DARK MATTER AND DARK SECTORS

Theory Frontier Session, Snowmass 2022

23 July 2022

Jonathan Feng, UC Irvine

INTRODUCTION

- Dark Matter and Dark Sectors is currently a topic of great interest.

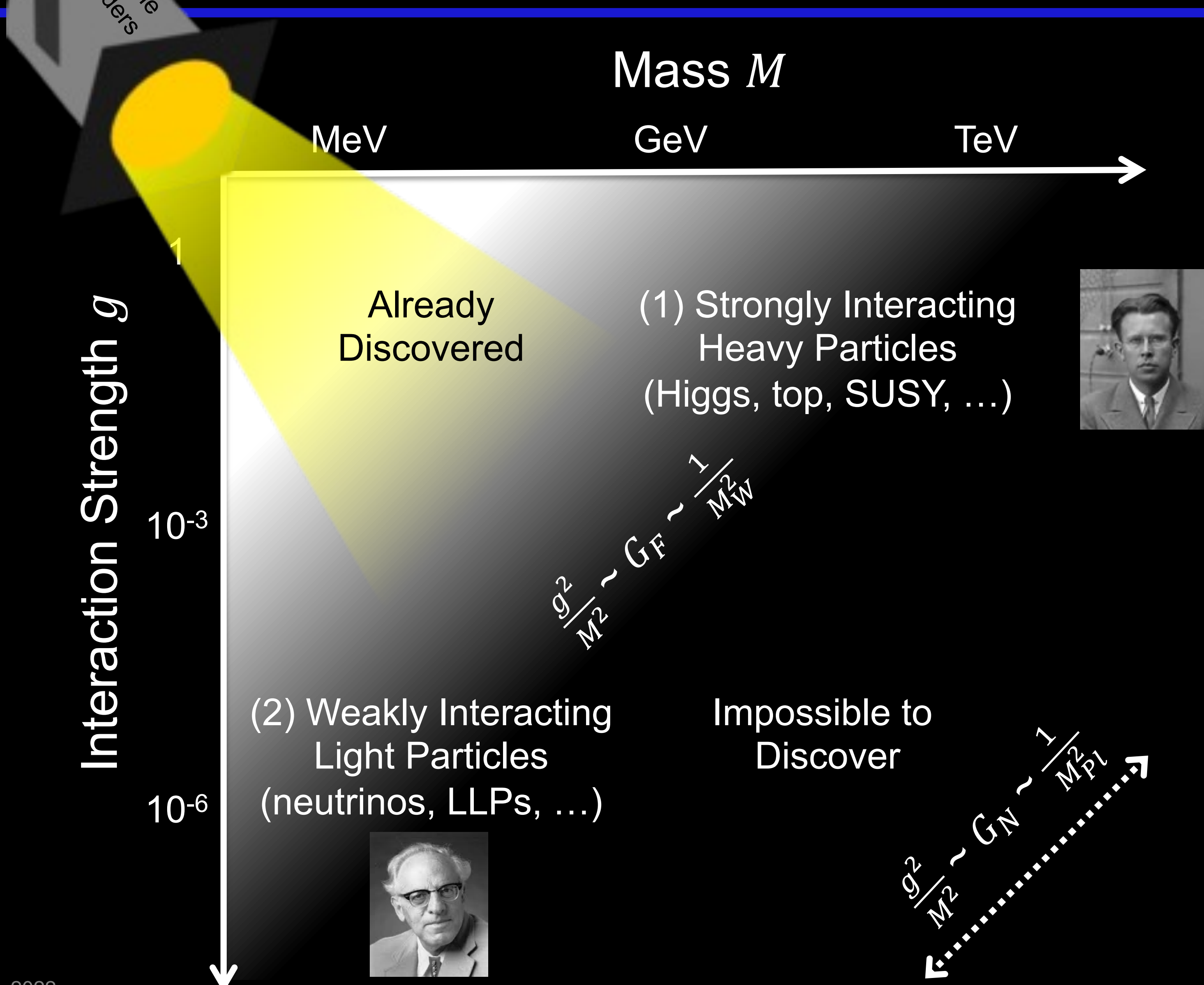
- Many talks at Snowmass, including several talks with almost the identical title:
  - Dark Matter and Dark Sectors: from Theory to Discovery in the Lab, Wednesday, Masha Baryakhtar
  - Dark Matter and Dark Sectors: from Theory to Discovery in the Sky, Wednesday, Joshua Foster
  - Understanding Dark Matter and Dark Sectors at RP Frontier, Wednesday, Stefania Gori
  - Dark Matter and Dark Sectors, Saturday, Jonathan Feng

- Some of the interest follows null results from LHC and ton-scale WIMP searches. But, as I will discuss, there are strong independent reasons to consider dark sectors, and much of the initial interest preceded these null results.

- Connections to almost every frontier, and also to adjacent fields (nuclear physics, condensed matter physics, AMO, and, of course, astrophysics).

- A beautiful example of what can result from the serious and persistent interaction of theorists and experimentalists.

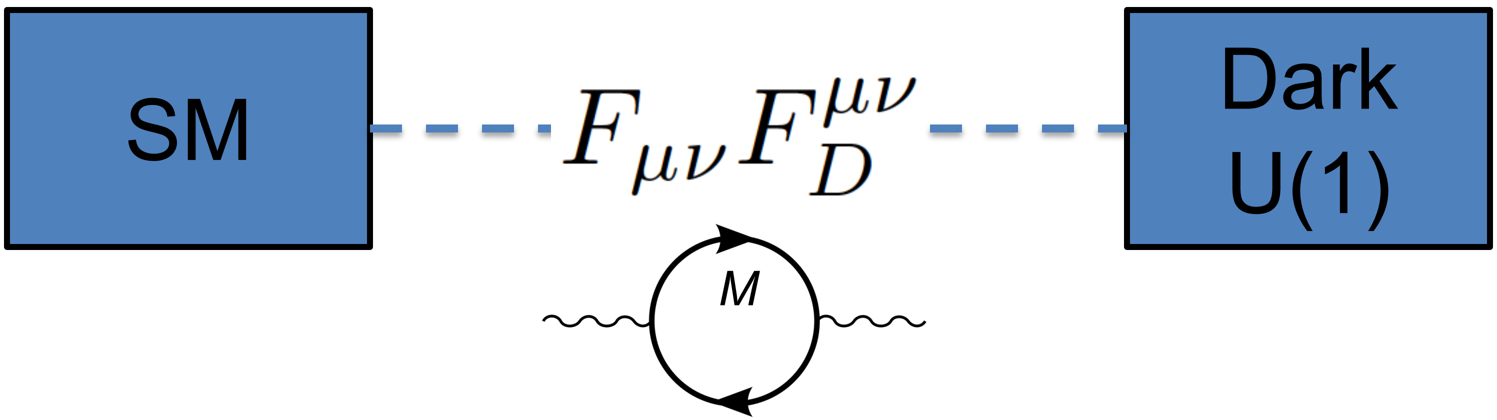
WHERE IS THE NEW PHYSICS?



DARK SECTORS

- DM is one of the strongest BSM motivations. In general, it is part of a dark sector. What are its most likely non-gravitational interactions?

- Suppose the dark sector has U(1) electromagnetism. There are infinitely many possible SM-dark sector interactions, but one is induced by arbitrarily heavy mediators:



- It is "most likely" because it is non-decoupling. Cf. $\dfrac{F_{\mu\nu}F_D^{\nu\alpha}F_\alpha^\mu}{M^2}$

- Note that it is also naturally small, since it is induced by a loop. This whole story is special to U(1).

Okun (1982), Galison, Manohar (1984), Holdom (1986)

DARK PHOTON, DARK HIGGS, STERILE NUS

- This provides an organizing principle that motivates specific examples of new, weakly interacting light particles. There are just a few options:

- Spin 1 — SM - - - $F_{\mu\nu}F_D^{\mu\nu}$ - - - Dark Force

→ dark photon, couples to SM fermions with suppressed couplings proportional to charge: εq_f. Holdom (1986)

- Spin 0 — SM - - - $h^\dagger h \phi_D^\dagger \phi_D$ - - - Dark Scalar

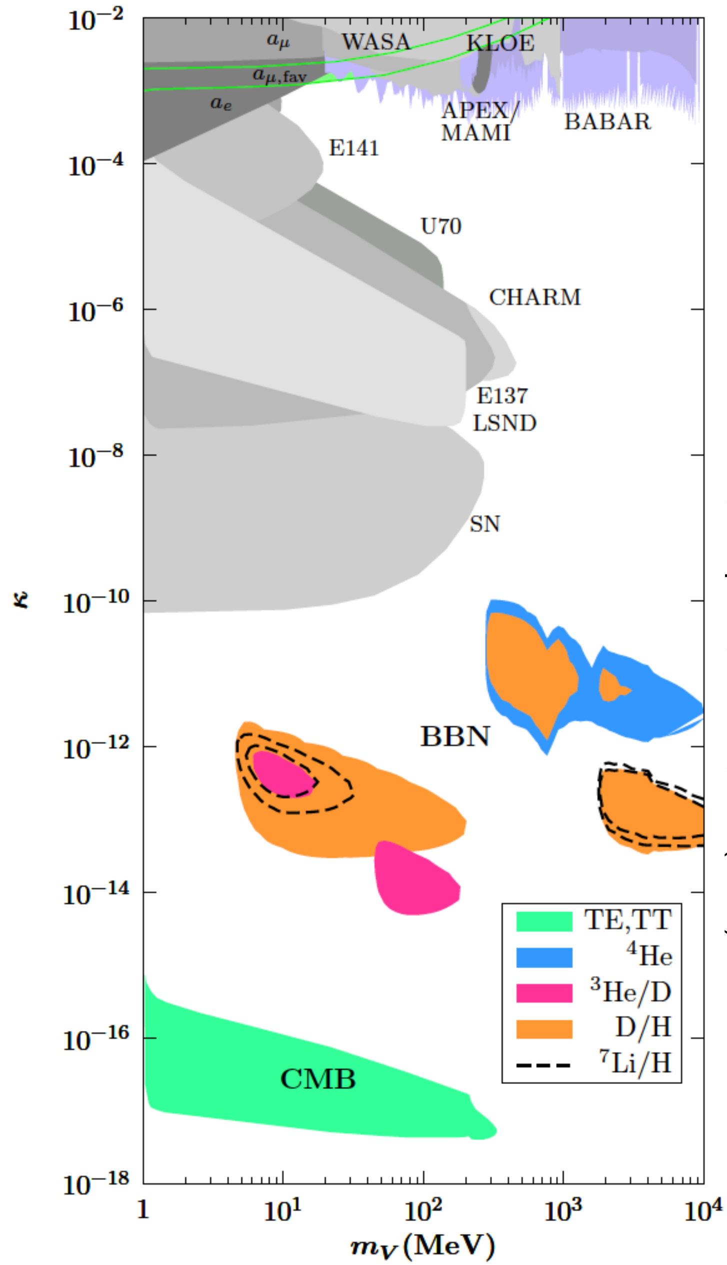
→ dark Higgs boson, couples to SM fermions with suppressed coupling proportional to mass: $\sin\theta\, m_f$. Patt, Wilczek (2006)

