Theory motivation overview

Stefania Gori
UC Santa Cruz

DarkQuest 1st collaboration meeting

October 20, 2023

Outline

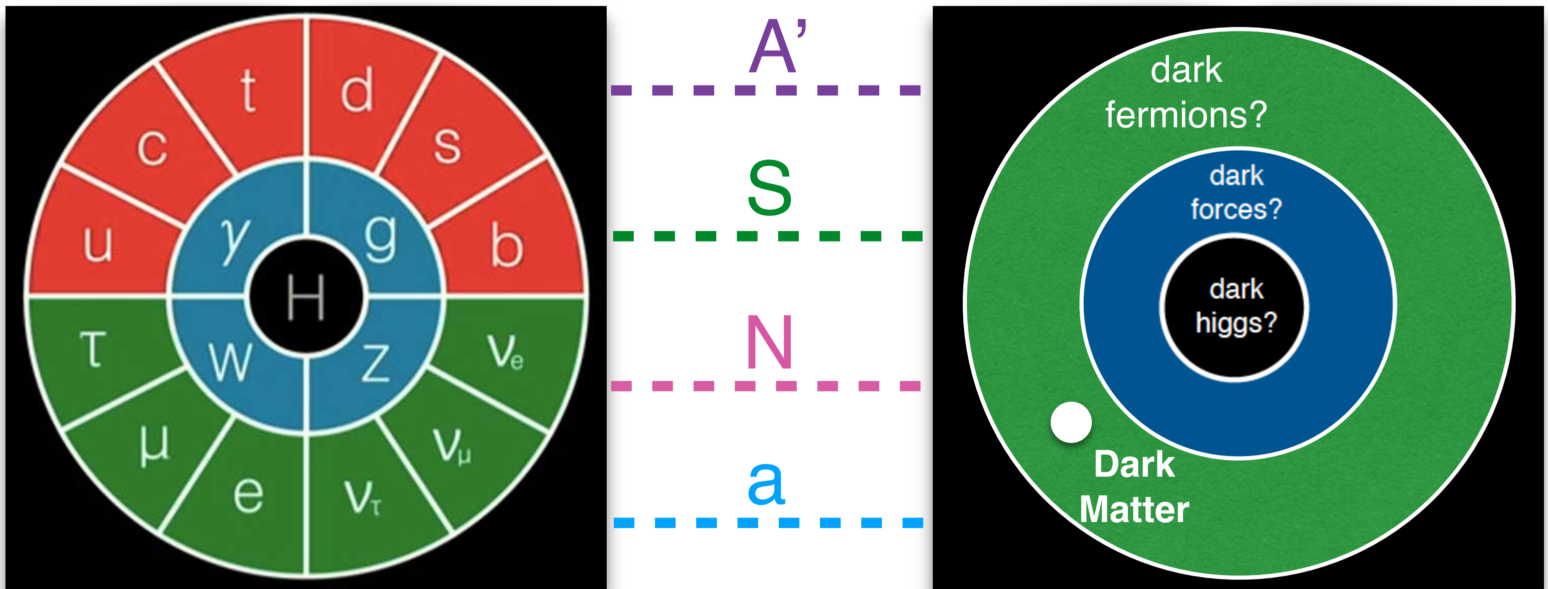
* Theoretical motivations:
  Dark Matter, strong CP problem, …

* Putting visible dark sectors in a context:
  Previous community efforts + Snowmass

* Review of phenomenological studies for DarkQuest

* Future studies & open questions

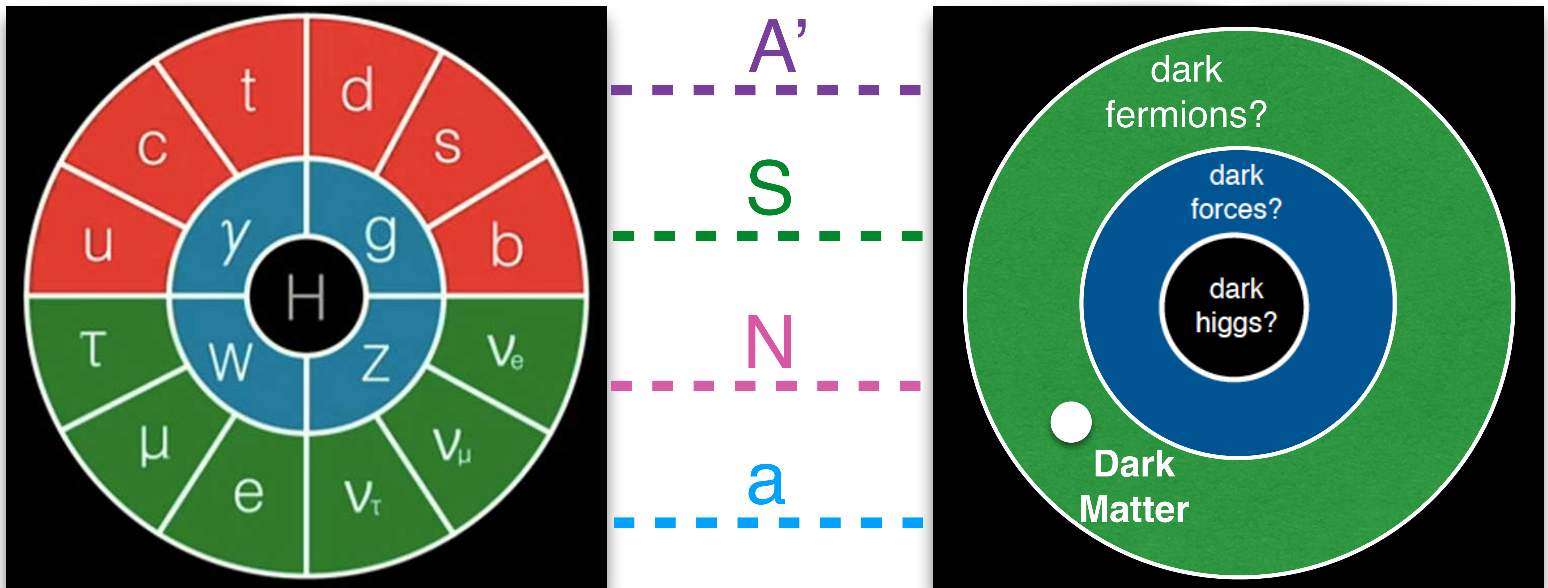
Dark Sectors in particle physics



not charged under
the Standard Model (SM)
gauge symmetries

+ possible new gauge bosons, from gauging approximate SM symmetries: B-L, $L_\mu - L_\tau$, …

Dark Sectors in particle physics



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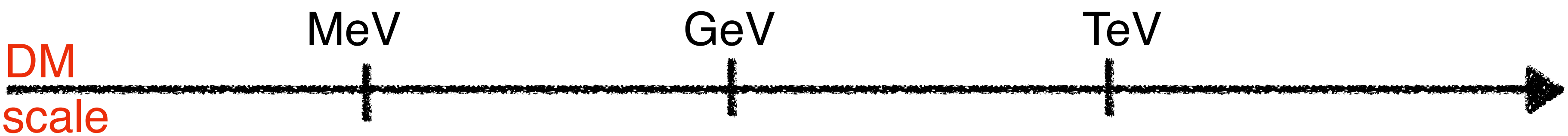
gauge symmetries

\+ possible new gauge bosons, from gauging approximate SM symmetries: B-L, $L_\mu - L_\tau$, …

Why do we want a dark sector?

MeV-GeV Dark Matter living in a dark sector

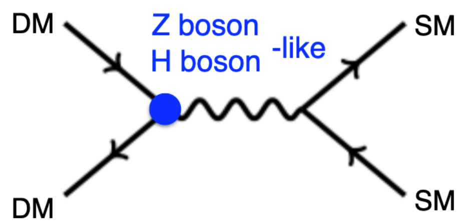
The DM mass scale

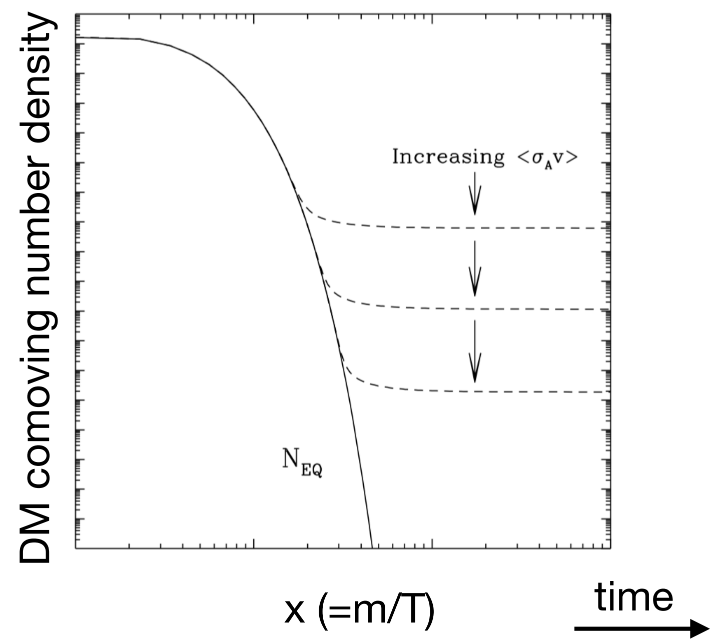


WIMPs

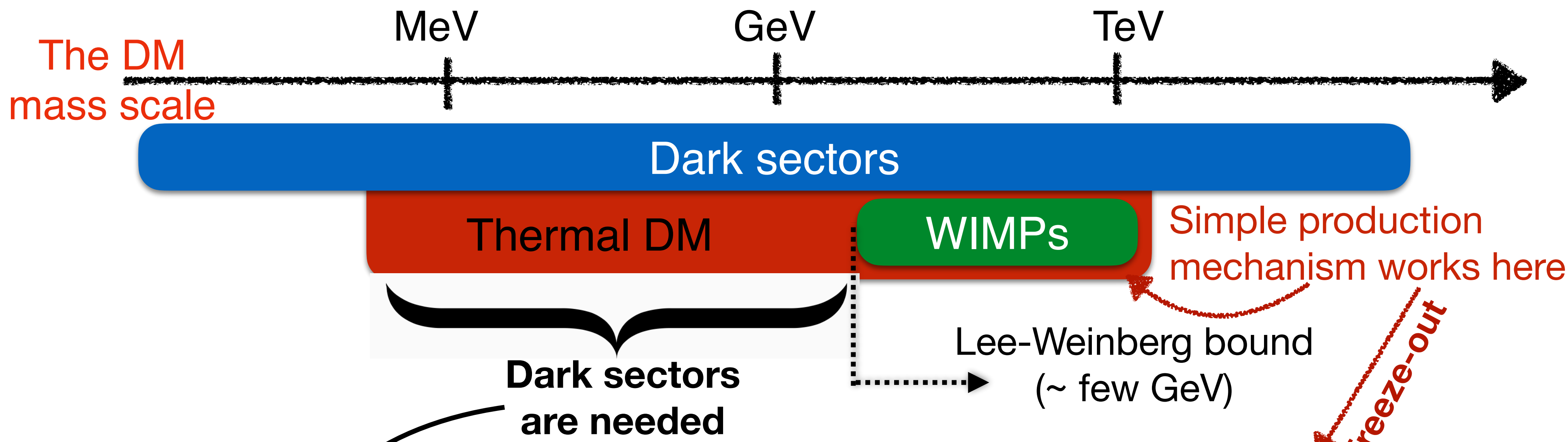
Simple production mechanism works here

freeze-out



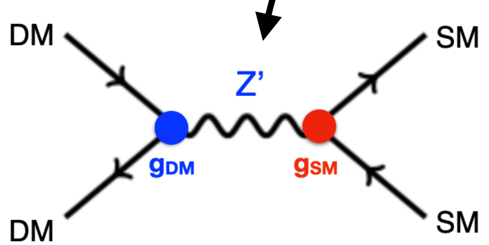


MeV-GeV Dark Matter living in a dark sector

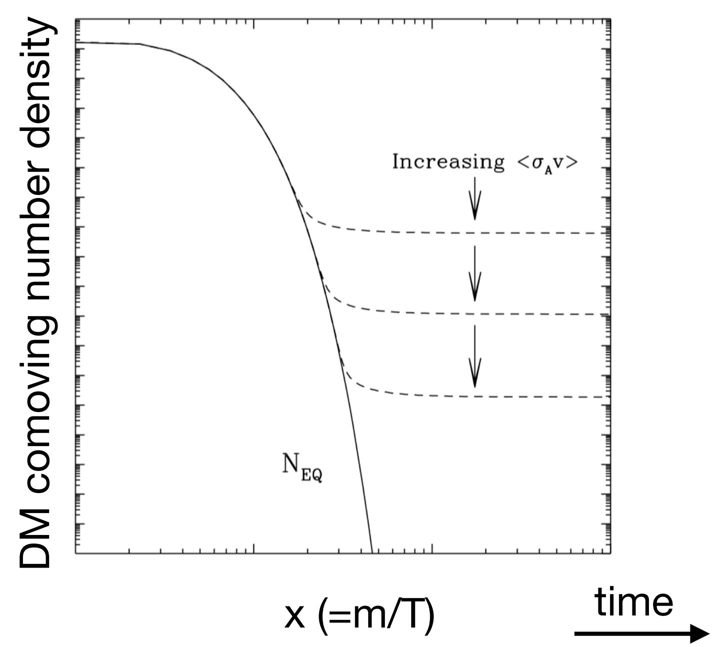


WIMP is a beautiful and predictive framework.

Can we extend it to lower masses?



YES



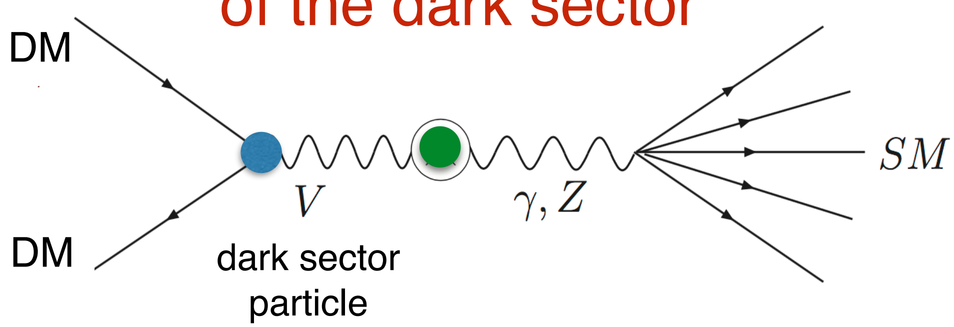
$$\langle\sigma v\rangle \sim 1\text{pb}\times\left(\frac{g_{\rm DM}}{0.5}\right)^2\left(\frac{g_{\rm SM}}{0.001}\right)^2\left(\frac{m_{\rm DM}}{100\text{ MeV}}\right)^2\left(\frac{1\text{ GeV}}{m_{Z'}}\right)^4\sim 1\text{pb}$$

for the measured relic abundance

Two general classes of thermal DM

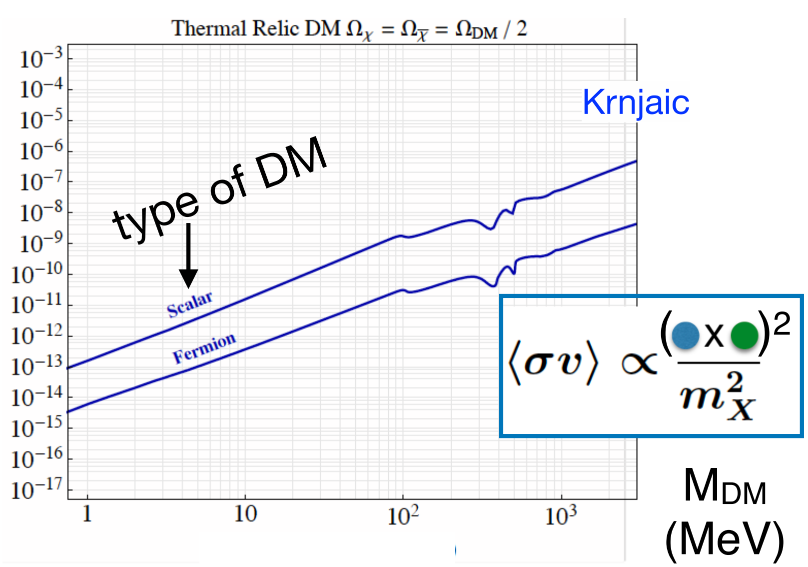
1.

