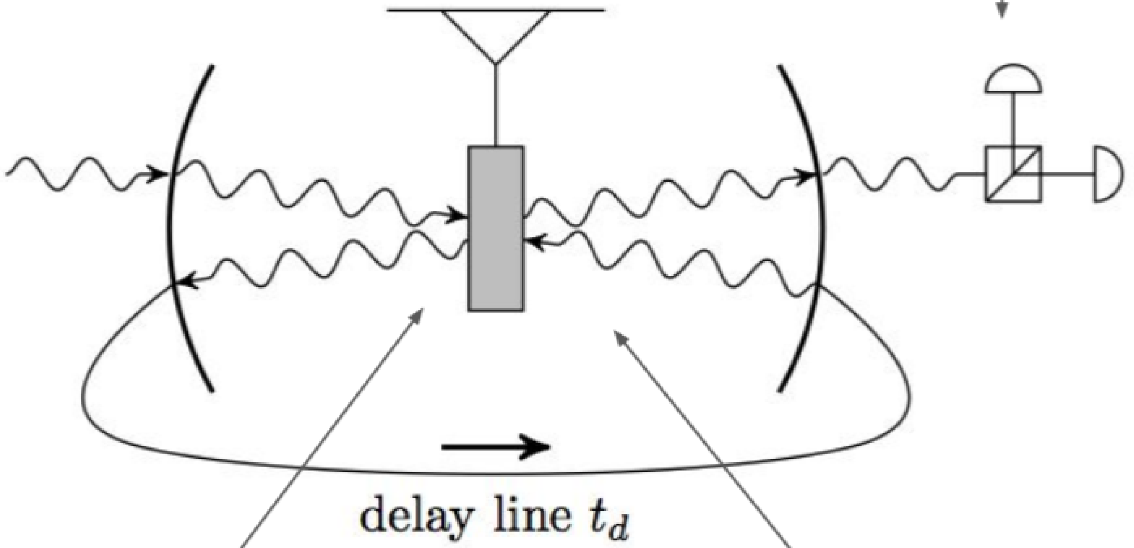
$$\mathcal{L}_{int} = g_{B-L} \not{A} \bar{n} n$$