- Spin 1/2 — SM - - - $h L \psi_D$ - - - Dark Fermion

→ sterile neutrino, mixes with SM neutrinos with suppressed mixing $\sin\theta$.

EXISTING CONSTRAINTS

- We now have a few portal models, characterized by just a few parameters, and we can start exploring the parameter space.
- Consider dark photons. There is a vast parameter space.
  - "Bump hunts" exclude $\epsilon > 10^{-3}$.
  - Fixed target experiments exclude most of the gray region.
  - Astrophysics (supernova, BBN, CMB) excludes patches at very low coupling.
- But overall, light, weakly-interacting particles are much less constrained than ~TeV, strongly-interacting particles.



Fradette, Pospelov, Pradler, Ritz (2014)

DARK PHOTON MODELS

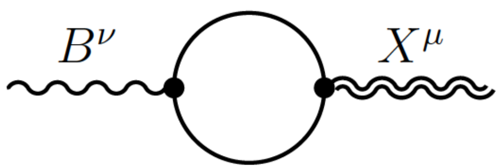
- If the dark photon is a portal particle, coupling arises from kinetic mixing:

Visible Sector
SM, $U(1)_{EM}$, B^ν

$$\frac{1}{2}\,\epsilon\, F^{\mu\nu} F_{D\mu\nu}$$

Dark Sector
DM, Dark Forces, X^μ

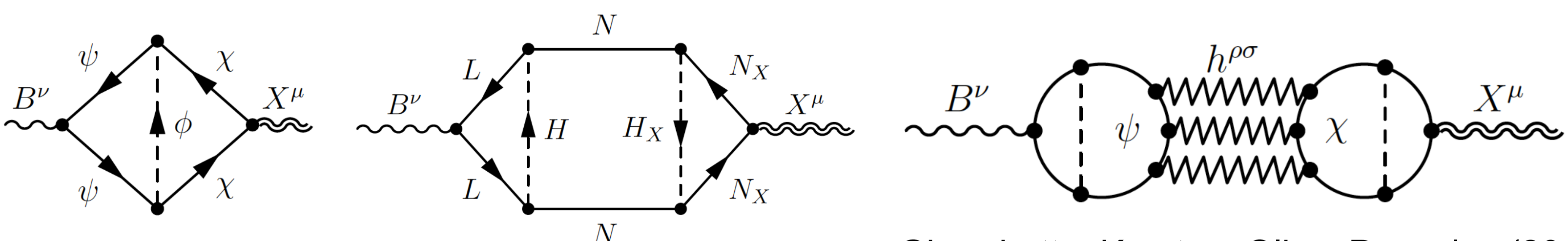
- Mixing can be generated at 1-loop. If 0 at high scale, expect $\epsilon \sim 10^{-3}$.



$$\epsilon = -\frac{g' g_X}{16\pi^2} \sum_i Y_i q_i \ln \frac{M_i^2}{\mu^2}$$

Holdom (1986)

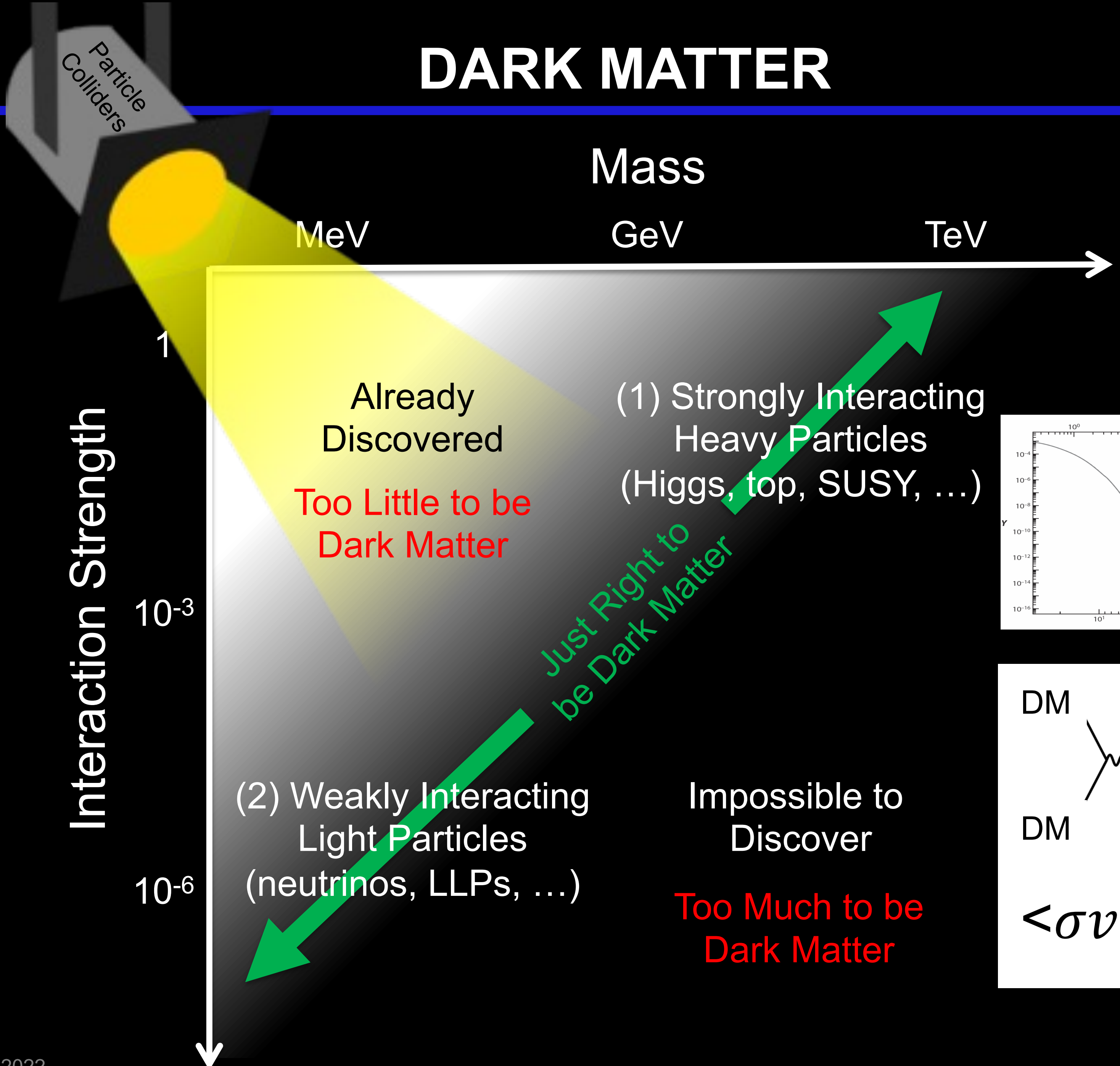
- But there are also theories with mixing generated only at higher loop level.

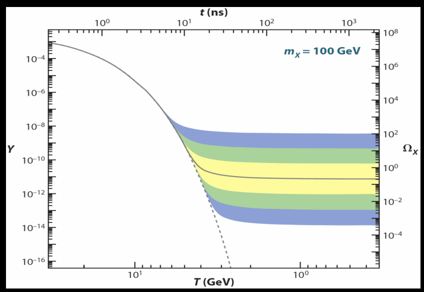


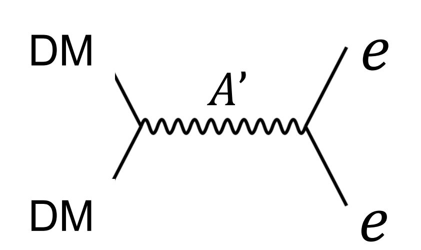
Gherghetta, Kersten, Olive, Pospelov (2019)

- Other than making us feel ok that $\epsilon > 10^{-3}$ is excluded, models don't provide much guidance about the coupling, and none at all about the mass.