DM is the lightest state
of the dark sector



Relic abundance regulated by ,

X



$$\langle \sigma v \rangle \propto \frac{(\;\text{x}\;)^2}{m_X^2}$$

Two general classes of thermal DM

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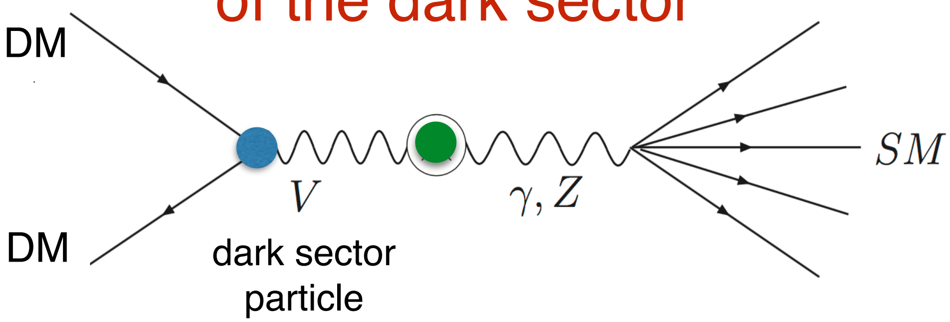
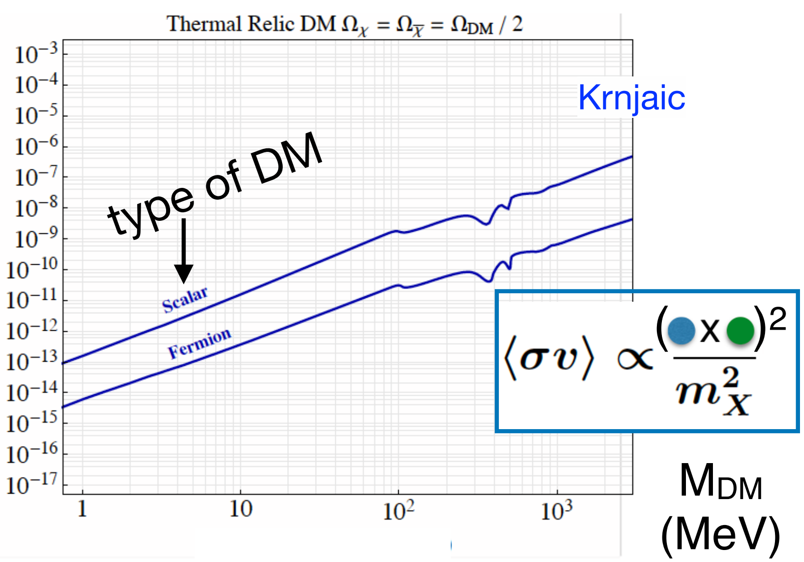


Relic abundance regulated by ●, ●

● X ●



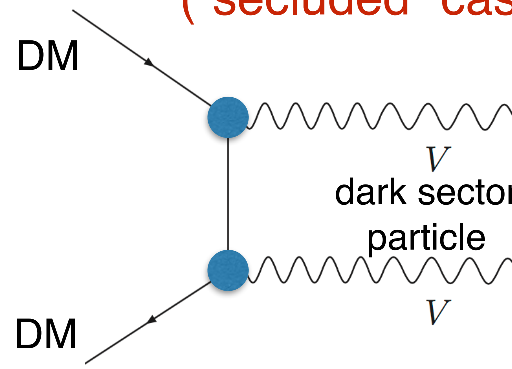
$$\boxed{\langle \sigma v \rangle \propto \frac{(\bullet \times \bullet)^2}{m_X^2}}$$

M_{DM} (MeV)

2. **One (or more) particles** of the dark sector **are lighter than DM**

("secluded" case)

Pospelov, Ritz, Voloshin, 0711.4866



$$\boxed{\langle \sigma v \rangle \propto \frac{\alpha_D^2}{m_X^2}}$$

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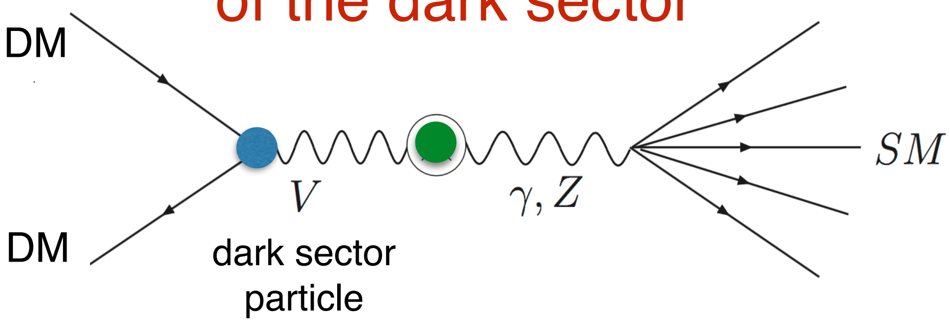

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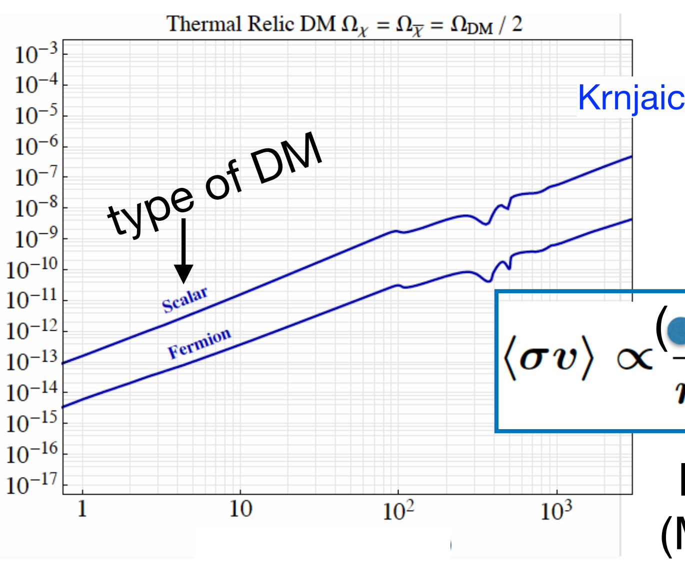

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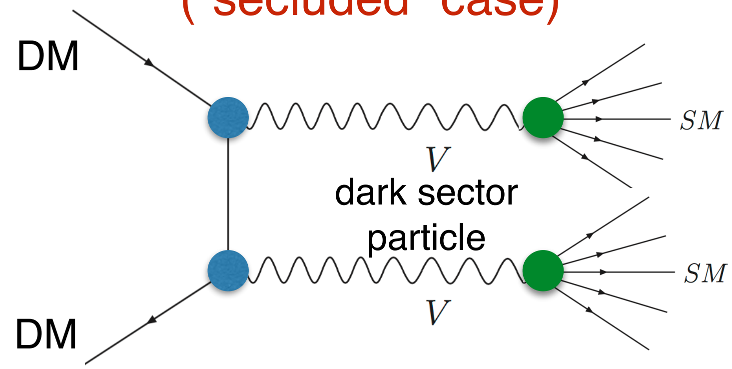
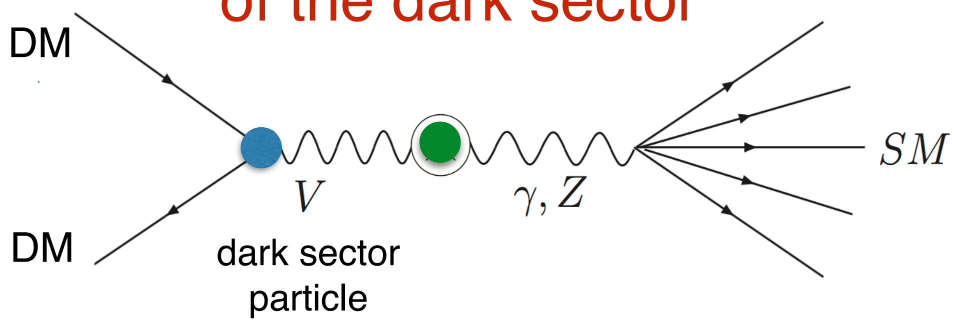


thermalization

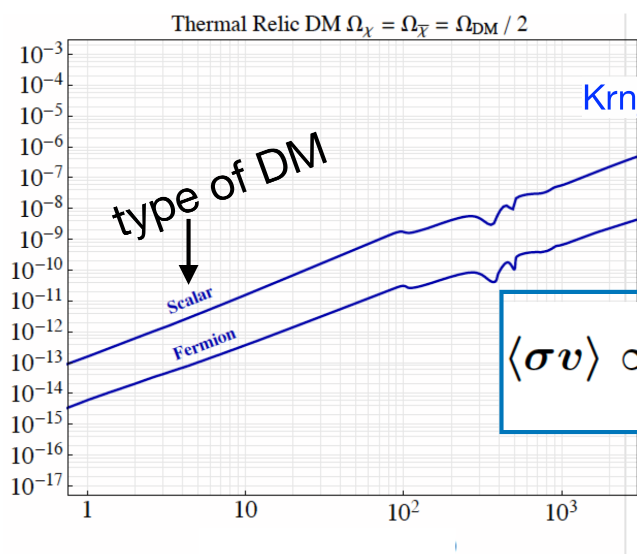
Two general classes of thermal DM

1. DM is the lightest state of the dark sector



Relic abundance regulated by ●, ●

● x ●



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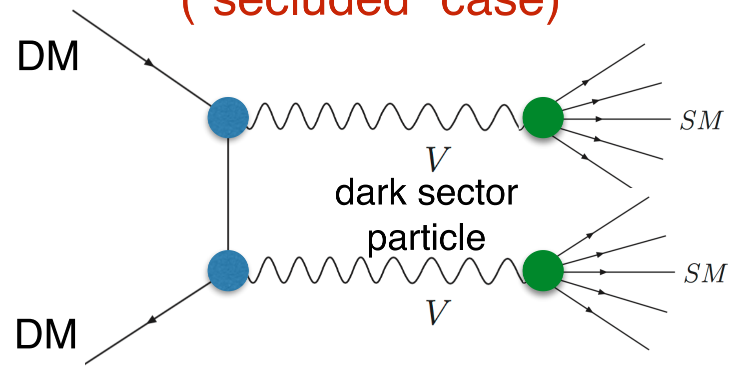
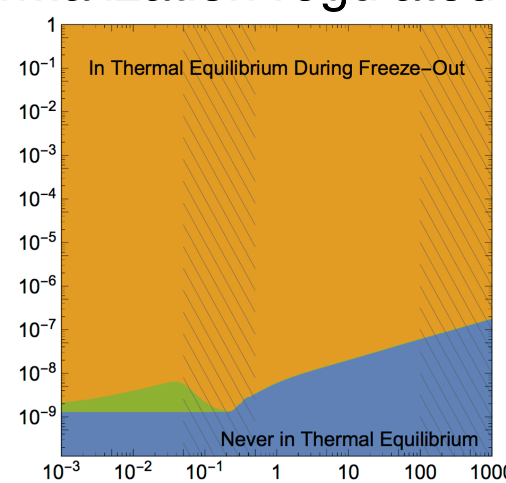


Thermalization regulated by ●

●



Lower bound

Evans, SG, Shelton, 1712.03974

M_{DM} (GeV)

Two general classes of thermal DM

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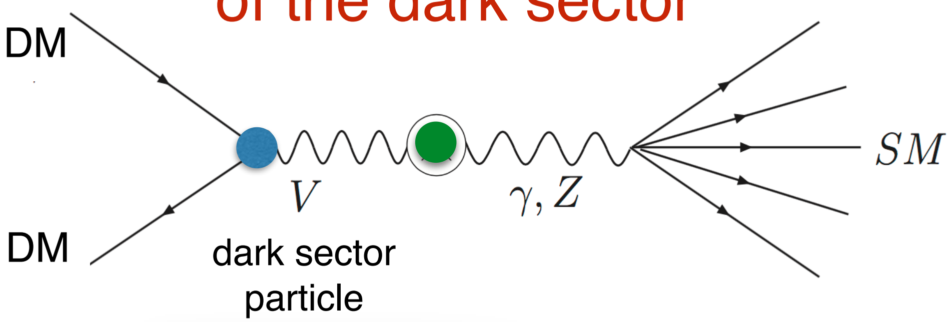

Relic

X

2. **One (or more) particles** of the dark sector **are lighter than DM**

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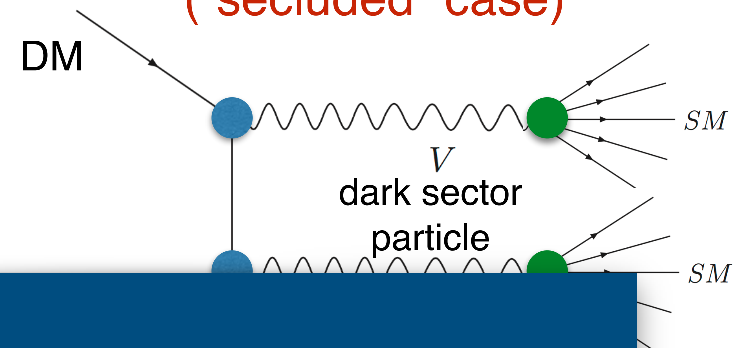
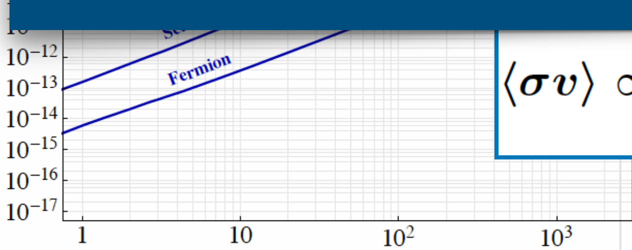


y

Take home message:

in both scenarios, thermal DM demands specific non-zero couplings with the Standard Model

experimental targets!