$$F = g_{B-L} N_n F_0 \sin(\omega_s t)$$

Back-action evasion measurement of velocity



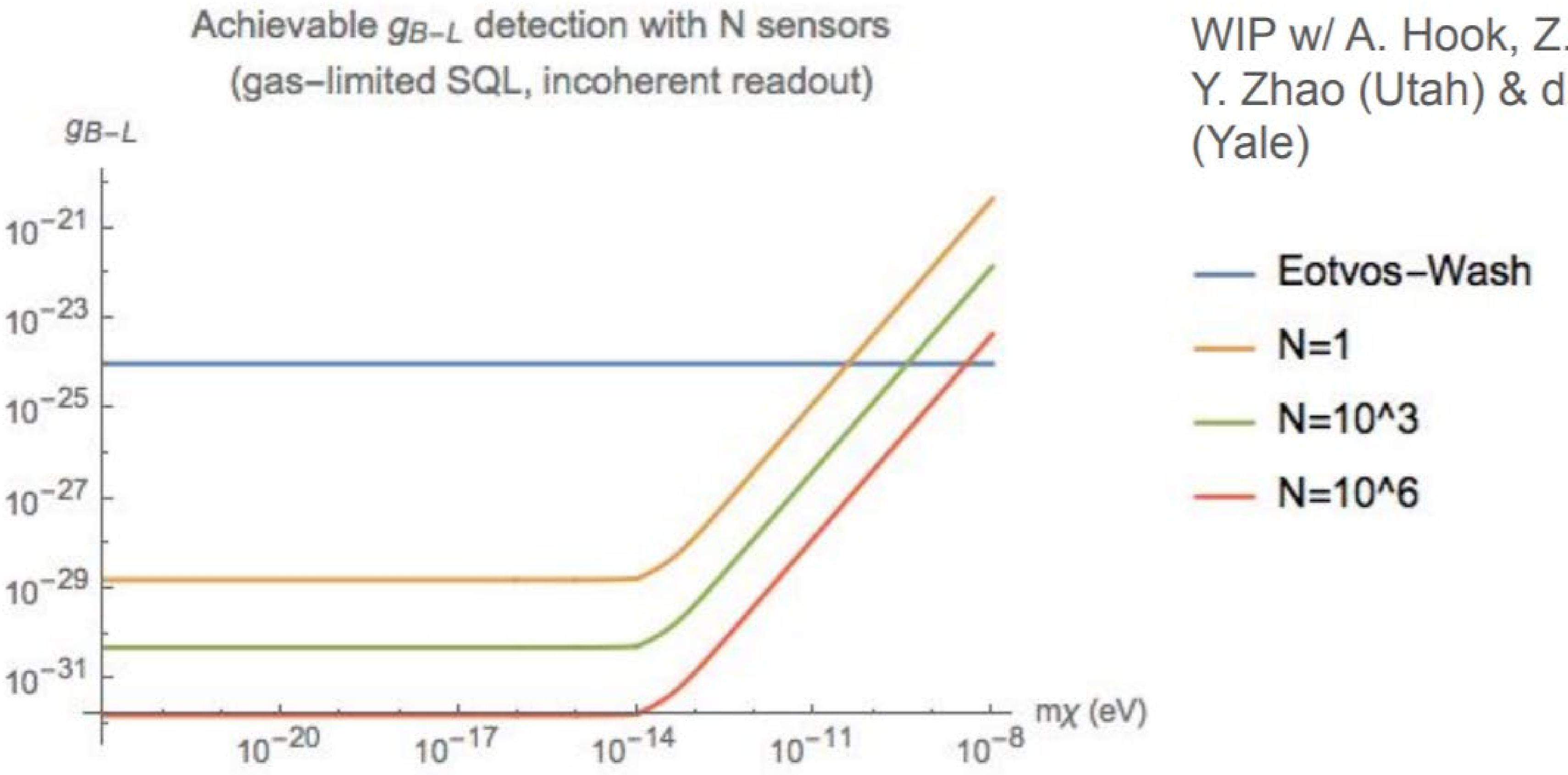
readout light phase via interferometer



light phase ~ $x(t_1)$
impart +p to mirror

light phase ~ $-x(t_2)$
impart -p to mirror

→ Light phase ~ $x(t_1)-x(t_2)$ ~ v, momentum transfer ~ 0.



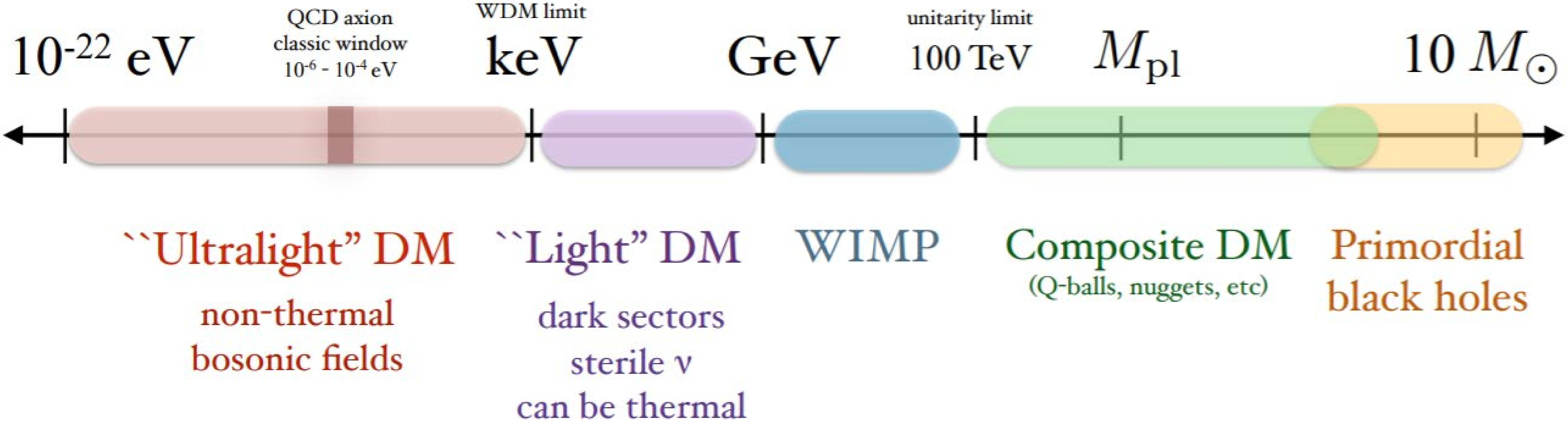
WIP w/ A. Hook, Z. Liu, J. Taylor (UMD), Y. Zhao (Utah) & discussions w/ D. Moore (Yale)

SNR ~ 1/sqrt(N_{total}) → huge win via scaling (signal = coherent oscillation of entire lattice)

Here plotting mg-scale detectors operating “just” at SQL.