DARK MATTER

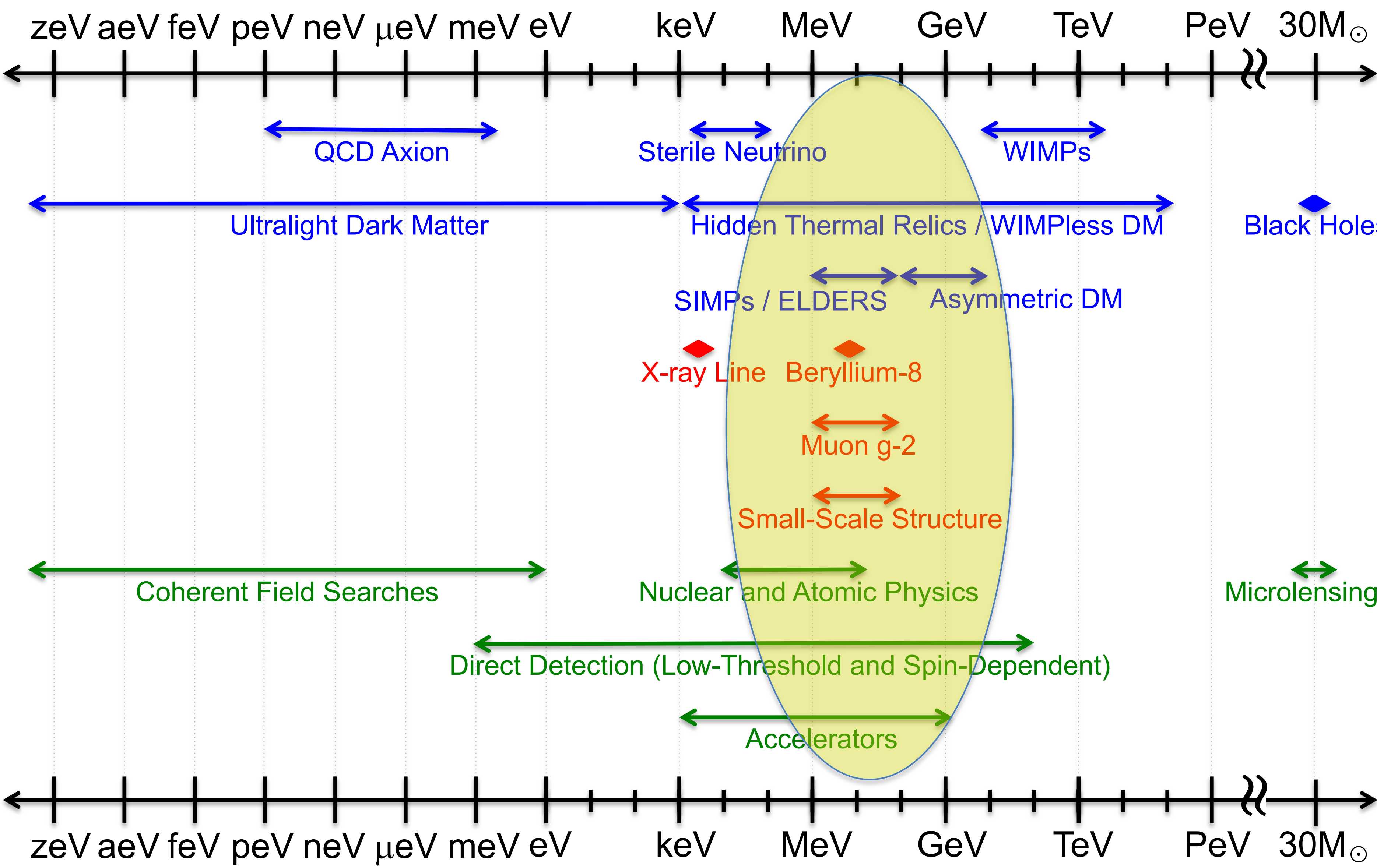






$$\langle \sigma v \rangle \sim \frac{\varepsilon^2}{m_{A'}^2}$$

Dark Sector Candidates, Anomalies, and Search Techniques

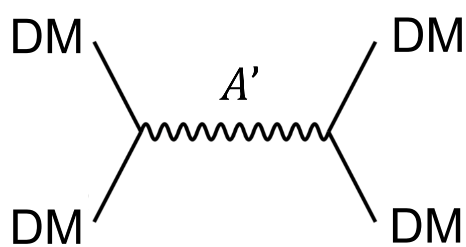


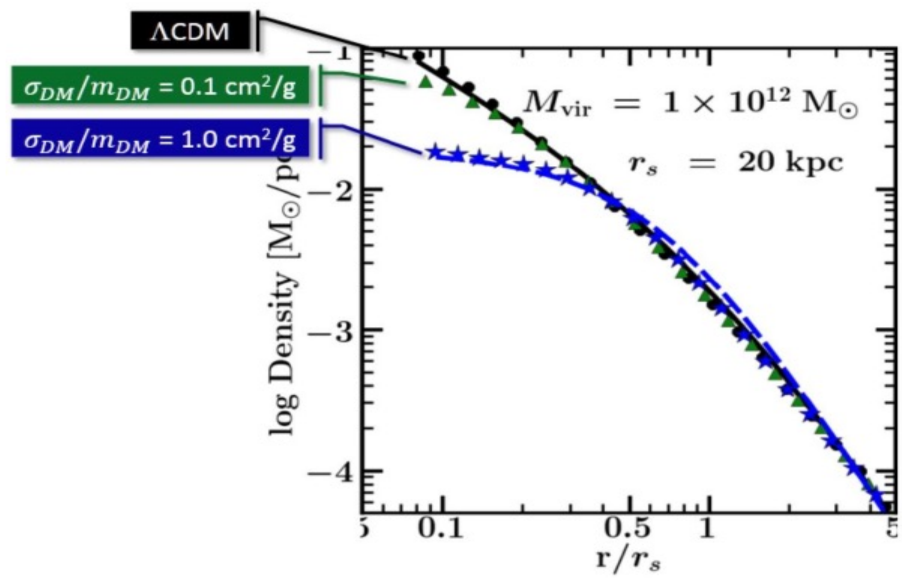
Cosmic Visions Report (2017)

SELF-INTERACTING DARK MATTER

- WIMP DM is in the “strongly interacting heavy particles” category. But there are indications that DM may not be WIMPs. No discovery so far, and also evidence from small-scale structure that dark matter may be strongly self-interacting.
- For example, there appear to be halo profiles that are not as cuspy (high central density) as predicted for standard collisionless cold dark matter (WIMPs, axions, sterile neutrinos, …).
- To smooth out the cusps, need a self-interaction cross section

$$\frac{\sigma}{m} \sim \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}} \sim (100\text{ MeV})^{-3}$$





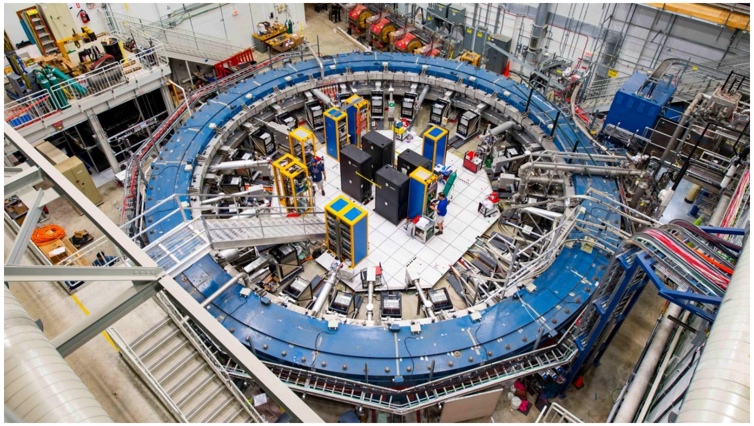
Tulin, Yu (2017)
Rocha et al. (2012); Peter et al. (2012)
Vogelsberger et al. (2012); Zavala et al. (2012)

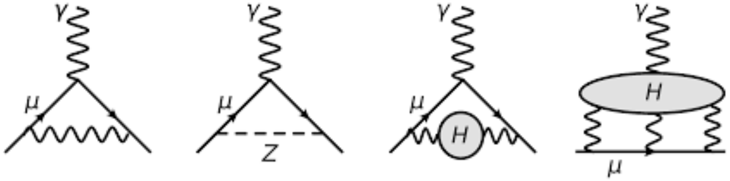
- This can be explained by a dark sector mass scale of ~ 10-100 MeV (“dark neutrons interacting through dark pions”).

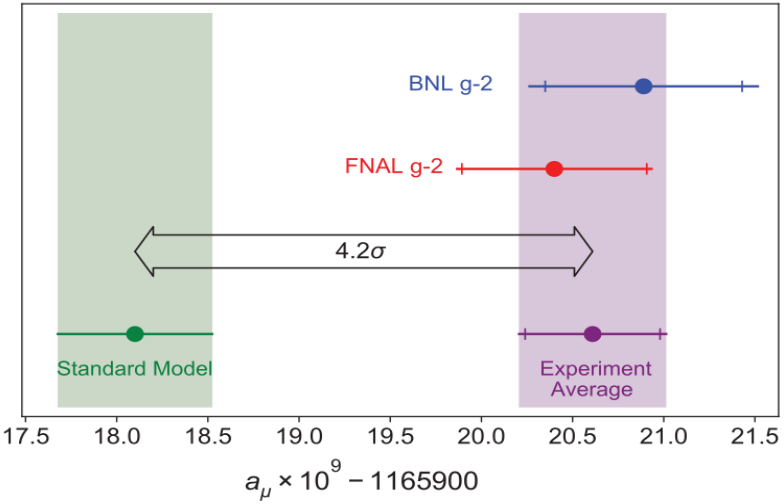
THE MUON'S ANOMALOUS MAGNETIC MOMENT

- In 2021, the Muon g-2 Collaboration announced a high precision measurement that deviates from the SM prediction by 3.3σ.
- It is sensitive to the weak interactions, but unlike other precision probes, it requires neither flavor nor CP violation, and so is a "natural" place for new particles to appear, provided they couple to muons.