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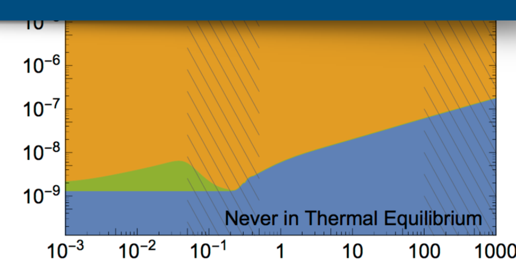
M_{DM} (MeV)

Evans, SG, Shelton, 1712.03974



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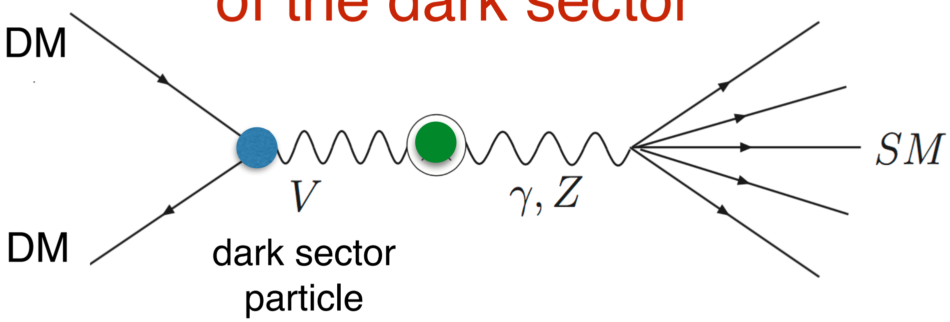


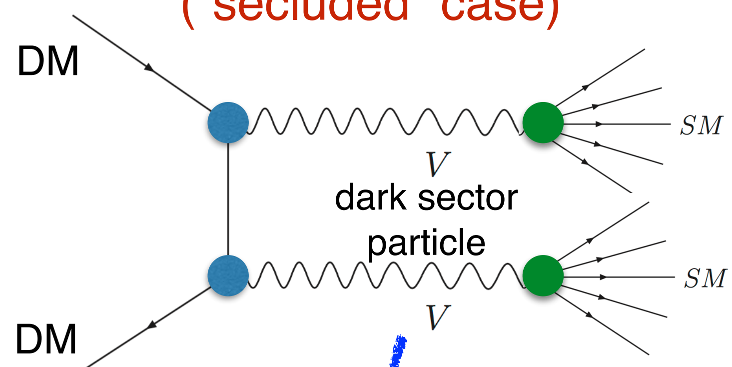
Signatures at accelerator experiments:

The dark sector particle, V, mainly decays **invisible** (to DM)

V→ DM DM

2. **One (or more) particles** of the dark sector **are lighter than DM**

("secluded" case)



Signatures at accelerator experiments:

The dark sector particle, V, decays **visible** (to SM particles)

V→ SM SM

Dark sectors: a generic feature of New Physics models

Beyond the Dark Matter motivation,
dark sectors arise in many theories beyond the Standard Model:

* Theories motivated by the hierarchy problem:
  - Supersymmetric theories (Next-to-Minimal-Supersymmetric-Standard-Model)
  - Neutral Naturalness
  - Relaxion theories
* Theories that explain the baryon-antibaryon asymmetry
* Theories that address the strong CP problem (axions and axion-like-particles)
* Theories for the generation of neutrino masses

* Several anomalies in data can be addressed by dark sectors
  (eg. $(g-2)_\mu$, B-physics anomalies, short-baseline neutrino anomalies, …)

From a phenomenological point of view,
the signatures to search for are often similar

Exploring the dark sector

Symmetries of Standard Model provide a framework for the systematic exploration of (weakly-coupled) dark sector physics

- SM gauge-invariant
- Dark sector gauge-invariant
- Lorentz invariant

simple set of requirements

- Lowest dimensional operator first
- Minimal number of particles first (*)
- Flavor invariant operators first (*)

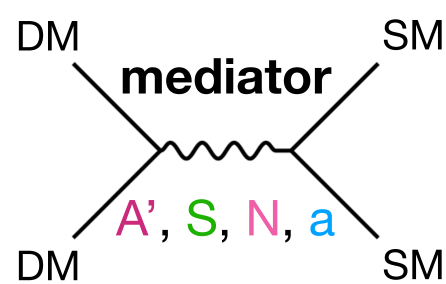
(*) some studies go beyond this assumption

Dark sector portals

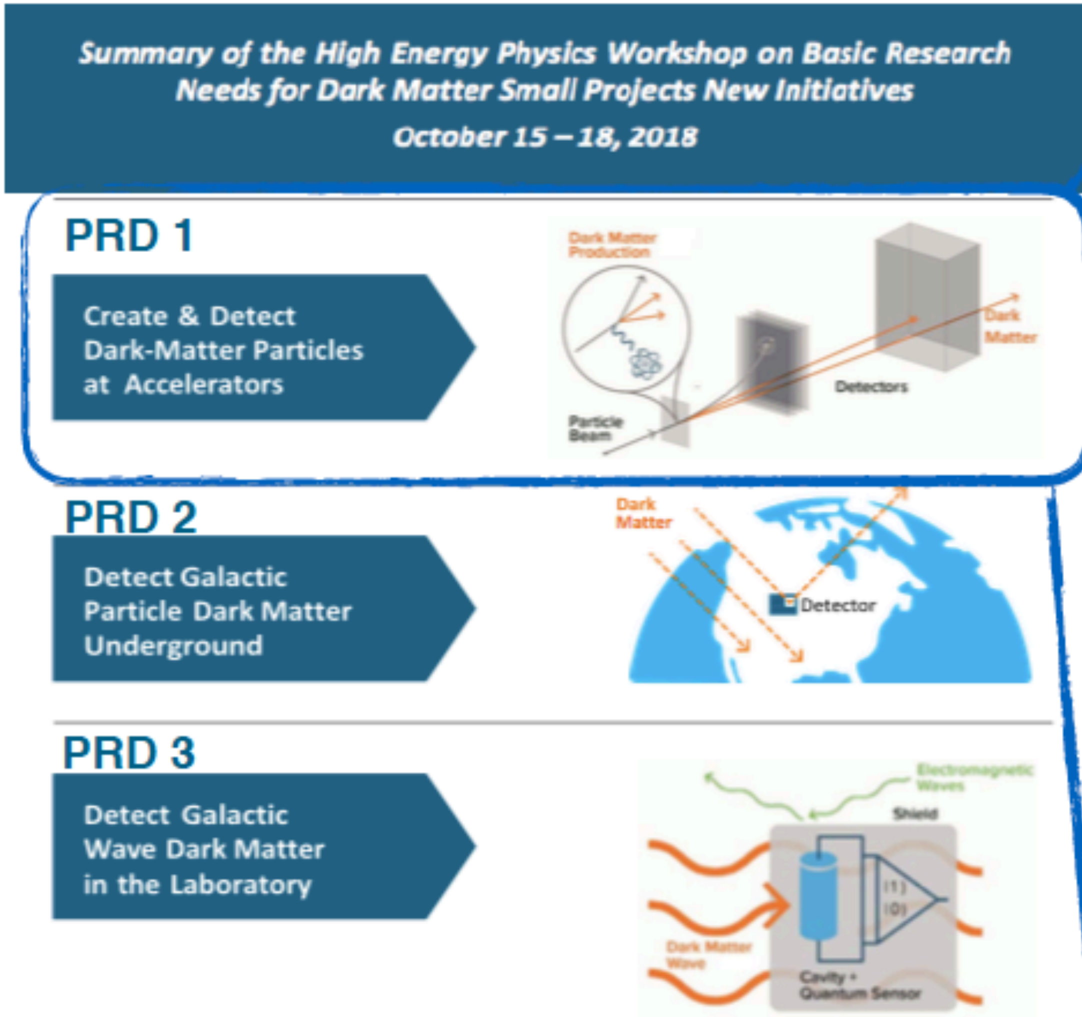
Experimental targets

- dark photon $\epsilon B^{\mu\nu} A'_{\mu\nu}$
- dark scalar $\kappa |H|^2 |S|^2$
- sterile neutrino $y H L N$
- Axion $g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$
- Gauging an anomaly free SM symmetry: B-L, $L_\mu - L_\tau$, …

the couplings are in general small but models do have a lower bound:
e.g., thermal freeze-out; thermalization; anomalies in data, …



DOE supported DM New Initiatives (DMNI)



https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

high intensities

Thrust 1 (near term):
Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.
(CCM & LDMX got partial support)

Thrust 2 (near and long term):
Explore the structure of the dark sector by producing and detecting unstable dark particles. **DarkQuest goal**

Snowmass, RF6, Dark Sectors at High Intensities

Conveners: SG, Mike Williams

Organization around science goals/questions.
We built on what we have learned since 2013 (previous Snowmass).

We defined **three Big Ideas** each with associated goals for the next decade

1. Dark matter production at intensity-frontier experiments
(focus on exploring sensitivity to thermal DM interaction strengths).
Editors: G. Krnjaic, N. Toro (https://arxiv.org/abs/2207.00597)

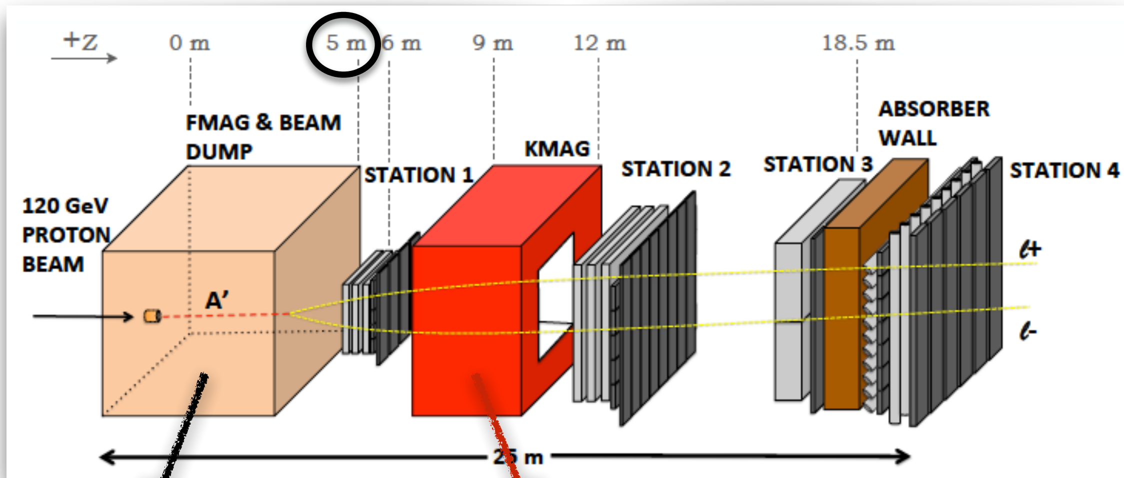
2. Exploring dark sector portals with intensity-frontier experiments
(focus on minimal portal interactions).
Editors: B. Batell, N. Blinov, C. Hearty, R. McGehee (https://arxiv.org/abs/2207.06905)

3. New flavors and rich structures of the dark sector at intensity-frontier experiments
(focus on beyond minimal models)
Editors: P. Harris, P. Schuster, J. Zupan (https://arxiv.org/pdf/2207.08990.pdf)

4. Experiments / facilities.
Editors: P. Ilten, N. Tran (https://arxiv.org/abs/2206.04220)

Report: https://arxiv.org/pdf/2209.04671.pdf

DarkQuest: a unique experiment



FMAG sweeps away soft SM radiation

1. Compact geometry

Sensitivity to (slightly) displaced dark particles with **d > 5m**

2. KMAG separating even very forward charged particles

Identification of very light dark particles/squeezed spectra

Experiment	Proton energy	POT	Dump	Decay volume
DarkQuest	120GeV	10^{18}	5 m	10 m
CHARM	400GeV	2.4×10^{18}	480 m	35 m
LSND	800MeV	10^{22}	30 m	10 m
NA62-dump	400 GeV	5×10^{19}	100 m	250 m
SHiP	400 GeV	2×10^{20}	35 m	100 m

Past

Proposed

+ SHADOWS (off-axis)

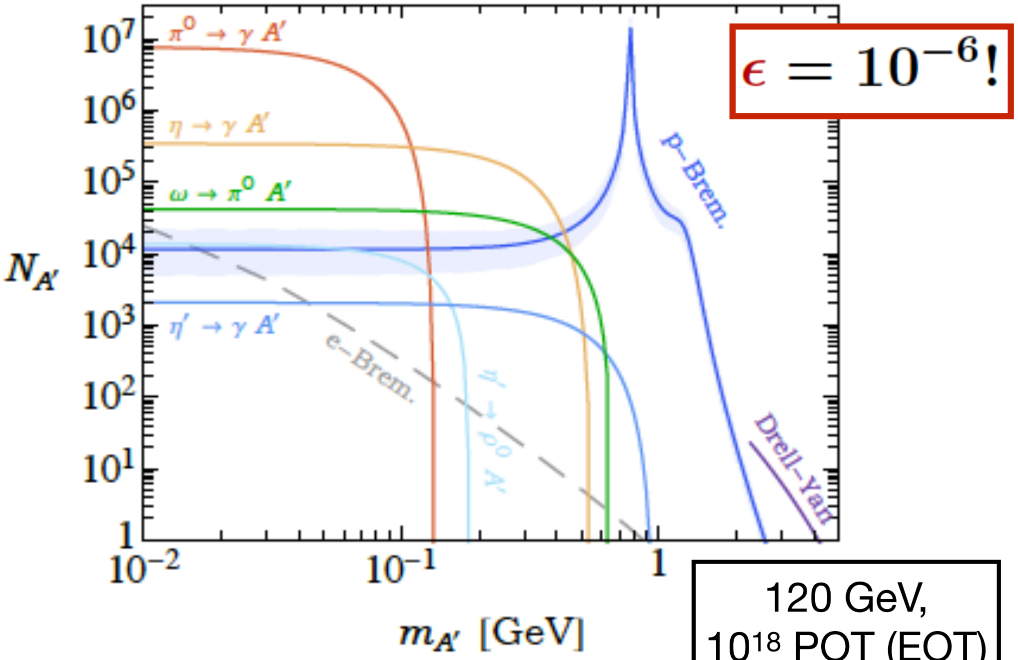
Why a high energy compact proton beam dump?

1. Large production rates of dark particles

$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta} \hat{V}_{\mu\nu} \hat{B}^{\mu\nu}$$

In the case of a dark photon:

Berlin, SG, Schuster, Toro, 1804.00661



120 GeV,
10^{18} POT (EOT)

1. A lot of light mesons: $\sim 10^{19}$ pions
past pion factories: $\sim 10^{11}$ pi

2. Larger Bremsstrahlung production than at electron fixed target:

proton: $\sigma \sim \alpha_{\rm em}\, \epsilon^2 \times \sigma_{pp}$

electron: $\sigma \sim \dfrac{\alpha_{\rm em}^3\, \epsilon^2}{m_{A'}^2}\, Z^2$

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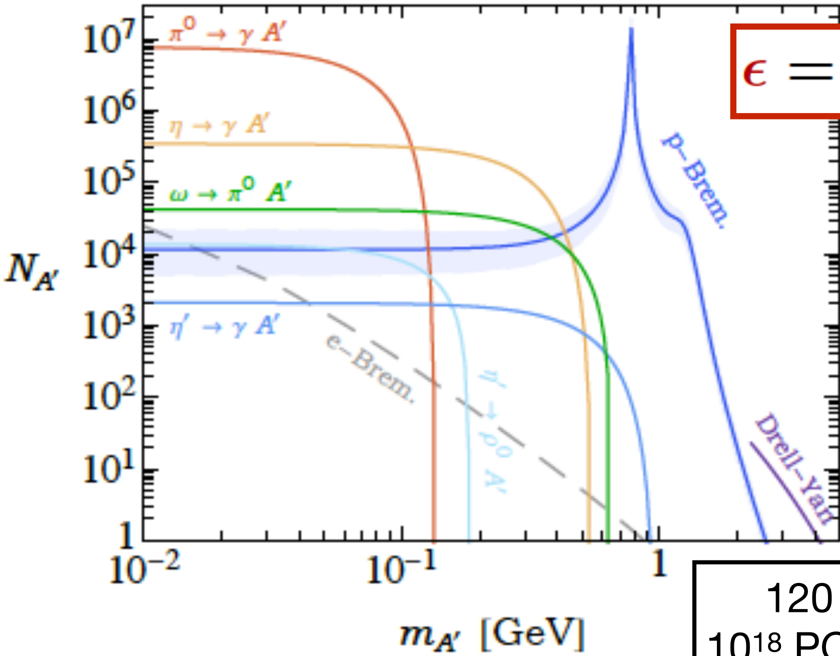