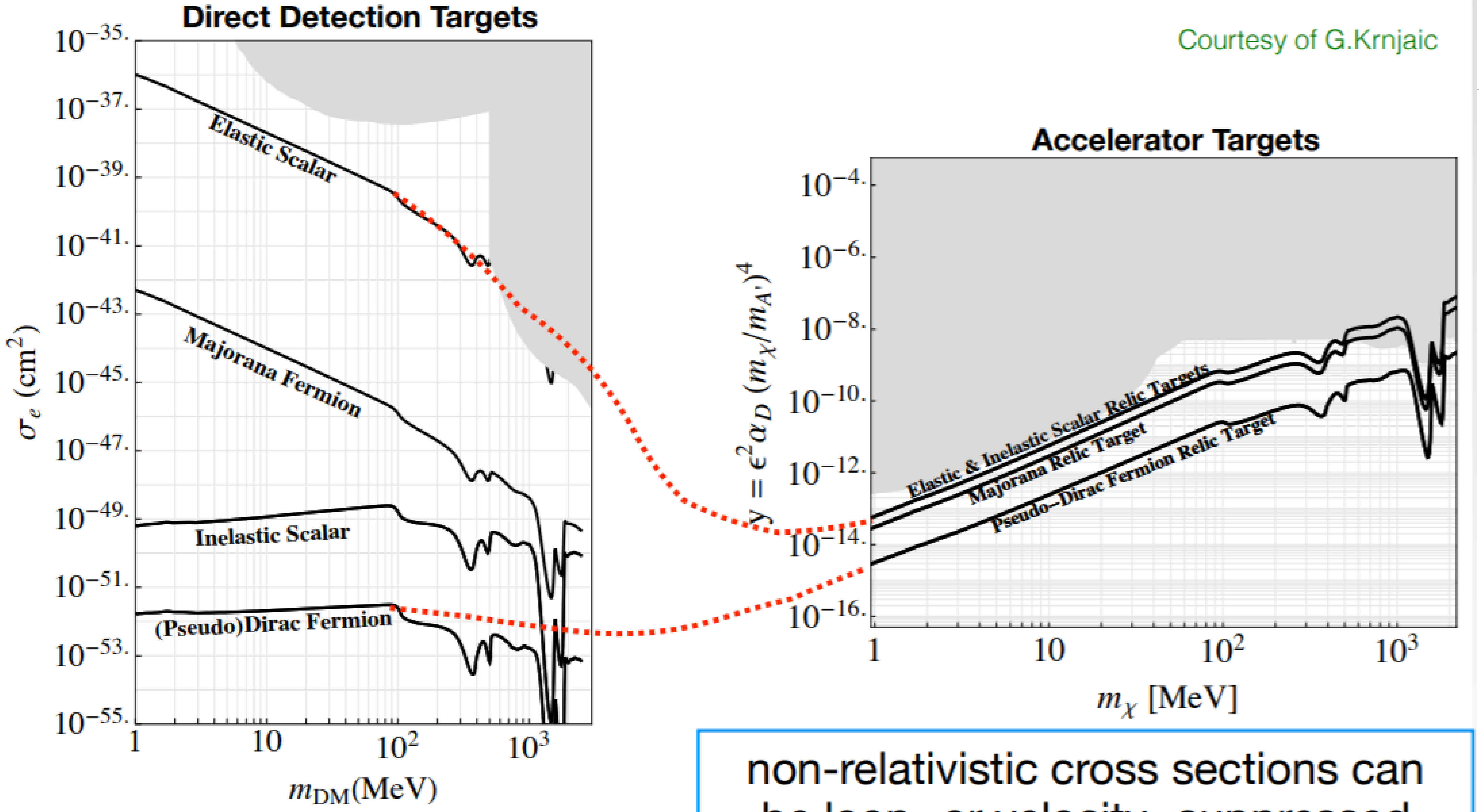
Backaction-evasion improves high-frequency limits.