$$\vec{\mu} = g\frac{q}{2m}\vec{S} \qquad a_l = (g_l - 2)/2$$

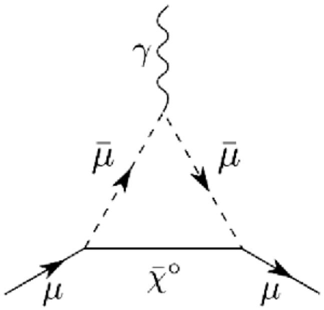


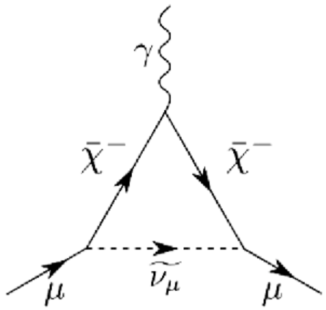


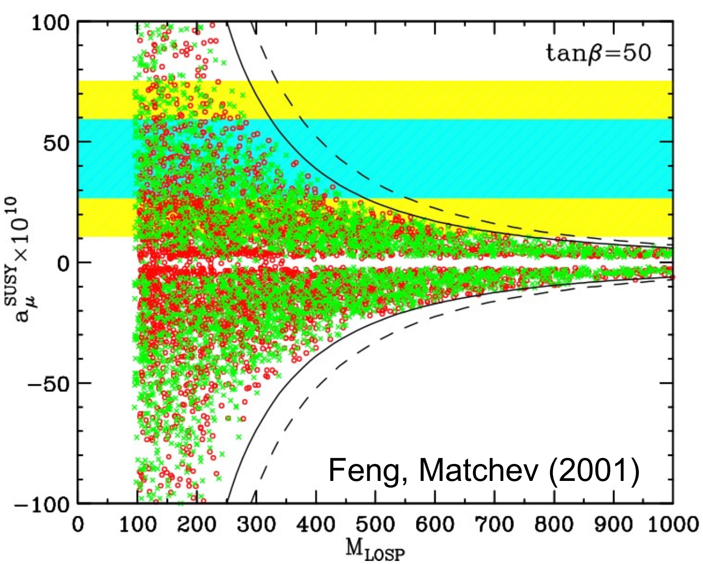


THE MUON'S ANOMALOUS MAGNETIC MOMENT

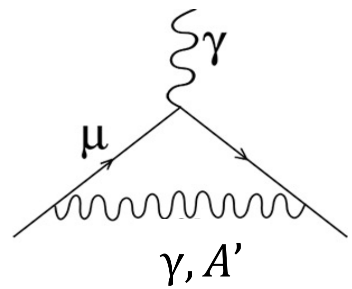
- The discrepancy can be resolved by heavy particles, e.g., SUSY with superpartners at the 100s of GeV to TeV scale.

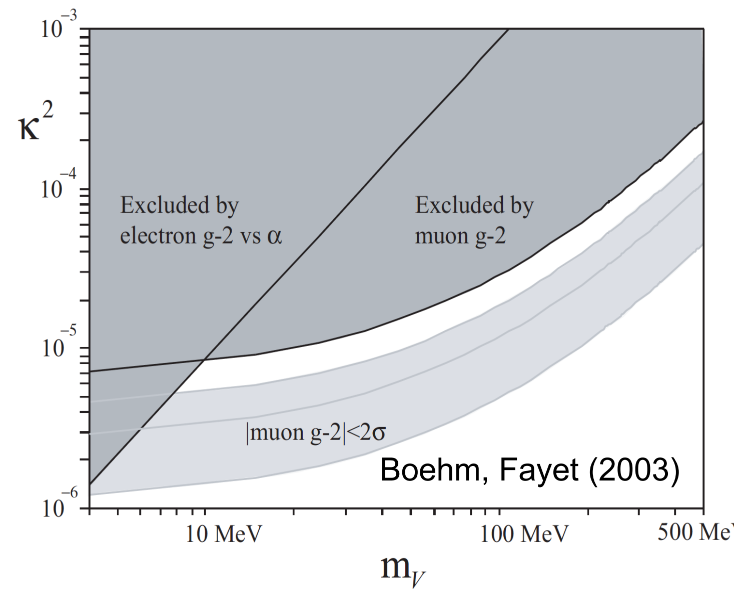






- But it can also be resolved with MeV-GeV masses and couplings ~ 10^{-3}. (Dark photon now excluded, but other similar particles remain viable.)





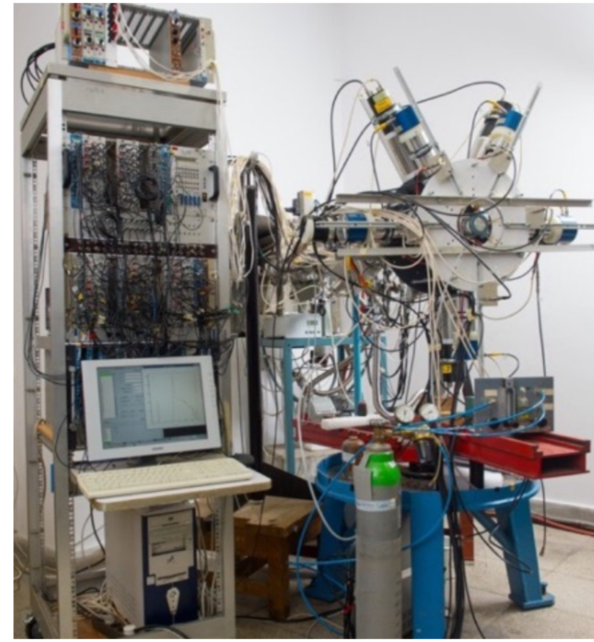
THE ⁸BE AND ⁴HE ATOMKI ANOMALIES

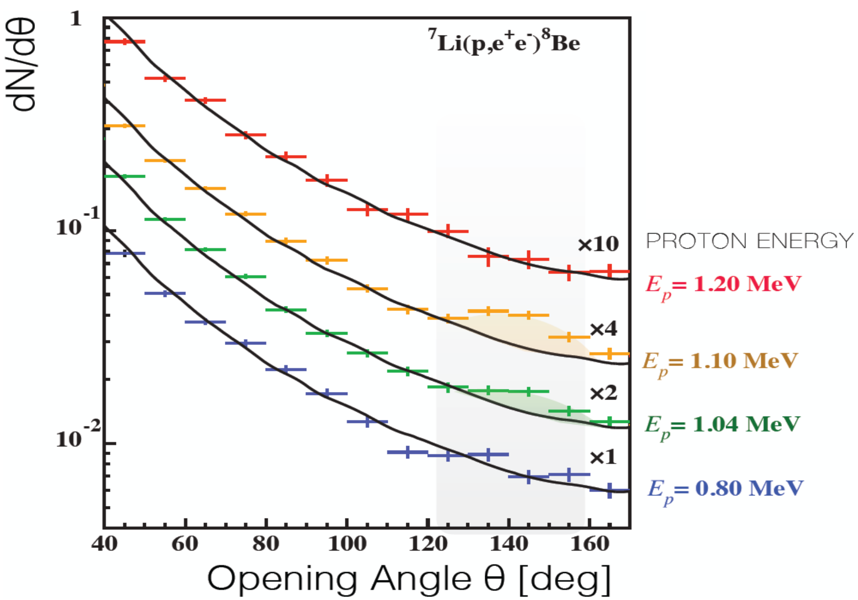
- New particles at the ~ 10 MeV scale and below can be produced in the decays of excited nuclei.

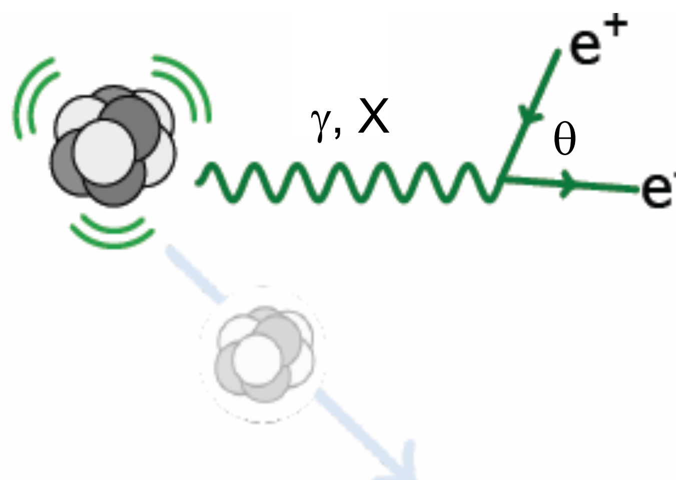
Treiman, Wilczek (1978); Donnelly, Freedman, Lytel, Peccei, Schwartz (1978); Savage, McKeown, Filippone, Mitchell (1986)

- In 2015, an ATOMKI group reported a 7σ excess in ^{8}Be (18.15) → ^{8}Be e^+e^- decays at $\theta_{e^+e^-} \approx 140°$.

Krasznahorkay et al., PRL, 1504.01527 [nucl-ex]







THE ^{8}BE AND ^{4}HE ATOMKI ANOMALIES

- The anomaly in the decays of excited ^{8}Be nuclei can be explained by a new protophobic gauge boson X with mass 17 MeV and couplings ~ 10^{-4} to 10^{-3}: ^{8}Be (18.15) → ^{8}Be X, followed by X → $e^+ e^-$.

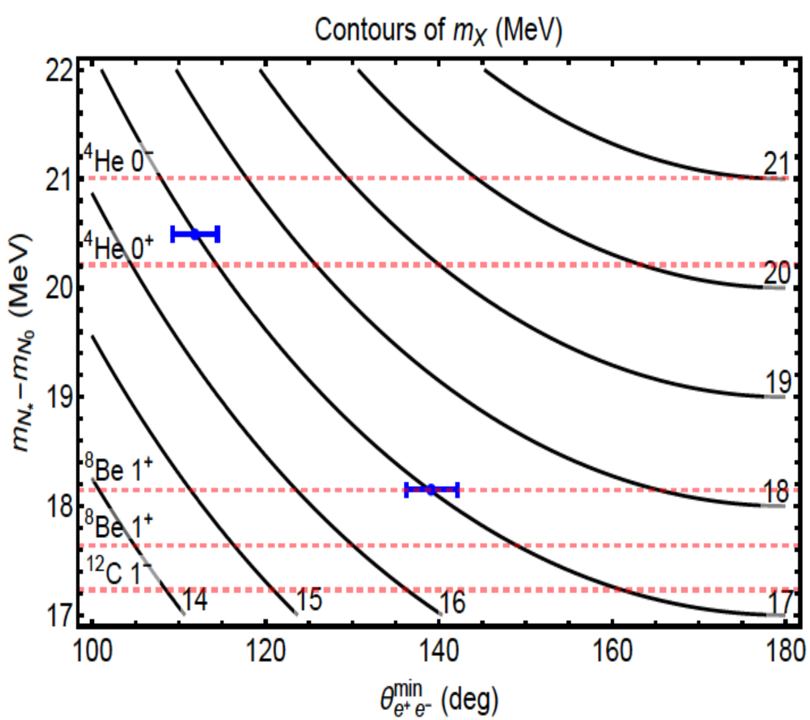
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)

- In 2019 the ATOMKI group reported a new 7σ excess in the decays of excited ^{4}He (20.49) nuclei at $\theta_{e^+e^-} \approx 115°$.