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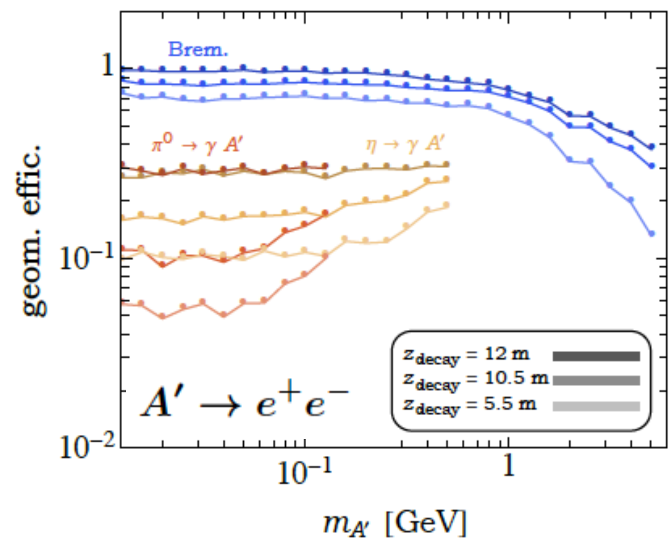
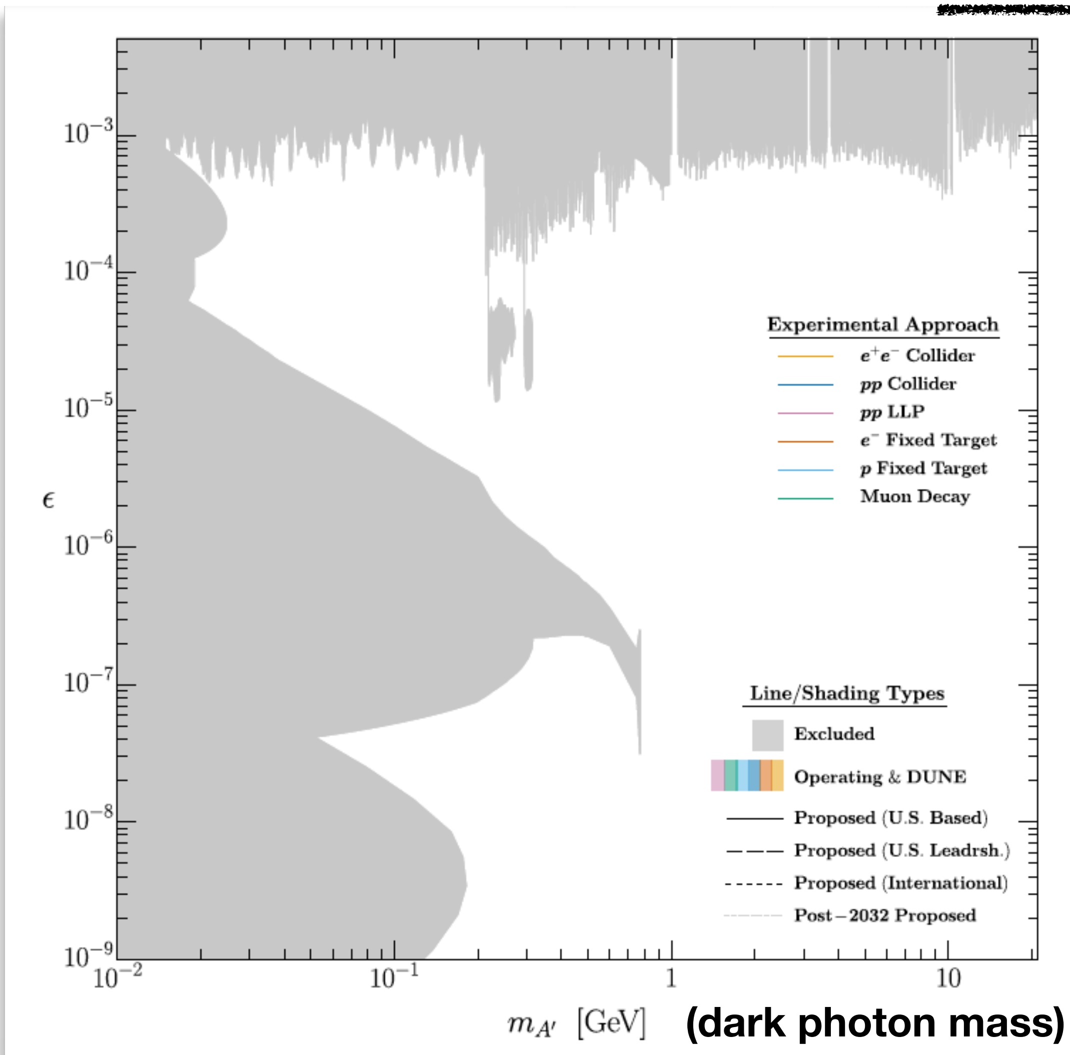


2. Large geometric acceptance of the decay products

Exploring visible dark photons

$\epsilon B^{\mu\nu} A'_{\mu\nu}$



(dark photon mass)

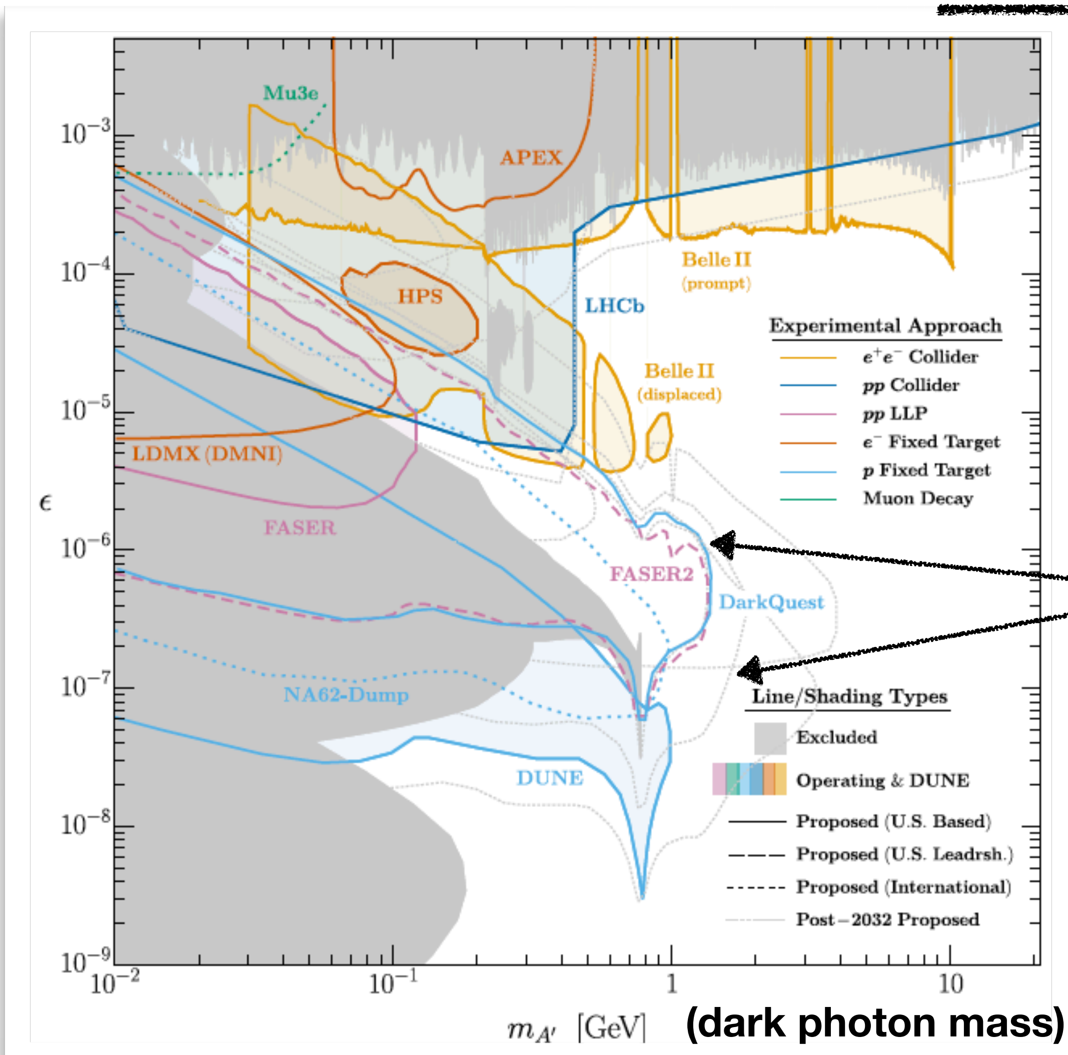
energy frontier

From Snowmass Big idea 2, Batell et al., 2207.06905

This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

Exploring visible dark photons

$\epsilon B^{\mu\nu} A'_{\mu\nu}$



energy frontier

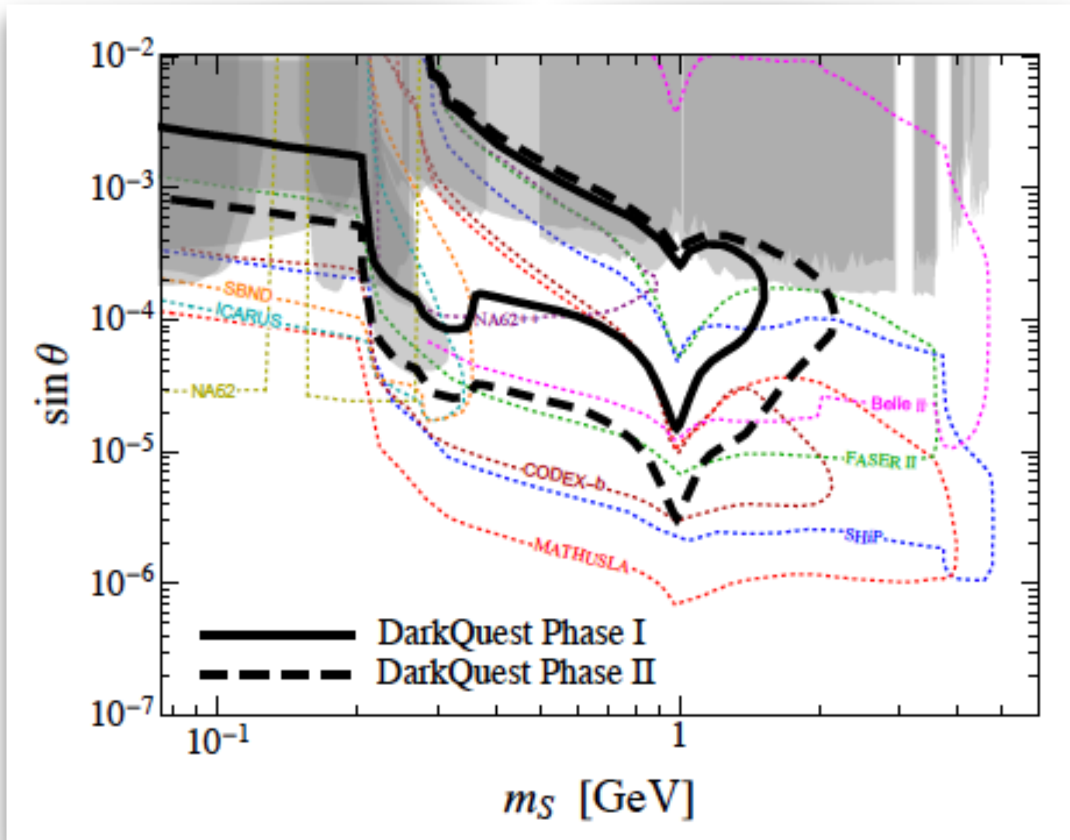
DarkQuest
(10^{18}, 10^{20} POT)

From Snowmass Big idea 2, Batell et al., 2207.06905

This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

Studies of other minimal models: dark scalars

Batell, Evans, SG, Rai, 2008.08108



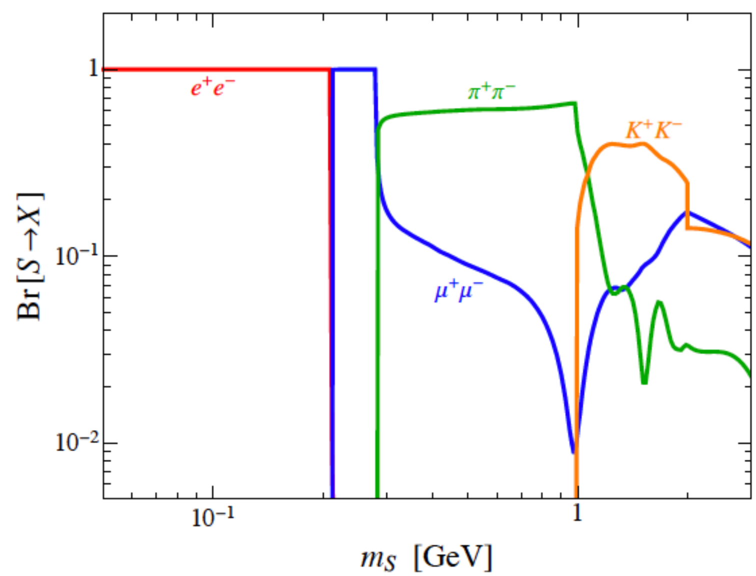
Ten signal events shown.

Possible backgrounds: $K_L \to \pi^{\pm}\ell^{\mp}\nu,$
$K_L \to \pi^{-}\pi^{+}\pi^{0},$
$K_L \to \pi^{-}\pi^{+}$

Large uncertainties in the calculations of branching ratios and lifetime of the scalar

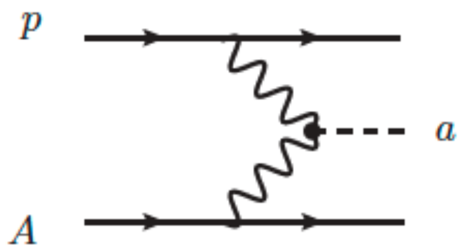
Winkler, 1809.01876

Reach computed considering all visible decay modes (except muons):



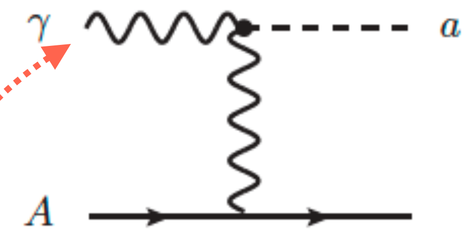
Studies of other minimal models: ALPs coupled to photons

1.

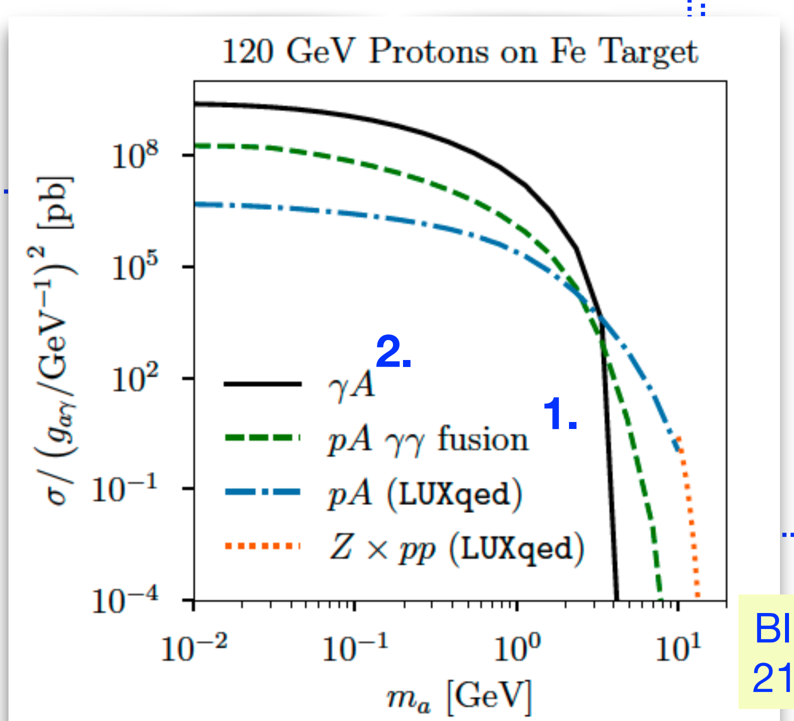


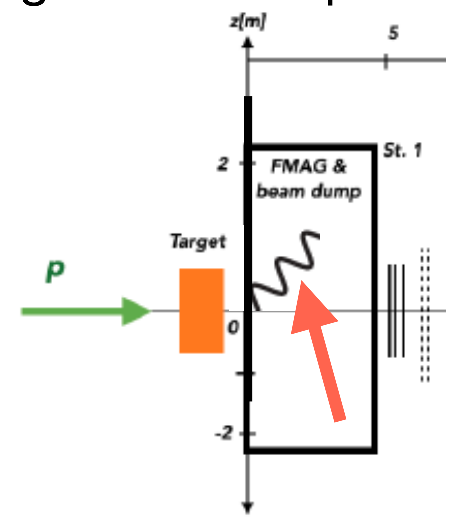
This was the main channel studied for proton beam dump experiments

2.