Summary

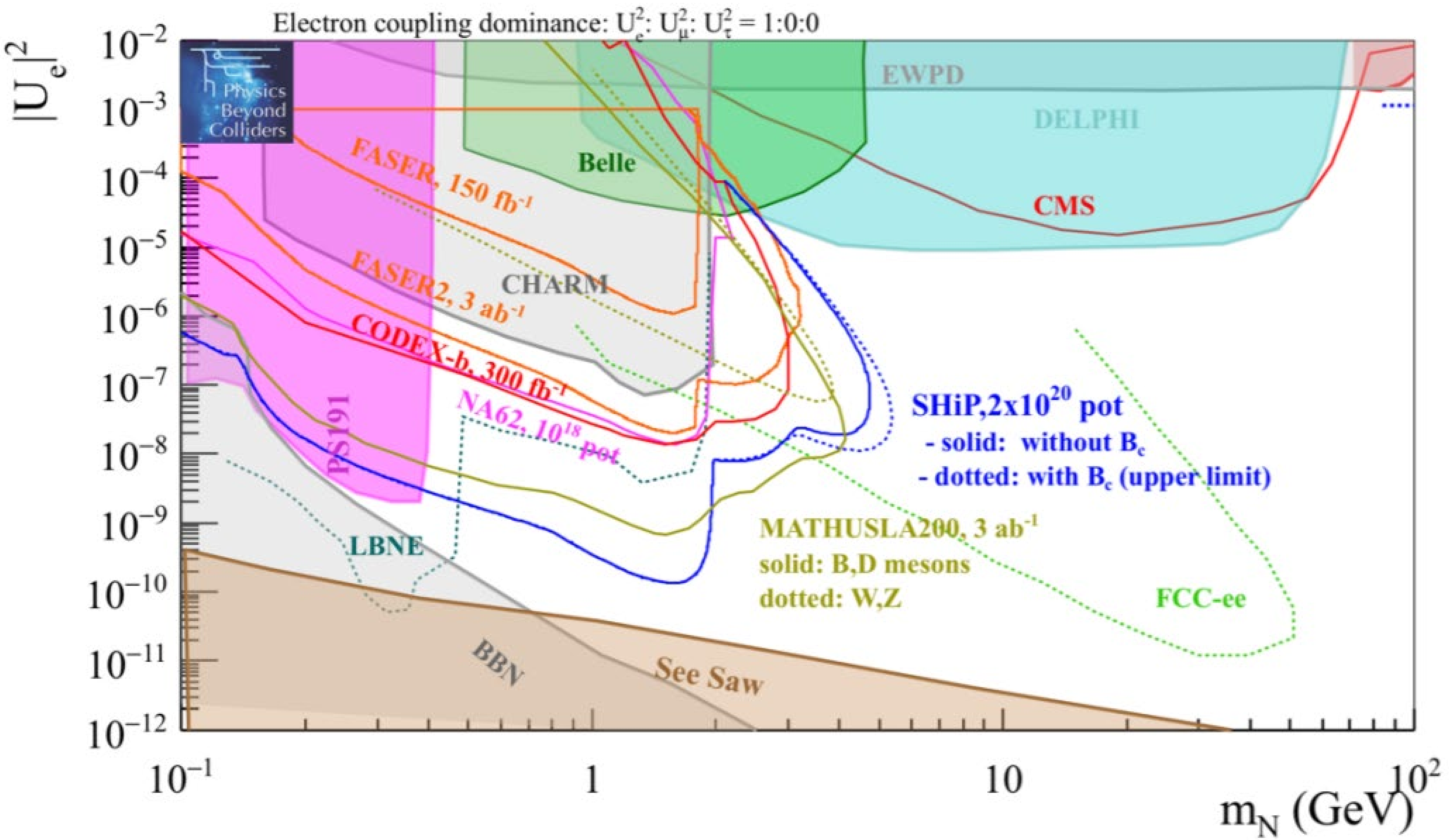


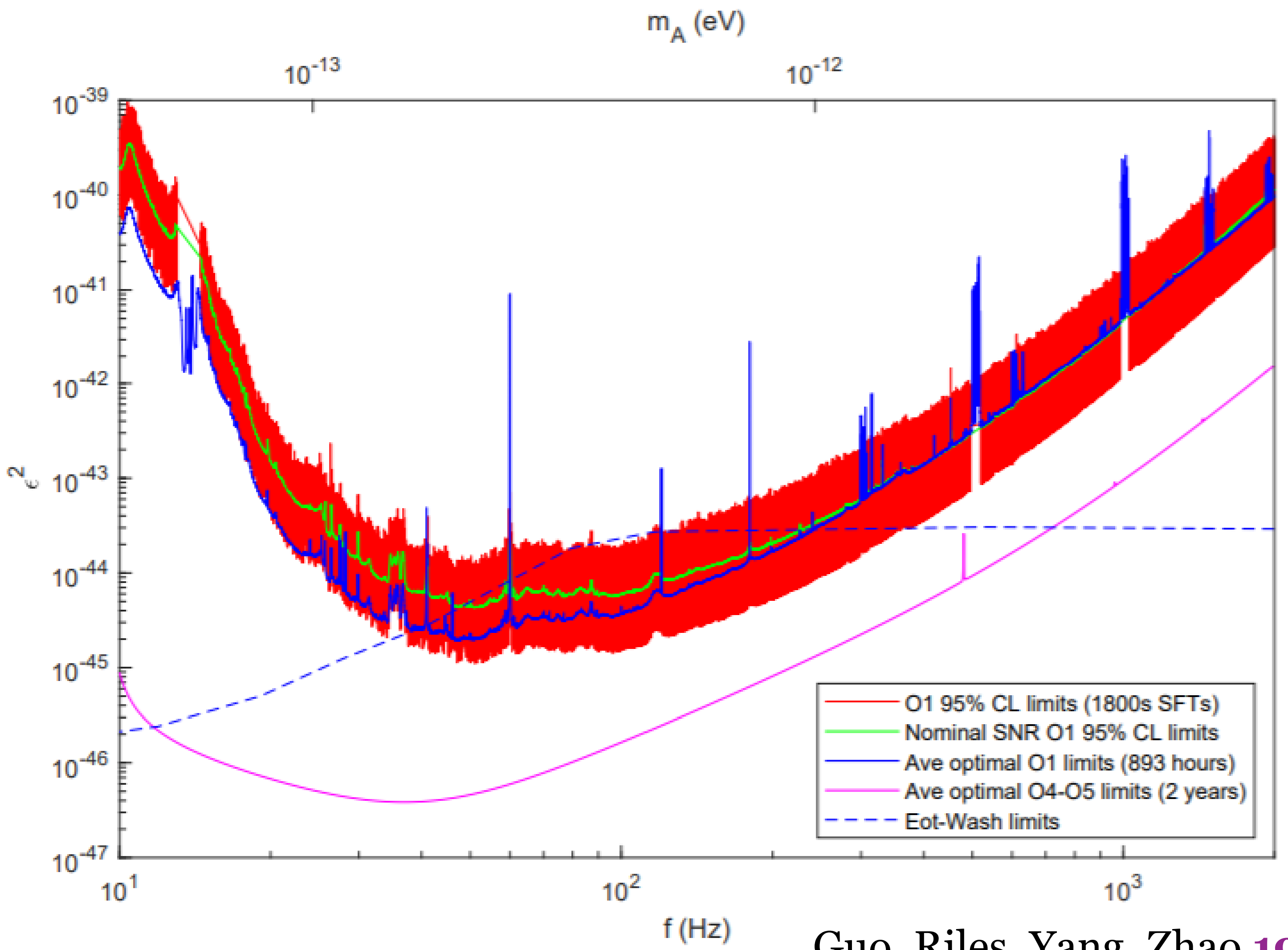
Lots of opportunities!

Backup



non-relativistic cross sections can be loop- or velocity- suppressed


Electron coupling dominance: U_e^2: U_μ^2: U_τ^2 = 1:0:0
|U_e|^2
m_N (GeV)
Physics Beyond Colliders
EWPD
DELPHI
Belle
CMS
FASER, 150 fb^-1
FASER2, 3 ab^-1
CHARM
CODEX-b, 300 fb^-1
NA62, 10^18 pot
PS191
SHiP,2x10^20 pot
- solid: without B_c
- dotted: with B_c (upper limit)
MATHUSLA200, 3 ab^-1
solid: B,D mesons
dotted: W,Z
LBNE
FCC-ee
BBN
See Saw



Guo, Riles, Yang, Zhao [1905.04316]