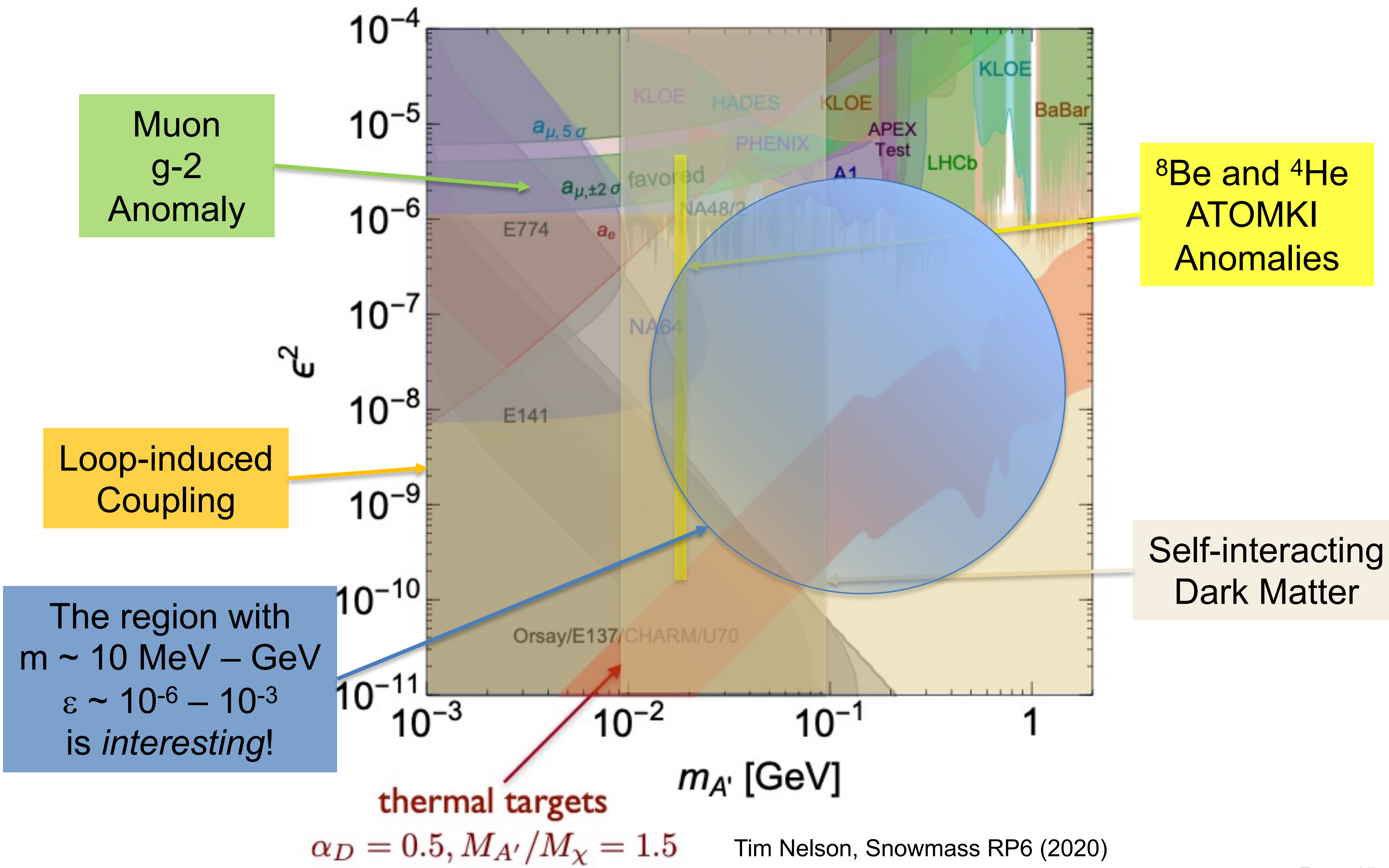
Krasznahorkay et al. (2019)

- Remarkably, this anomaly can be explained by the same new particle, which can also reduce the muon g-2 discrepancy to 2σ.

Feng, Tait, Verhaaren (2020)
See also Zhang, Miller (2020)



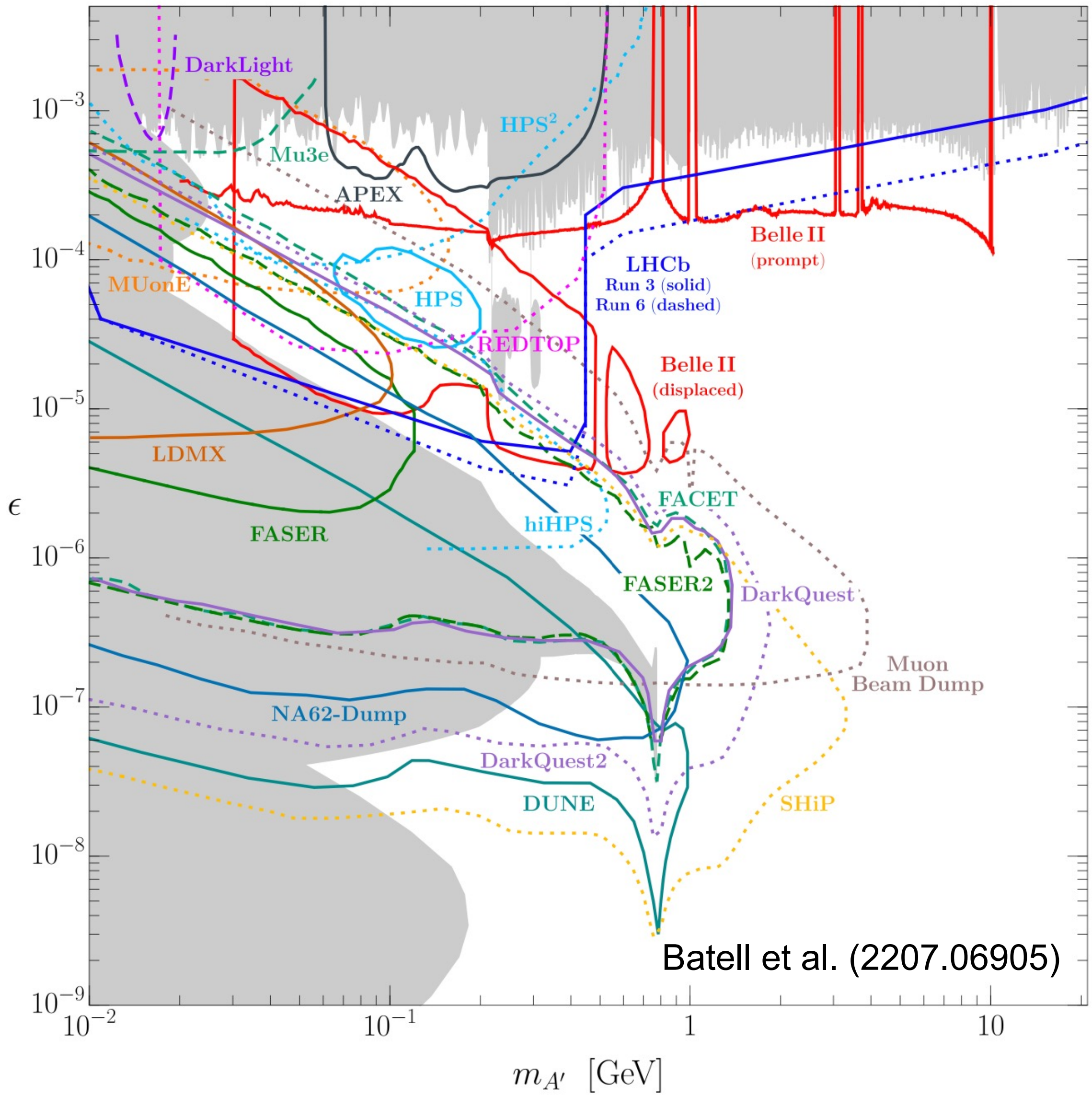
TARGETS IN DARK PHOTON PARAMETER SPACE



Tim Nelson, Snowmass RP6 (2020)

CURRENT EXPERIMENTAL SEARCHES

- In the next few years, this region will be probed by currently running experiments (LHCb, Belle2, NA64, FASER, …) and also proposed experiments. This is the low-hanging fruit of dark sectors – similar to Z-mediated WIMP cross sections. Soon this parameter space will look completely different.



PROTOPHOBIC GAUGE BOSONS

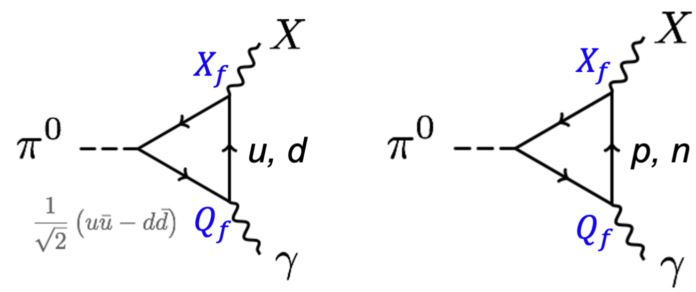
- Photophobic gauge bosons X are quite different from dark photons
  - No production by dark bremsstrahlung off protons
  - No production in pion decays: protophobic → pion-phobic
  - Dominantly produced in η / η’ decays.