Secondary photon beam from meson decays at the beginning of the dump



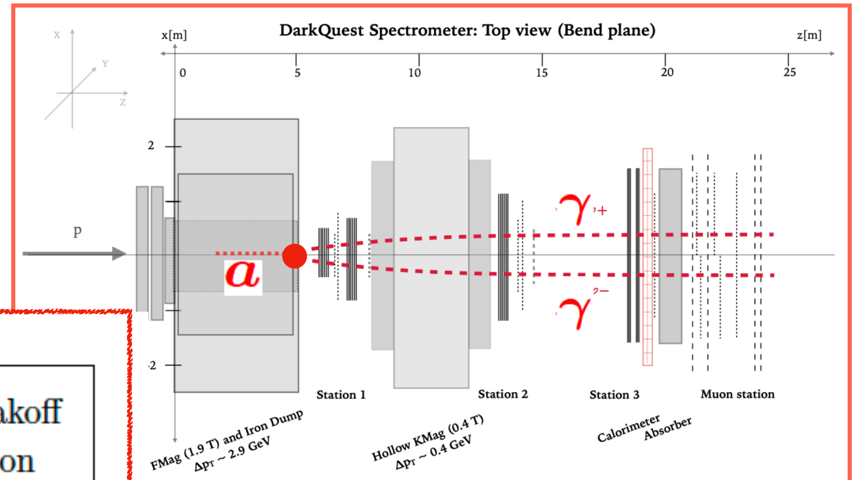


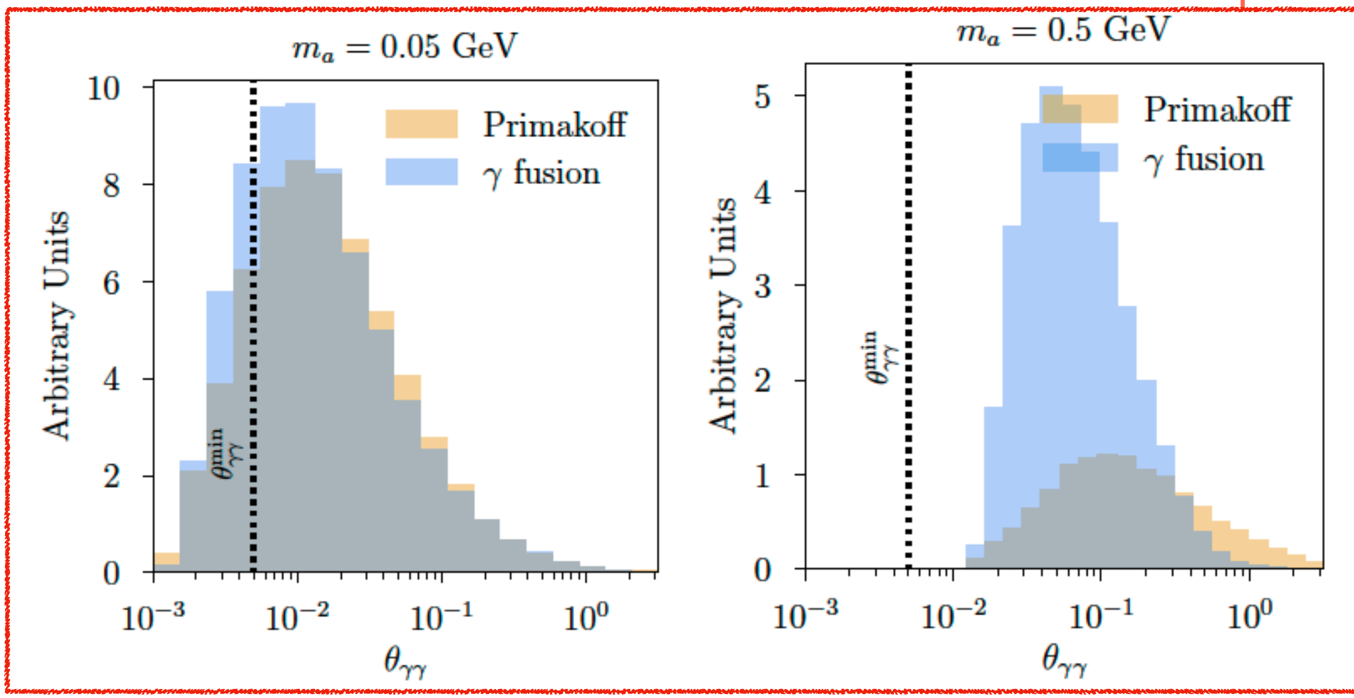
Blinov et al, 2112.09814

see also Dobrich et al, 1904.02091

Photon separation & acceptance

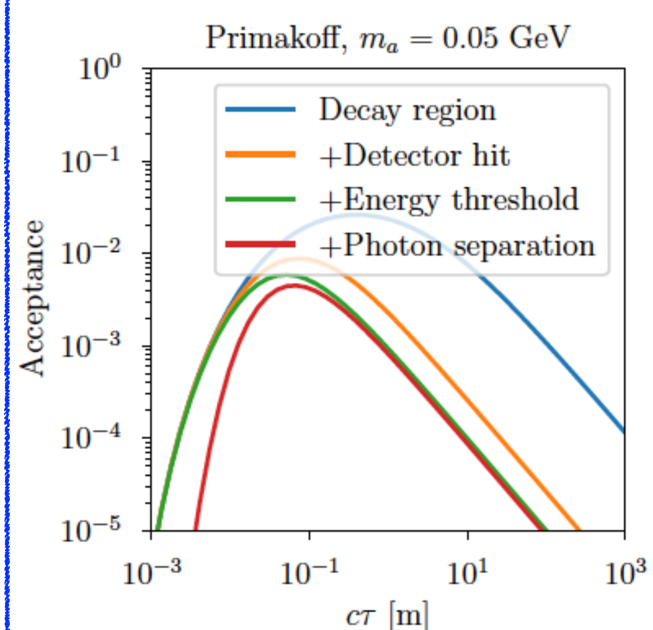
Blinov et al, 2112.09814





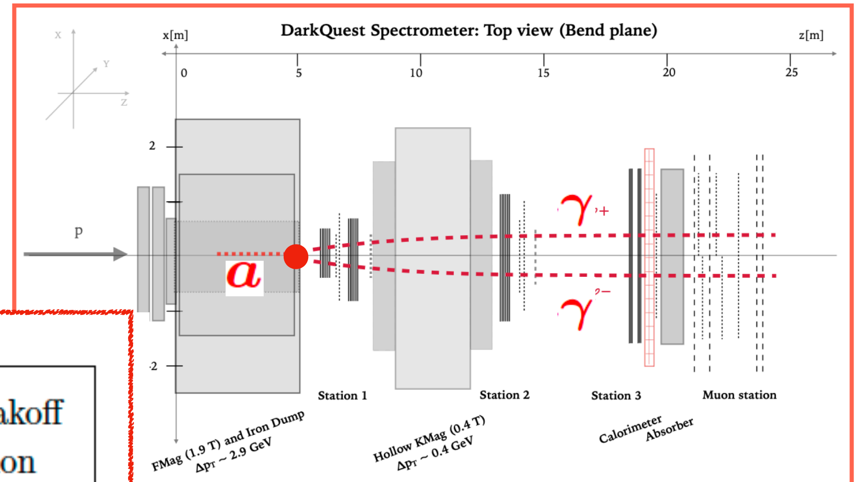
for >5.5 cm separation

very high acceptance

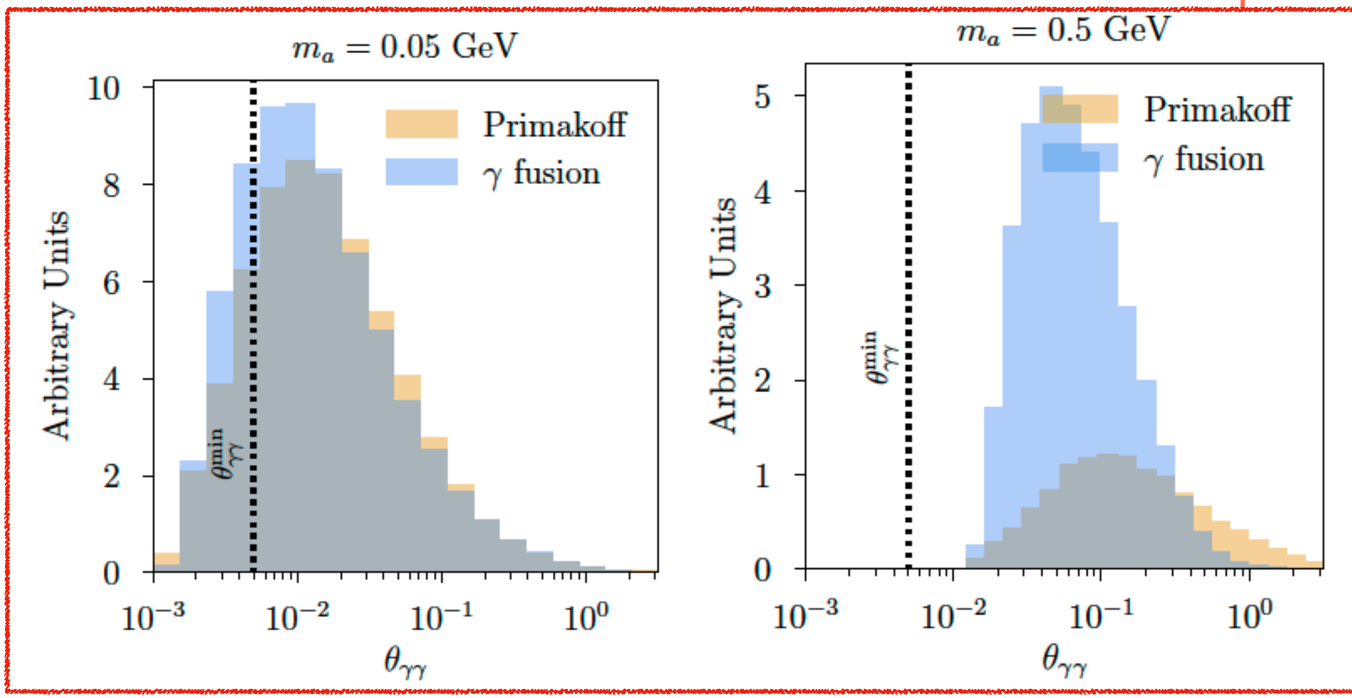


7-19m fiducial region

Photon separation & acceptance



Blinov et al, 2112.09814



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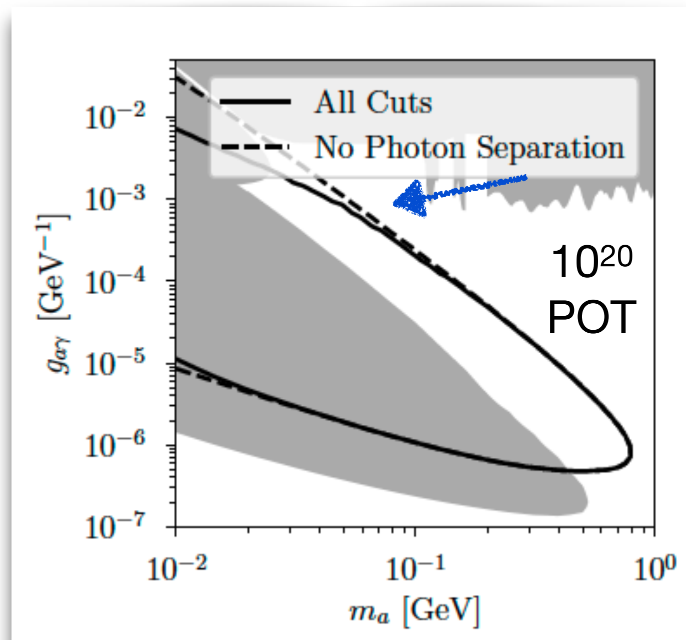


7-19m fiducial region

photons with E>1GeV

S.Gori

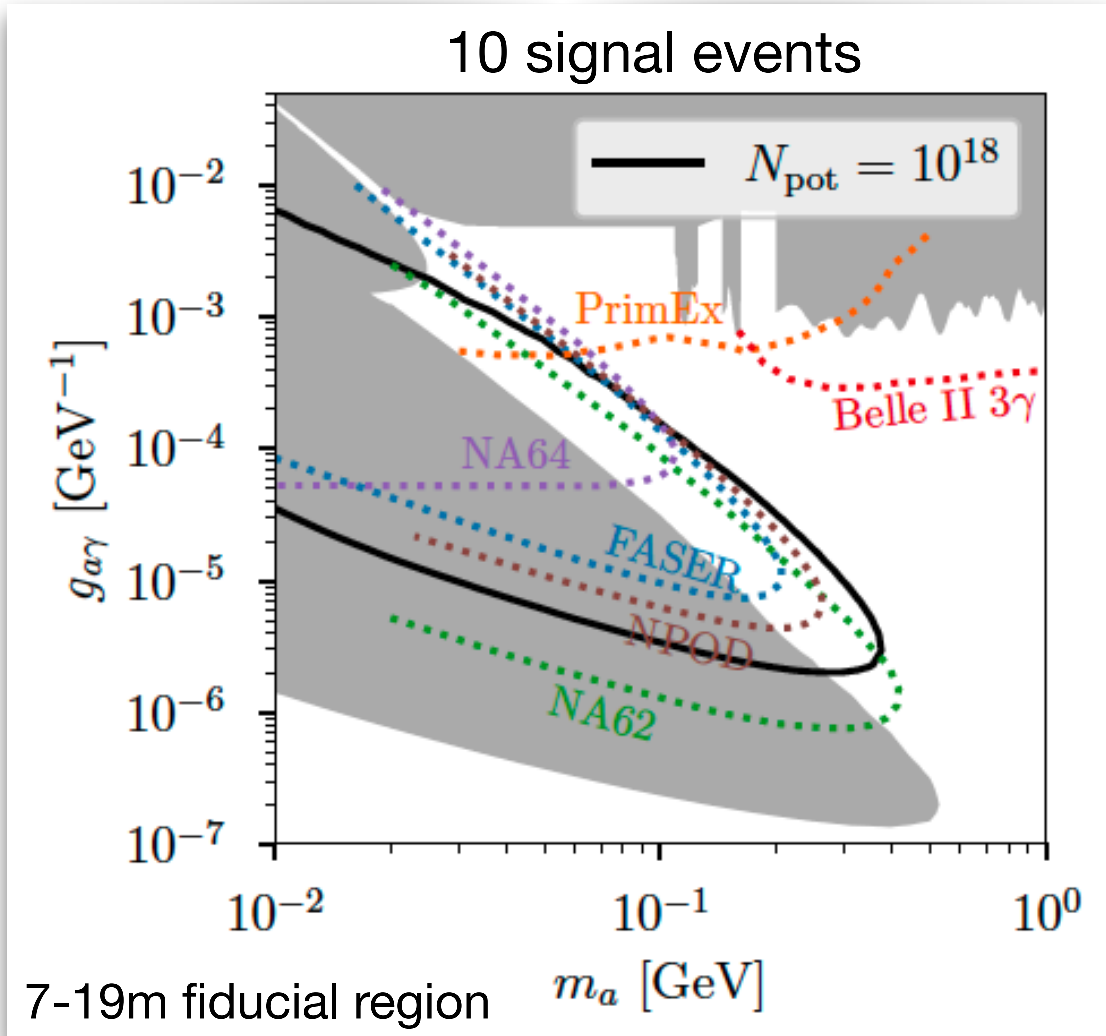
DarkQuest reach on photon-coupled ALPs

NA64,
$\gamma N \to Na$, $a \to \gamma\gamma$
5×10^{12} EOT

Dusaev et al, 2004.04469

FASER,
300/fb

Feng et al, 1806.02348



Blinov et al, 2112.09814

LUXE, phase 0,
Bai et al, 2107.13554

NA62
dump-mode
10^{18} POT

Dobrich et al, 1904.02091

What about backgrounds?

Is this search background free? If not, how to ameliorate backgrounds?
Blinov, SG, Hamer, in progress

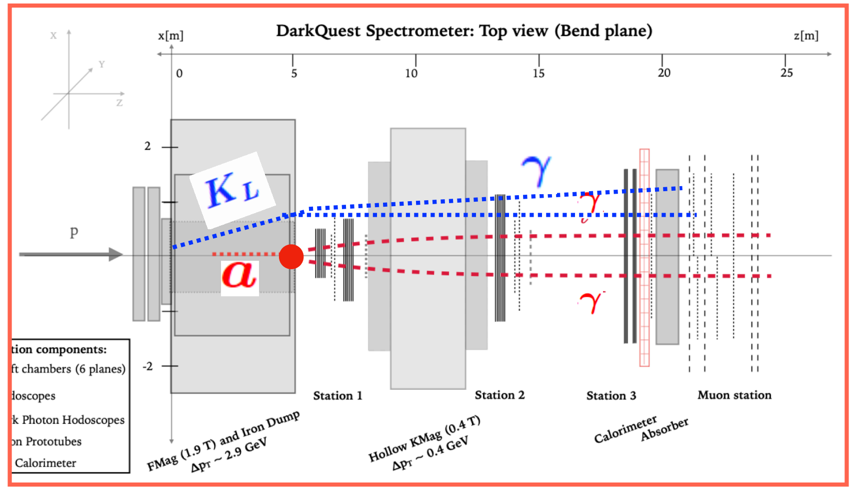
1. Backgrounds from **primary interactions**:

$K_L \to \gamma\gamma$ and $K_L \to 3\pi^0 \to 6\gamma$

Life time $K_L \sim 15$m

10^{18} POT $\begin{cases} \mathcal{O}(10^4), & z_{\rm dump} = 5m \\ \mathcal{O}(1), & z_{\rm dump} = 7m \end{cases}$ **6γ**

γγ background: O(10^{-3}) smaller



No cut on the kinematics. Vetoing additional photons can reduce the $N_{\rm background}$

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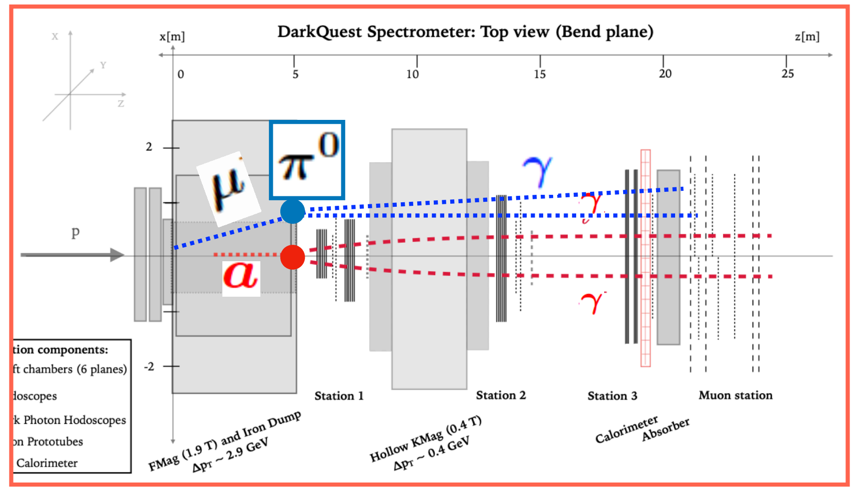
$\gamma\gamma$ background: $O(10^{-3})$ smaller



No cut on the kinematics. Vetoing additional photons can reduce the $N_{\text{background}}$

2. Backgrounds from **secondary interactions**:

$\pi^0 \to \gamma\gamma$ (produced from muon secondary beam undergoing deep inelastic scattering)

$O(10^6)$ for 10^{18} POT

muons lose only about ~ 10 MeV/cm

➡ 5m or 7m dumps lead roughly to the same result

Di-Photon mass resolution is key here. ~15%

Richer dark sectors (Snowmass big idea 3)

Harris et al., https://arxiv.org/pdf/2207.08990.pdf

New Flavors and Rich Structures in Dark Sectors.

To-date, much of the emphasis for experimental work on dark sectors has been anchored to minimal models (i.e. minimal number of particles & flavor universality).

New necessary step: more complete coverage of non-minimal dark sector models

Richer phenomenology ⇨ rethinking of experimental strategies for achieving optimized sensitivities

2 themes:

* Dark sector benchmarks that address anomalies in data
  E.g. $(g-2)_\mu$, flavor anomalies, Xenon 1T excess, MiniBooNE excess, …

* Commonly used benchmarks going beyond the assumption of minimality
  E.g. (1) flavor violating ALPs, (2) DM models with a DM excited state (inelastic DM, strongly interacting massive particles, …))

Addressing anomalies in data, $(g-2)_\mu$

After Snowmass 2013, our community was able to probe minimal dark sector models addressing the $(g-2)_\mu$ anomaly.

Can we fully probe a light explanation of $(g-2)_\mu$ even beyond minimal models?

Only a few models are left unexplored: $\mathcal{L} \supset g_S S \bar{\mu} \mu$

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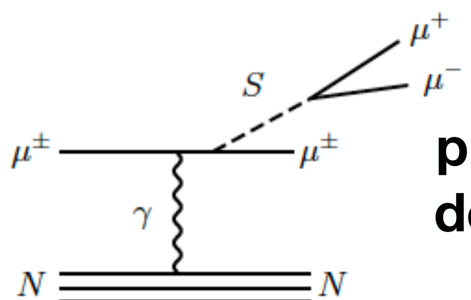
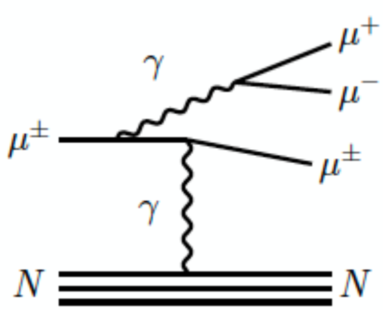
Scalars produced from the secondary muon beam

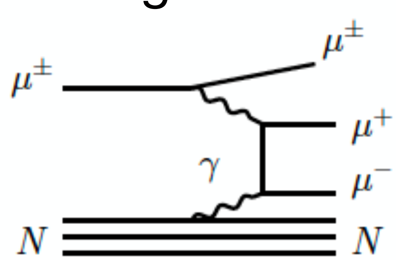
$m_S > 2m_\mu$

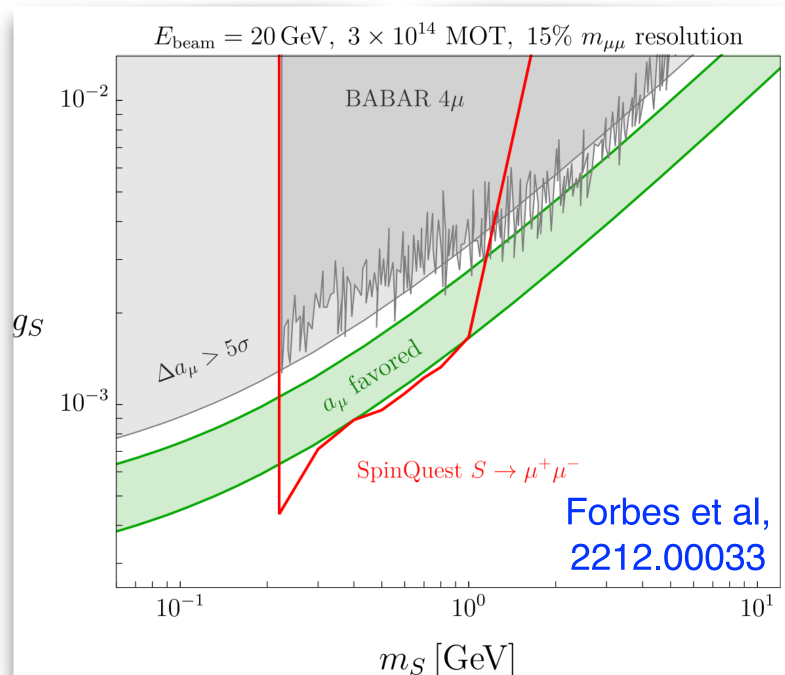


promptly decaying

Muon backgrounds:







Forbes et al, 2212.00033

Some of this region will also be probed by Belle II with full luminosity

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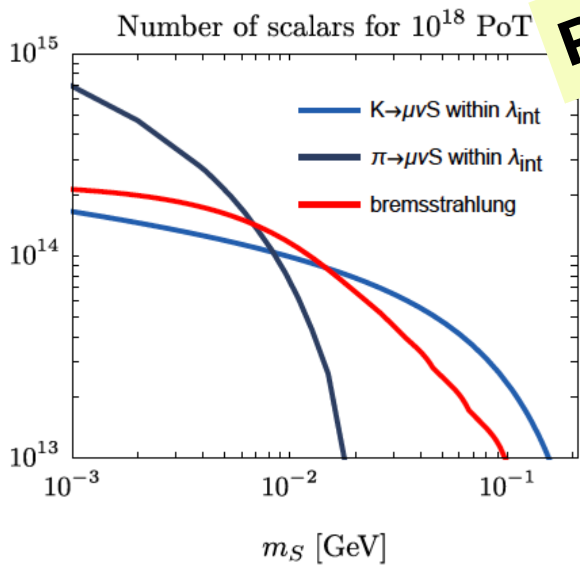
Scalars produced from the secondary muon beam

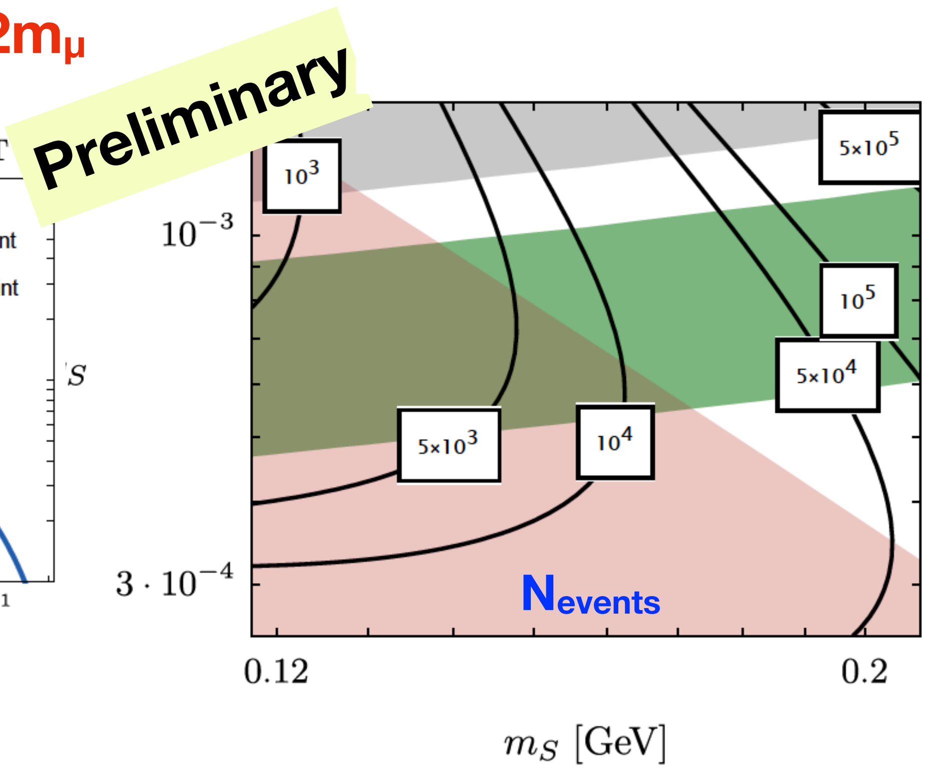
+ meson decays

$\pi \to \mu\nu S$,

$K \to \mu\nu S$

$m_S < 2m_\mu$





Long lived scalar, $S \to \gamma\gamma$

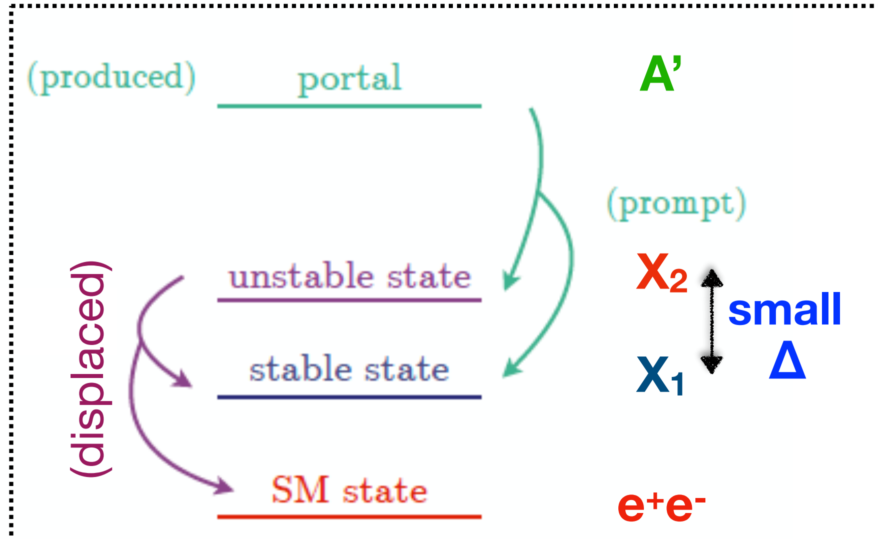
Blinov, SG, Hamer, in progress

DM models with metastable particles

Inelastic Dark Matter

Tucker-Smith, **Weiner**, 0101138

$$\mathcal{L} \supset \frac{i e_D \, m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}} A'_\mu \left(\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1\right)$$



* A non-minimal freeze-out mechanism:

X_1 X_2 → SM

DM **DM excited state**

DM models with metastable particles

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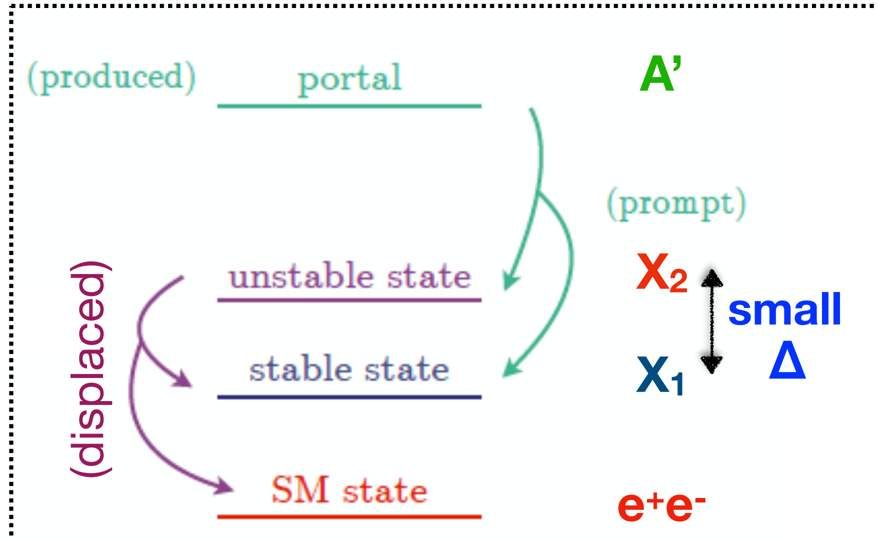

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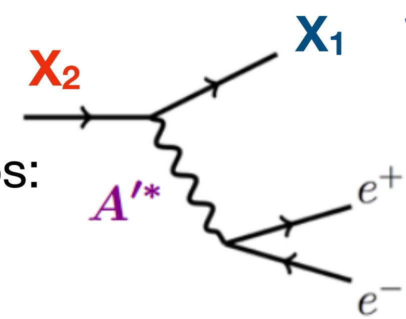
DM **DM excited state**

* Signatures in our labs:

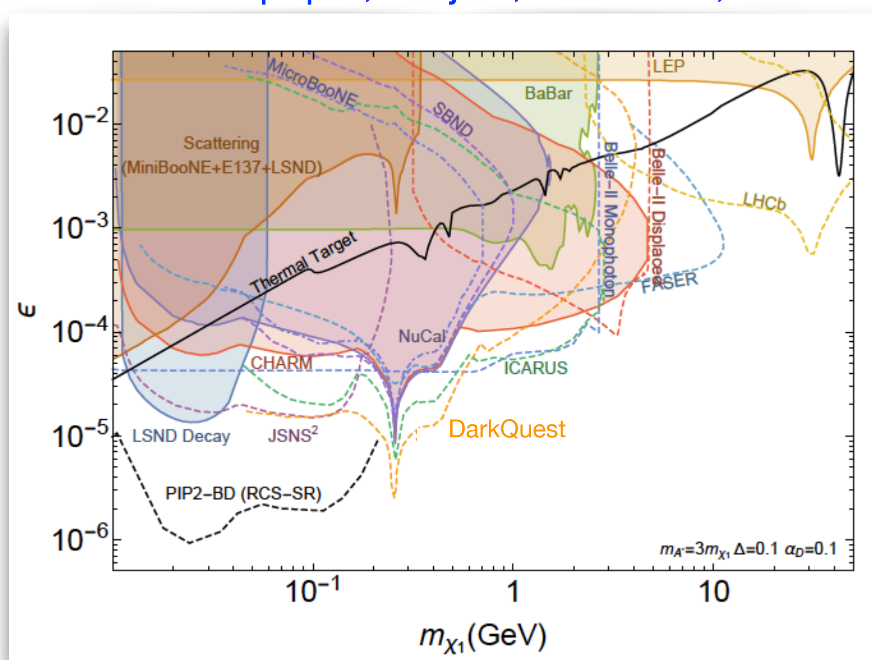


$X_2 \to X_1\, e^+ e^-$

$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq \frac{4\epsilon^2\, \alpha_{\rm em}\, \alpha_D\, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

- Long lived particles
- Invisible component

Snowmass white paper, Krnjaic, Toro et al., 2207.00597



DM in a strongly interacting dark sector

Dark Matter can be the lightest state of a dark QCD-like theory (e.g. a **dark pion**)

Novel process responsible of freeze-out: $3 \rightarrow 2$ annihilation ⇦ Motivation to consider MeV-GeV DM!