- Consider a model-independent analysis: fix g_u , g_d ~ 10^{-3} (very large!) to explain ATOMKI, scan over g_e .

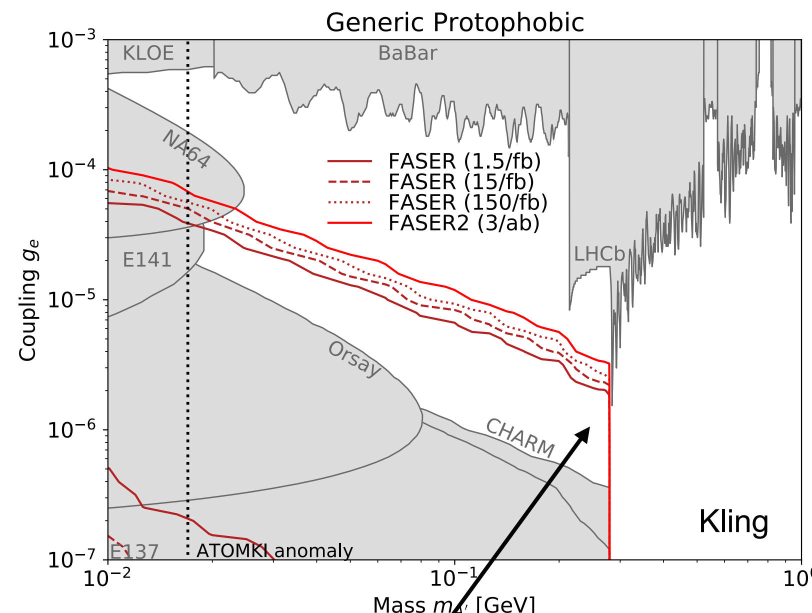
- With 1 fb^{-1}, FASER will probe the low g_e region. NA64 will probe high g_e.

- The 7-year-old ATOMKI anomalies will likely be first confirmed or refuted by high-energy experiments.

Feng, Kling (2022)



This is eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$.

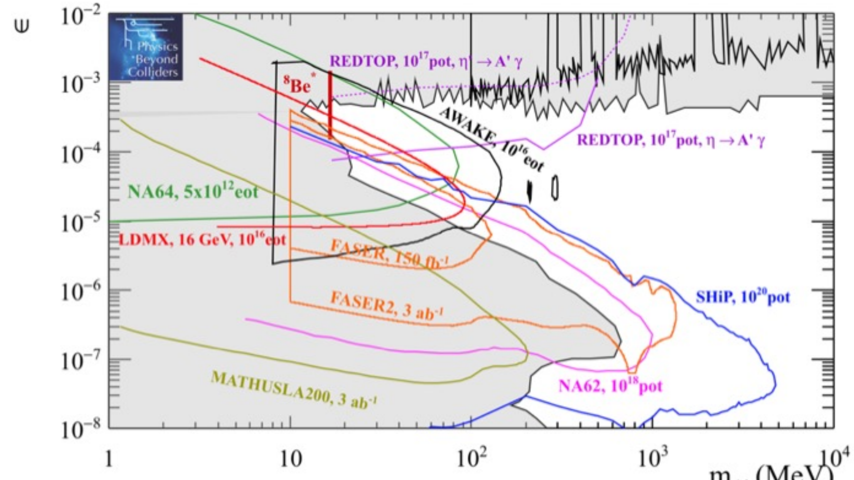


$X \rightarrow \mu^+ \mu^-$ for $2m_\mu < m_X < 2m_\pi$

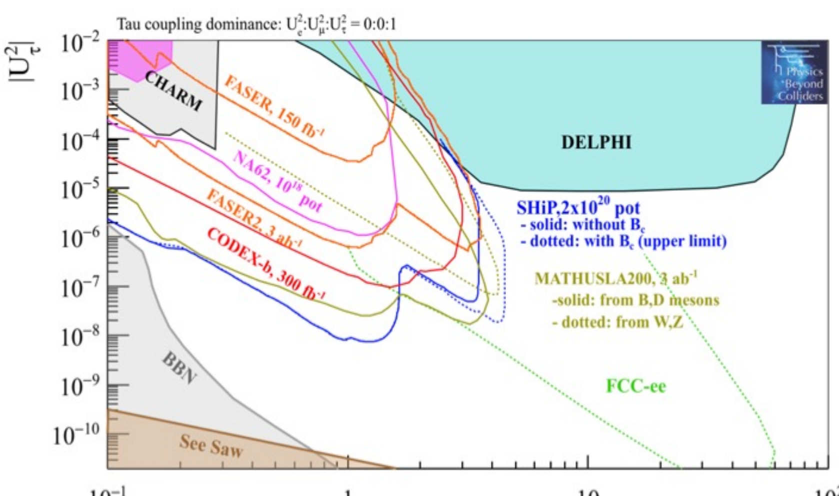
FUTURE EXPERIMENTAL SEARCHES

- For the future, dedicated detectors have significant discovery potential for a wide variety of dark sector particles: dark photons; B-L and related gauge bosons; dark Higgs bosons; HNLs with couplings to e, mu, tau; ALPs with photon, gluon, fermion couplings; light neutralinos, inflatons, relaxions, and many others.

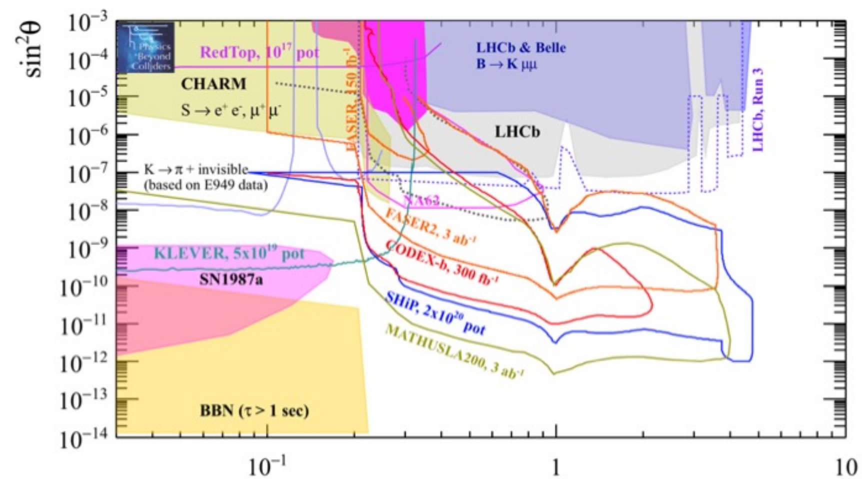
FPF White Paper (2022)



Dark Photon



Dark Fermion



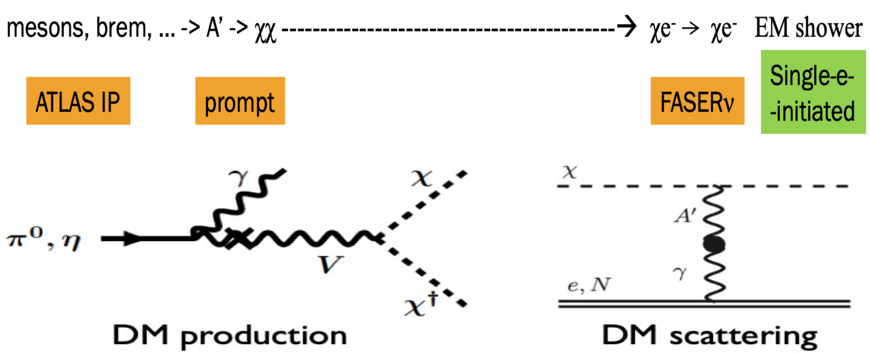
Dark Scalar

DARK MATTER DIRECT DETECTION

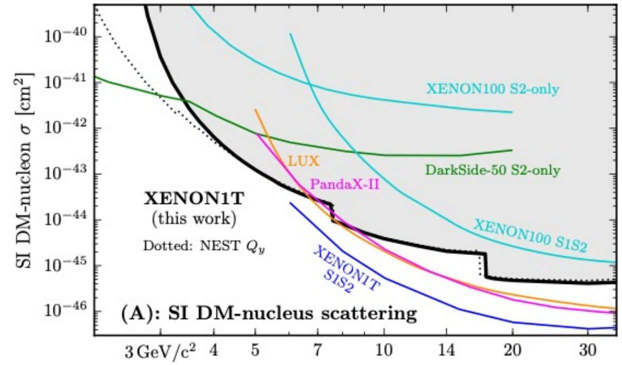
- What if the portal particle decays back to the dark sector? Light DM with masses at the GeV scale and below is famously hard to detect, but there is a great deal of creative work going on in this area.

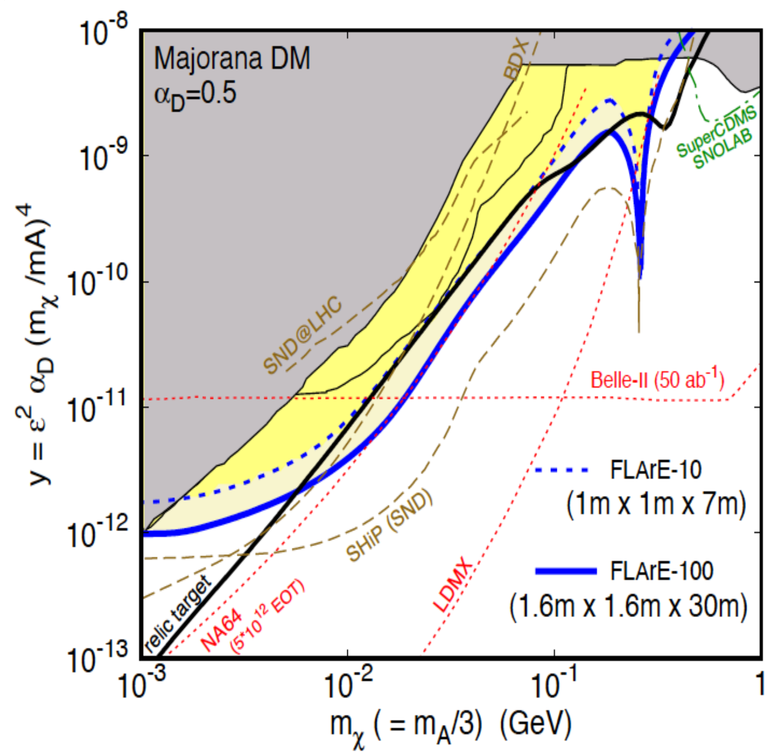
  See Asher Berlin's talk

- At the LHC, we can produce DM at high energies, look for the resulting DM to scatter in FLArE, Forward Liquid Argon Experiment, a proposed 10 to 100 tonne LArTPC.



- FLArE is powerful in the region favored/allowed by thermal freezeout. Note complementarity: q vs. e coupling, direct detection vs. missing X, etc.





Batell, Feng, Trojanowski (2021)

SUMMARY

- Dark matter and dark sectors are currently among the leading motivations for BSM searches.

- In general, dark sectors predict new particles with an enormous range of masses and interaction strengths and also many qualitatively different possibilities; milli-charged particles, hadrophilic gauge bosons, quirks, …; see backup slides.

- But there is a relatively small region of parameter space that has motivations comparable to WIMPs: masses ~ MeV to GeV, couplings ~ micro to milli.
  - WIMPs: coincidence of particle experiment (current threshold of what is observable), particle theory (gauge hierarchy problem), cosmology (WIMP miracle), astrophysics (large-scale structure), anomalies
  - Dark sectors: coincidence of particle experiment (current threshold of what is observable), particle theory (portals), cosmology (WIMPless miracle), astrophysics (small-scale structure), anomalies

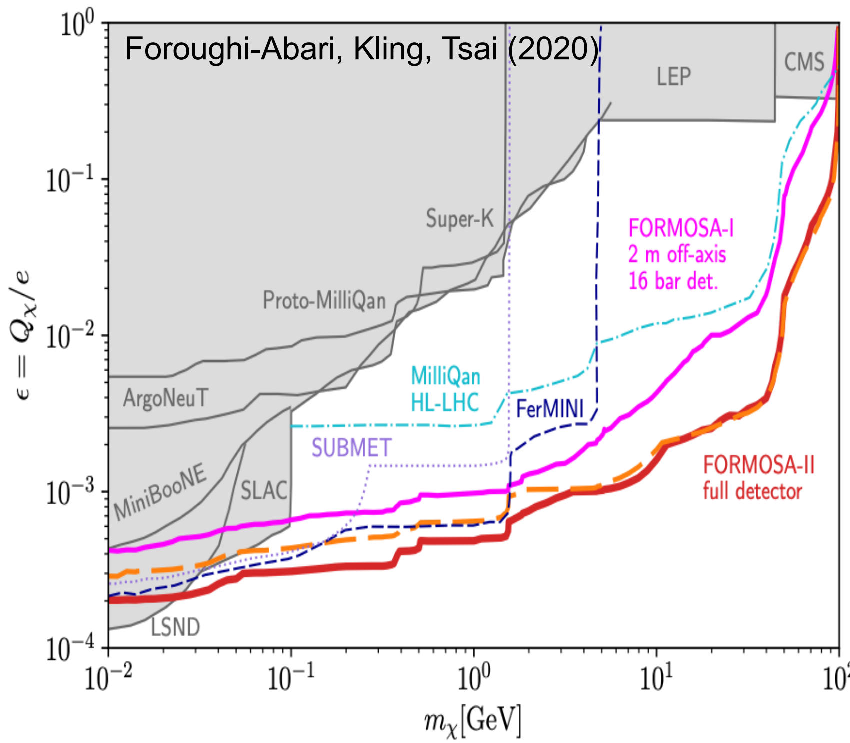
- Most importantly, this region can be probed by many experiments in the coming 10 years. Just as WIMP DM became the subject of a world-wide research program in the 2000's and 2010's, dark sectors will become the subject of a world-wide research program in the 2020's and 2030's.

BACKUP

MILLI-CHARGED PARTICLES

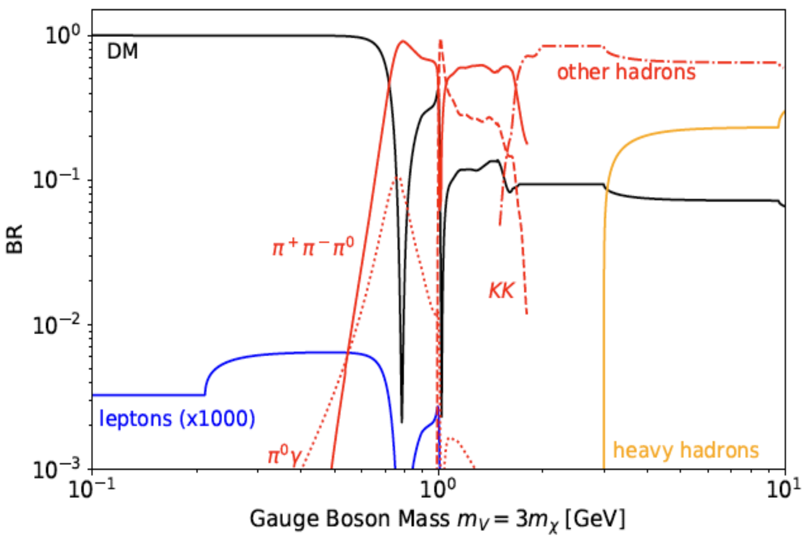
- A completely generic possibility motivated by dark matter, dark sectors. Currently the target of the MilliQan experiment, located at the LHC near the CMS experiment in a “non-forward” tunnel.

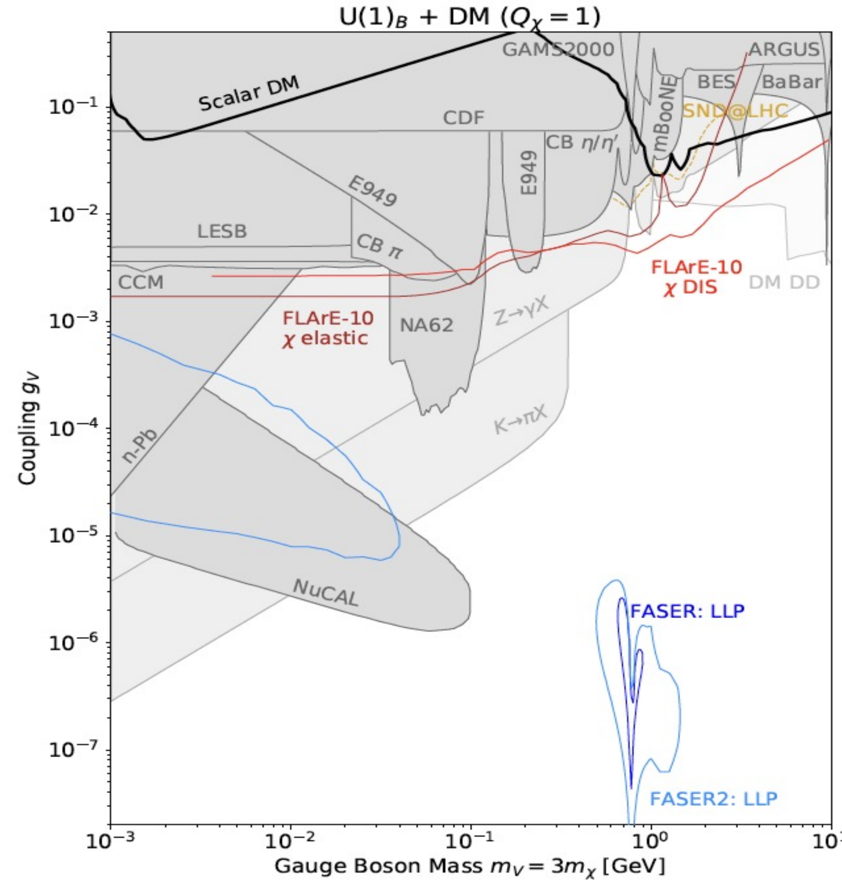
- The MilliQan Demonstrator (Proto-MilliQan) already probes new region. Full MilliQan can also run in this location in the HL-LHC era, but the sensitivity may be improved significantly by moving it to the FPF (FORMOSA).



NEW SIGNALS: B AND B-3τ GAUGE BOSONS

- Consider a light gauge boson coupled to baryon number
- Produced through $q\bar{q} \rightarrow V$
- Many interesting hadronic decays
  $V \rightarrow \pi^0\gamma,\ \pi^+\pi^-\pi^0,\ K^+K^-,\ K_S\,K_L$
- Greatly expands the standard e^+e^-, $\gamma\gamma$ signatures; similar signatures for "anomaly-free" gauge bosons

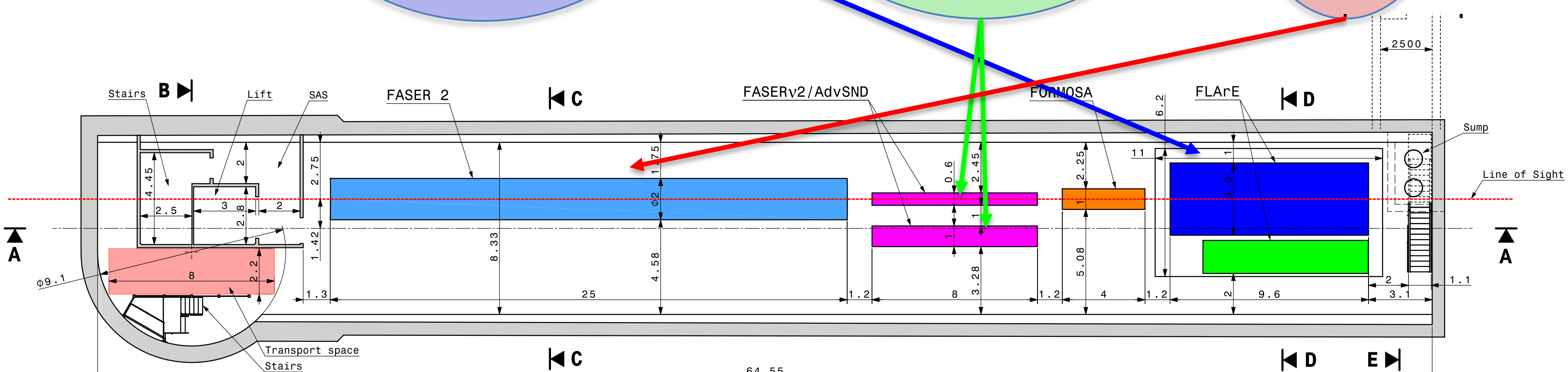




Batell, Feng, Fieg, Ismail, Kling, Abraham, Trojanowski, 2111.10343; see also Boyarsky, Mikulenko, Ovchynnikov, Shchutska, 2104.09688

SIGNATURES FOR OTHER FPF EXPERIMENTS

Signature	DM DIS	DM Elastic	ν NC DIS	ν_τ CC DIS	LLP decays
Models	$U(1)_B$, $U(1)_{B-3\tau}$	$U(1)_B$, $U(1)_{B-3\tau}$	$U(1)_{B-3\tau}$	$U(1)_{B-3\tau}$	$U(1)_B$, $U(1)_{B-3\tau}$
Production	$pp \to V \to \chi\chi$	$pp \to V \to \chi\chi$	$pp \to D_s \to \nu_\tau$	$pp \to V \to \nu_\tau \bar{\nu}_\tau$	$pp \to V$
Detection	$\chi N \to \chi X$	$\chi p \to \chi p$	$\nu_\tau N \to \nu_\tau X$	$\nu_\tau N \to \tau X$	$V \to$ hadrons



Plan view - Cavern
1:100

Batell, Feng, Fieg, Ismail, Kling, Abraham, Trojanowski, 2111.10343

NEW SIGNALS: QUIRKS

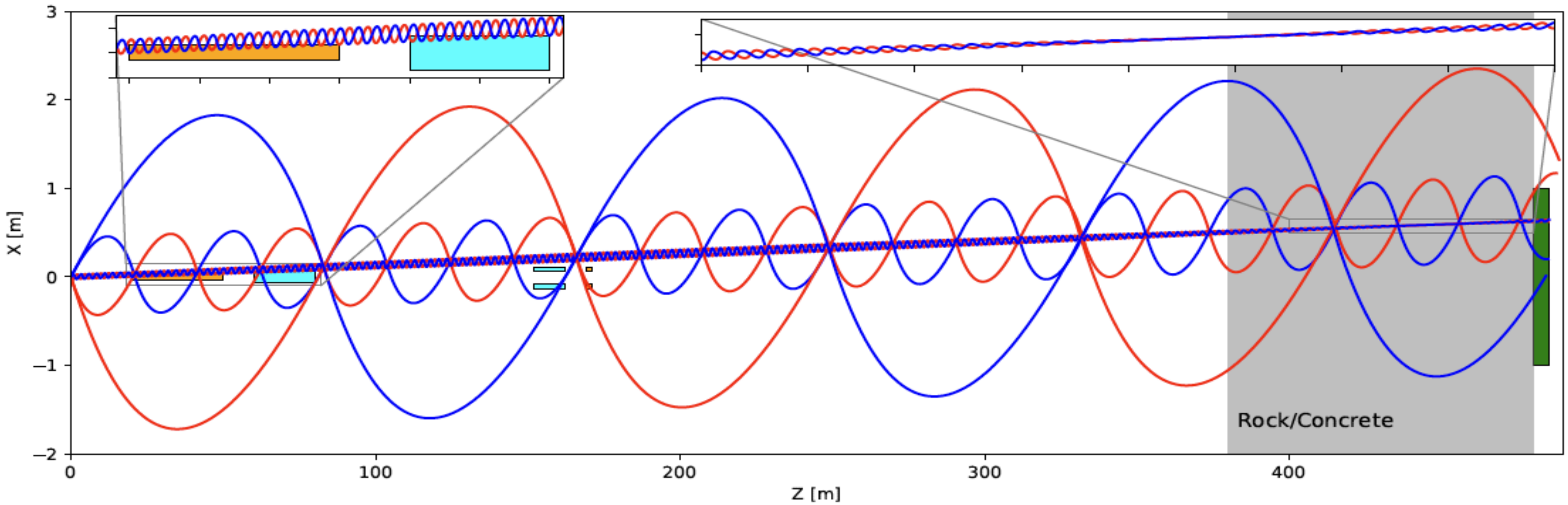
Kang, Luty (2008)

- Quirks are matter particles charged under a hidden strong force with mass m >> Λ_{hidden}. E.g., m ~ 100 GeV – TeV, Λ_{hidden} ~ keV.
- Quirks may also have SM charge and color. They are then pair produced at the LHC, and are connected by a hidden color string.
- For quarks and standard QCD, m << Λ_{QCD}, and so it becomes energetically favorable to pair produce new quarks from the vacuum. Quarks hadronized.
- But for quirks, since m >> Λ_{hidden} , it is never energetically favorable to break the string by pair producing quirks from the vacuum: quirks do not hadronize, they oscillate.

QUIRK SIGNATURE

- Of course, the quirk – anti-quirk system has low p_T.
- The pair therefore oscillates, with length scale ~ 1/ Λ_{hidden}.
- For a range of Λ_{hidden} , the quirk system travels down the beamline, escaping most LHC detectors, but ultimately leaving (strange!) tracks in FASER.

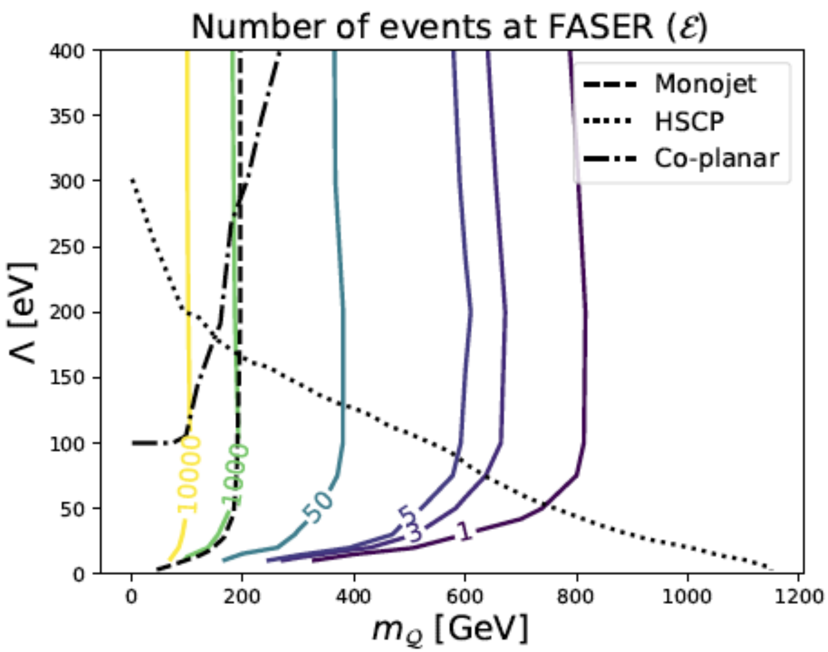
Li, Pei, Ran, Zhang, 2108.06748

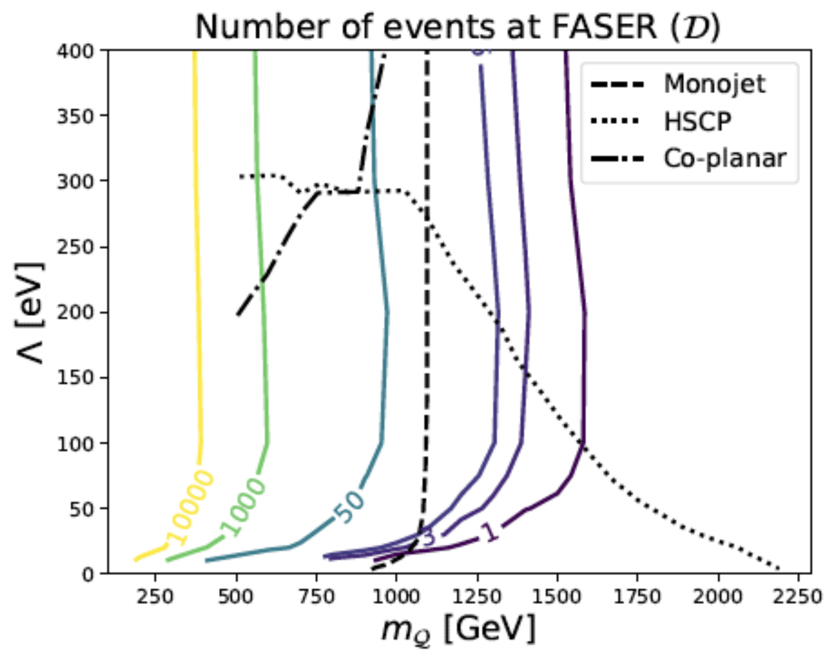


QUIRK DISCOVERY PROSPECTS

- Far-forward detectors at the LHC are ideally suited to search for quirks.
  - Like heavy particles, they require the LHC to be produced
  - Like light particles, they are dominantly produced along the beamline

- ~1000 of events possible at FASER in Run 3





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