The additional dark states will lead to a richer phenomenology

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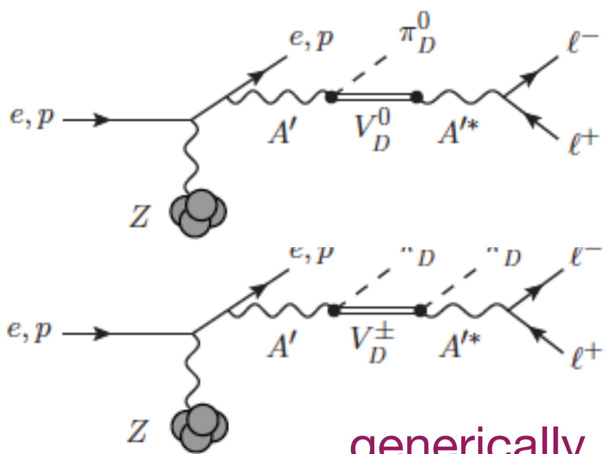
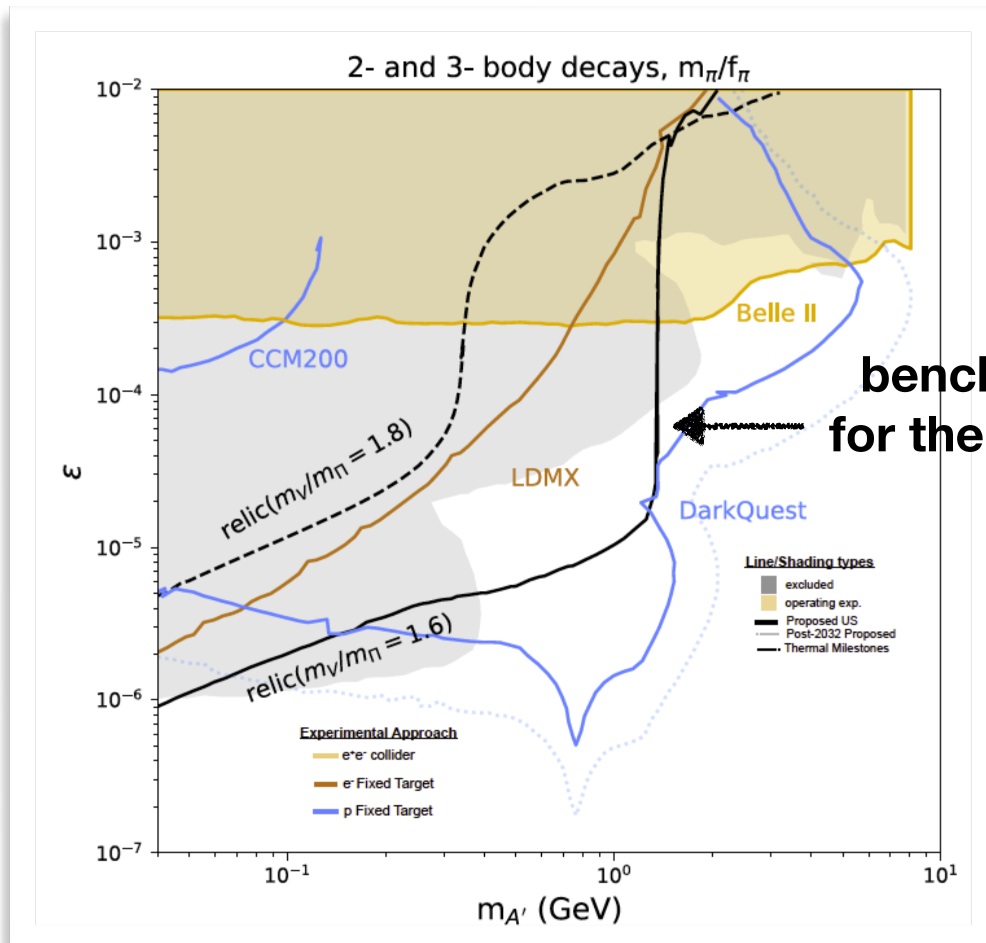


generically long-lived

$A' \to V_D \pi_D$ ← DM state

$$\begin{cases} V_D \to A'^* \to e^+e^-, \quad \text{or} \\ V_D \to \pi A'^* \to \pi e^+e^- \end{cases}$$



benchmarks for thermal DM

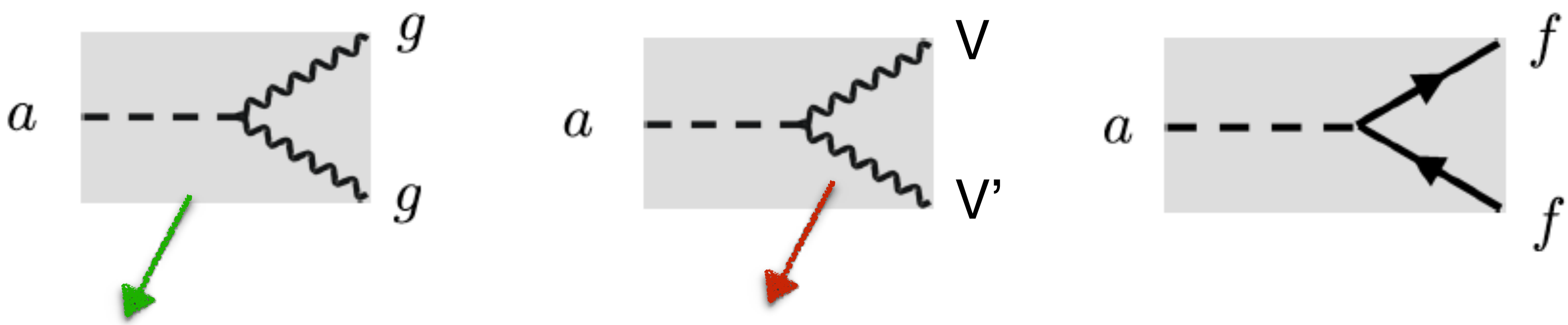
Non-minimal models for axion-like-particles

At dimension 5, the most general Lagrangian for a spin 0, CP-odd particle with an approximate shift symmetry, a → a+c:

Georgi, Kaplan, Randall 1986

$$\mathcal{L} \supset -\frac{g_{ag}}{4}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{g_{aW}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - \frac{g_{aB}}{4}\, a\, B_{\mu\nu}\tilde{B}^{\mu\nu} + i g_{af}(\partial_\mu a)(\bar{f}\gamma^\mu\gamma_5 f)$$

$$\boxed{g_i \propto \frac{1}{f_a}}$$



Minimal coupling expected if connection to the strong CP problem.

A ALP-photon coupling is generated in the broken phase

$$g_{aB}\cos^2\theta + g_{aW}\sin^2\theta$$

This is the main coupling that has been considered for phenomenological studies of ALPs in the sub-GeV scale (see also earlier in this talk).

Going beyond the photon coupling

Motivated by the strong CP problem, one could expect ALPs to be coupled to gluons

$$\frac{c_{ag}}{4} a G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\Downarrow$$

The gluon coupling induces a mixing between the ALP and the Standard Model neutral pion:

$$\varepsilon\, \partial_\mu a\, \partial^\mu \pi^0$$

$$\varepsilon \sim \frac{f_\pi}{\alpha_s} c_{ag} \frac{m_d - m_u}{m_d + m_u}$$

This mixing induces a coupling with **photons**: $g_{a\gamma}^{\rm eff} a F_{\mu\nu}\tilde{F}^{\mu\nu}$

$$g_{a\gamma}^{\rm eff} = \sin^2\vartheta \frac{\sqrt{2}\alpha}{8\pi f_\pi}$$

$$\left(\sin\vartheta \simeq \varepsilon \frac{m_a^2}{m_\pi^2 - m_a^2} \right)$$

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What about the reach?

ALPs produced from meson decays (example: $\pi^+ \to a e^+ \nu$) and direct gluon-gluon scattering.

ALPs decaying to two photons or two charged light mesons

What about the reach on other couplings (quarks, leptons)?

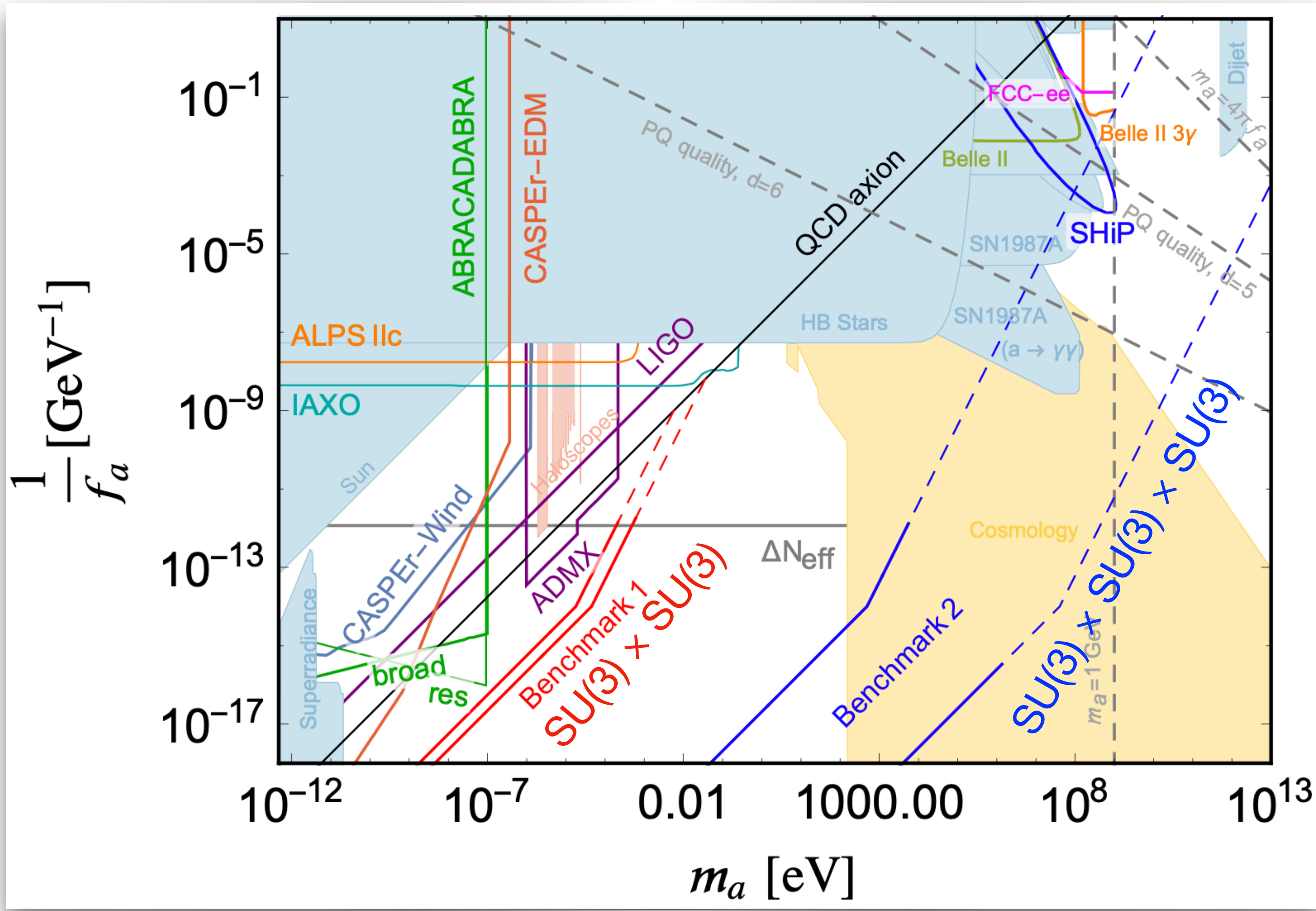
Conclusions & Outlook

DarkQuest is a unique experiment for probing well-motivated dark sector models.
Energy, intensity, and short baseline.

Several phenomenological studies (especially for minimal models).
More studies are needed.

Looking forward to the experiment!!

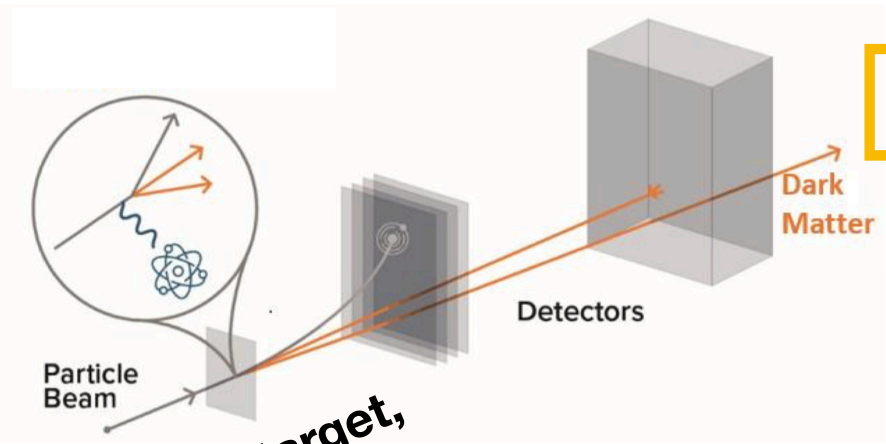
An extended QCD axion model



Agrawal, Howie, 1710.04213

Search techniques for dark sectors at high intensities

Production of dark matter



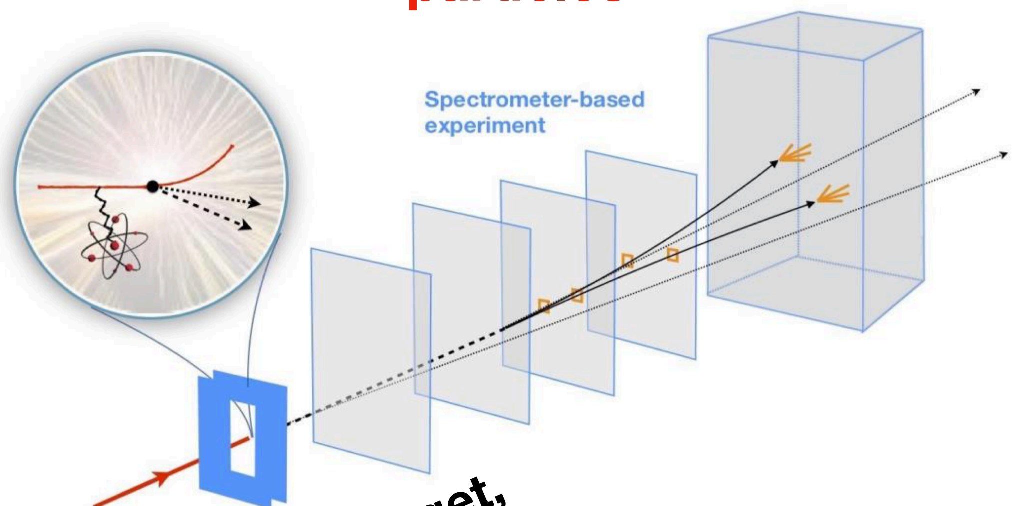
2. Re-scattering

1. 2. fixed target, colliders

1. Missing energy/ momentum

The experimental techniques are only 3

Production of unstable dark sector particles



1. 2. fixed target, colliders

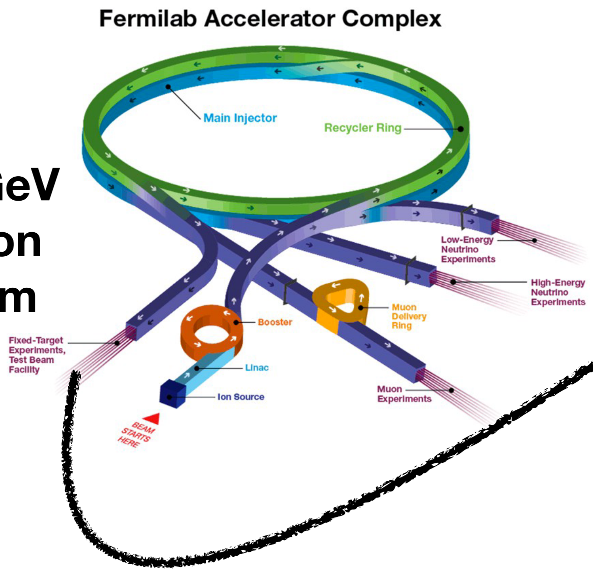
3. Visible decay products

Basic Research Needs for
DM Small projects New Initiatives (DMNI), 2018

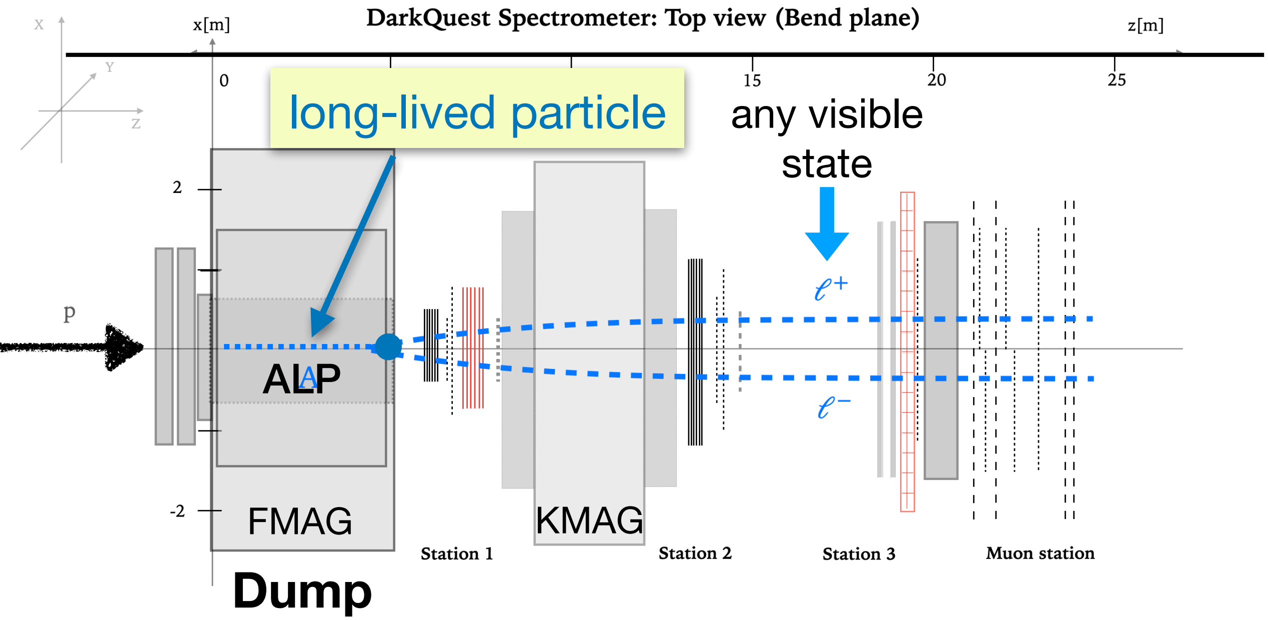
https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

DarkQuest, a future proton beam dump experiment

120 GeV proton beam



Fermilab accelerator complex



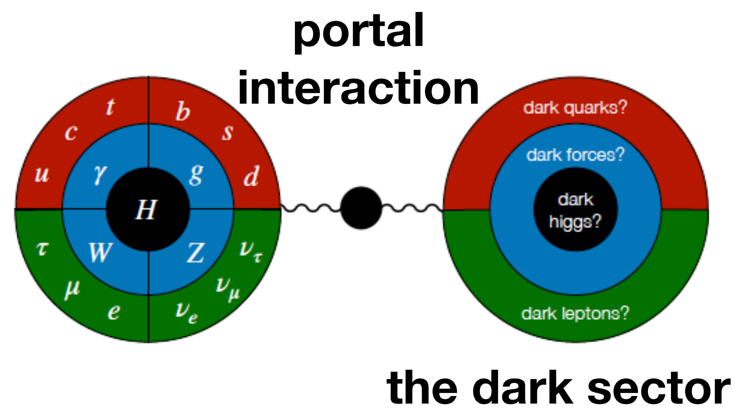
SeaQuest
1706.09990

→ SpinQuest
polarized target
+ displaced trigger
muon signatures
2023-2024

→ DarkQuest
proposed upgrade
(calorimeter +
more tracking layers +
hodoscope for triggering)
all visible signatures
~2025-2026

Initial proposal: Berlin, SG, Schuster, Toro, 1804.00661
Snowmass white paper: 2203.08322

Dark Sectors at High Intensity



The existence of dark matter motivates a dark sector neutral under the SM forces

Dark sectors are a compelling possibility for new physics, with potential relevance to
lightness of SM neutrinos, baryon-antibaryon asymmetry,
hierarchy problem, strong-CP problem (e.g., axions, axion-like-particles),
anomalies in data

Dark sectors are generically weakly coupled to SM matter (via portal interactions) and can naturally have MeV-to-GeV masses.

➡ Only mild constraints from precision atomic physics & high-energy colliders

➡ Intensity-frontier experiments offer unique and unprecedented access to:

Big idea 1	• Light dark matter production
Big idea 2	• Systematic exploration of dark sector portals
Big idea 3	• Searches for new flavors and rich structures in dark sectors

Big idea 2: dark sector portals at high intensities

https://arxiv.org/abs/2207.06905

Explore the structure of the dark sector by producing and detecting unstable dark particles: Minimal Portal Interactions.

- dark photon $\epsilon B^{\mu\nu} A'_{\mu\nu}$
- dark scalar $\kappa |H|^2 |S|^2$
- sterile neutrino $y H L N$
- ALP $g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$
- New gauge symmetries: B-L, $L_\mu - L_\tau$, …

$$A' \to \ell^+ \ell^-, \ldots$$
$$S \to \mu^+ \mu^-,\ \pi^+ \pi^-, KK, \ldots$$
$$N \to \ell \pi, \ldots$$
$$a \to \gamma\gamma,$$
$$Z' \to \mu^+ \mu^-, \ldots$$

“visible” signatures

How to test these couplings?

Sizable coupling → **prompt** decay (generically larger backgrounds)

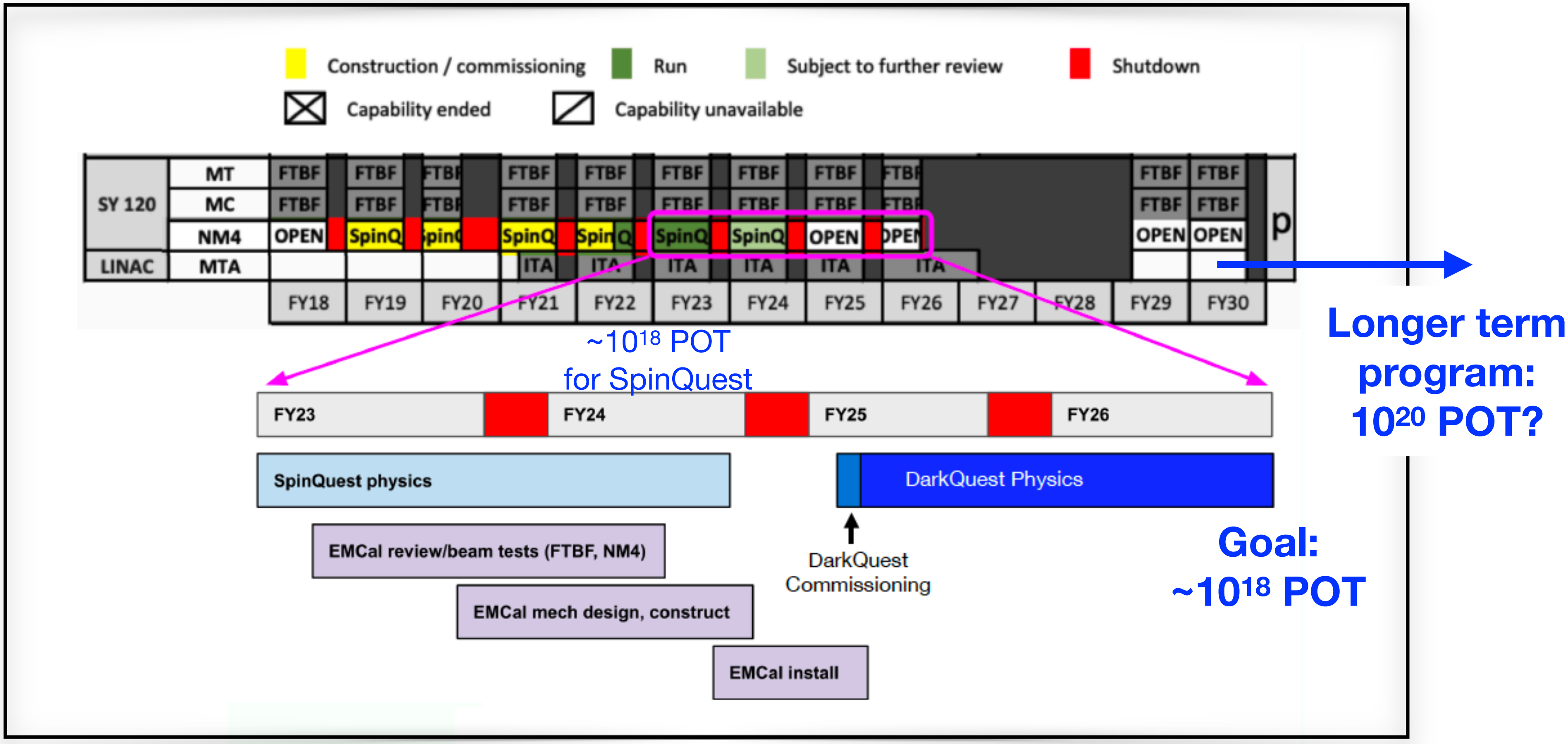
Small coupling → **displaced** decay (generically small backgrounds)

Experimental targets:

Secluded DM scenarios (Pospelov, Ritz, Voloshin, 0711.4866)

Forbidden DM scenarios (D’Agnolo, Ruderman, 1505.07107)

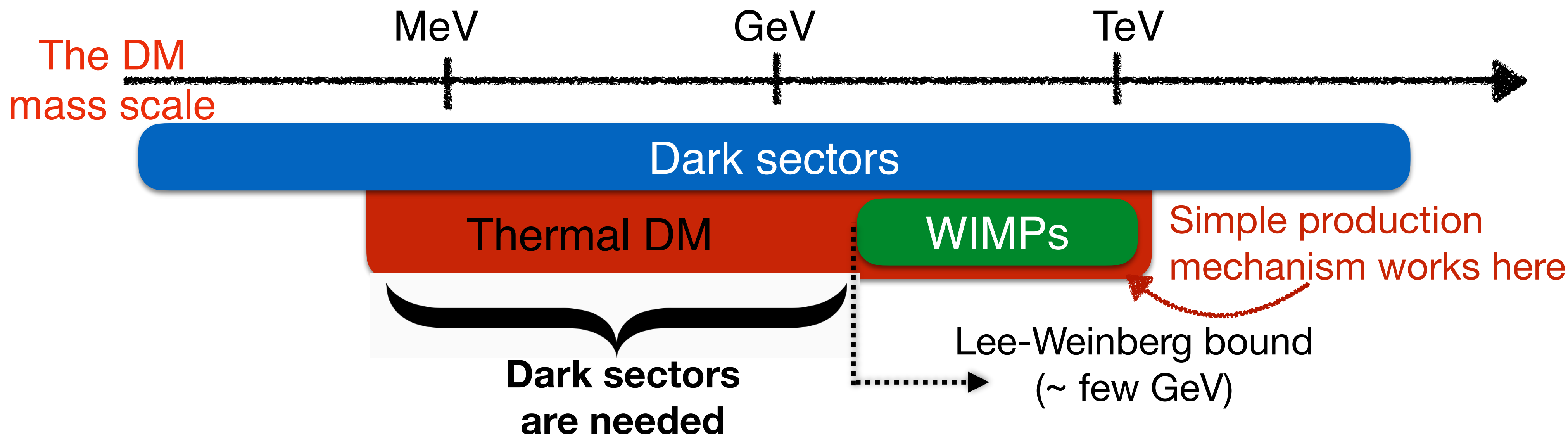
DarkQuest timeline



From the National Science Foundation Major Research Instrumentation proposal
“Development of DarkQuest: A dark sector upgrade to SpinQuest at the 120 GeV Fermilab Main Injector”

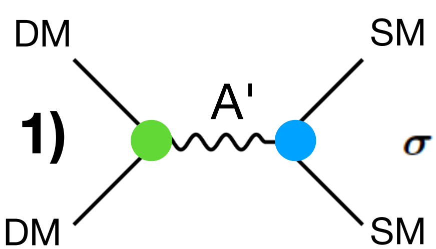
August 2023: we got funded for construction!

MeV-GeV Dark Matter living in a dark sector



DM thermal freeze-out targets

1)



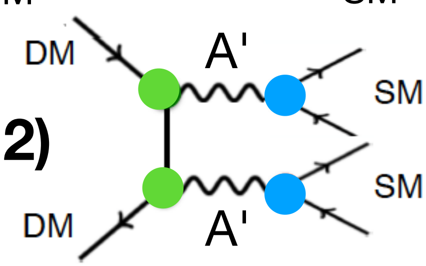
if $m_{A'} > 2m_{DM}$

$$\sigma \propto \frac{y}{m_{\rm DM}^2}, \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_{\rm DM}}{m_{A'}}\right)^4$$

→ A'

Invisible signatures

2)



if $m_{A'} < m_{DM}$

$$\sigma \propto \frac{\alpha_D^2}{m_{\rm DM}^2}$$ **BUT**

Thermalization:

ε is lower bounded

→ A'

Visible signatures

The community effort after Snowmass 2013

The worldwide search for Dark Sectors has involved hundreds of scientists, new models, many new analyses & experiments in last few years

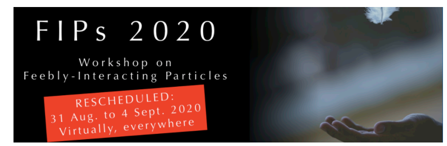
Vibrant theory + experimental community

Many workshops since 2013:

Dark Interactions Workshop, BNL, 2014

Dark sectors workshop, SLAC, 2016

Light Dark World International Forum
KAIST, 2018



Cosmic Visions community workshop 2017 (~mini-Snowmass). Community report: Battaglieri et al., 1707.04591

This is also an international effort:
The Physics Beyond Colliders Study Group at CERN, https://pbc.web.cern.ch

More recently, Basic Research Needs (BRN) workshop 2018:
DOE-charged panel with the goal of identifying priority science in Dark Matter scope, achievable with small US-based experiments.
DM Small projects New Initiatives (DMNI)

https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf