BSM and dark sector: introduction

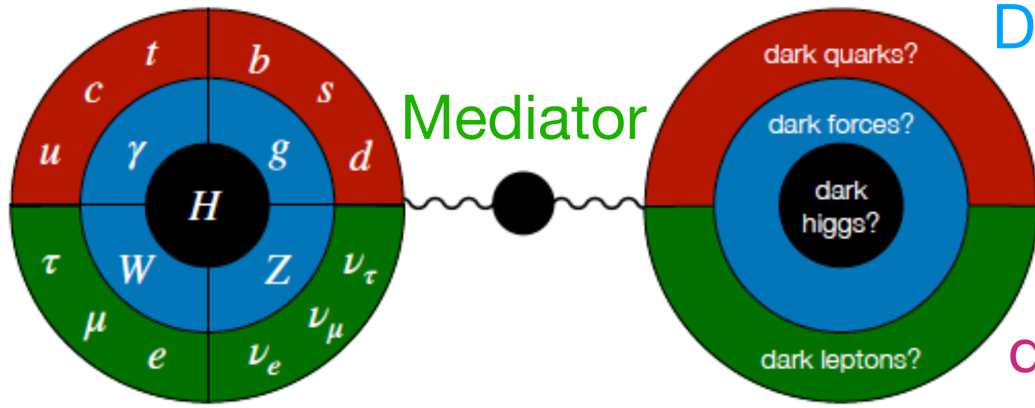
Stefania Gori
UC Santa Cruz

Vietnam Flavour Physics Conference 2022

Quy Nhon

August 19, 2022

What's a dark sector?



Dark Matter (DM)

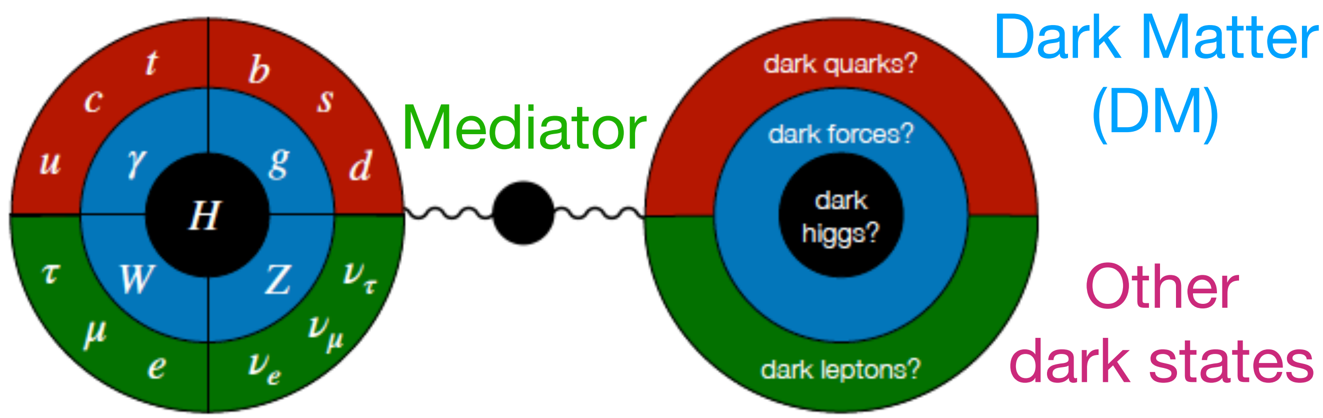
Other dark states

The Standard Model (SM)

The dark sector

Particles neutral under the SM gauge symmetries

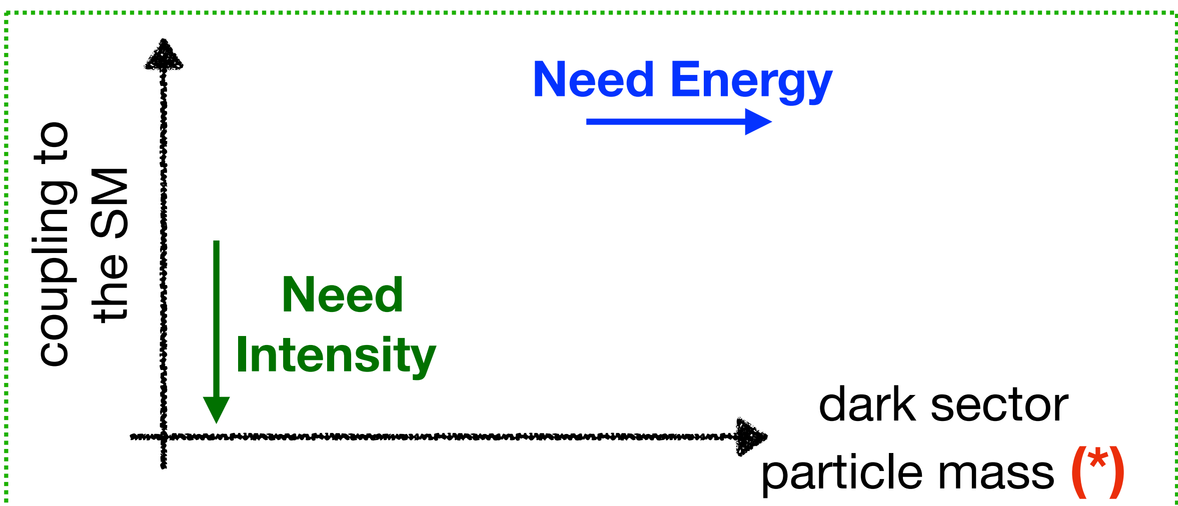
What's a dark sector?



The Standard Model (SM)

The dark sector

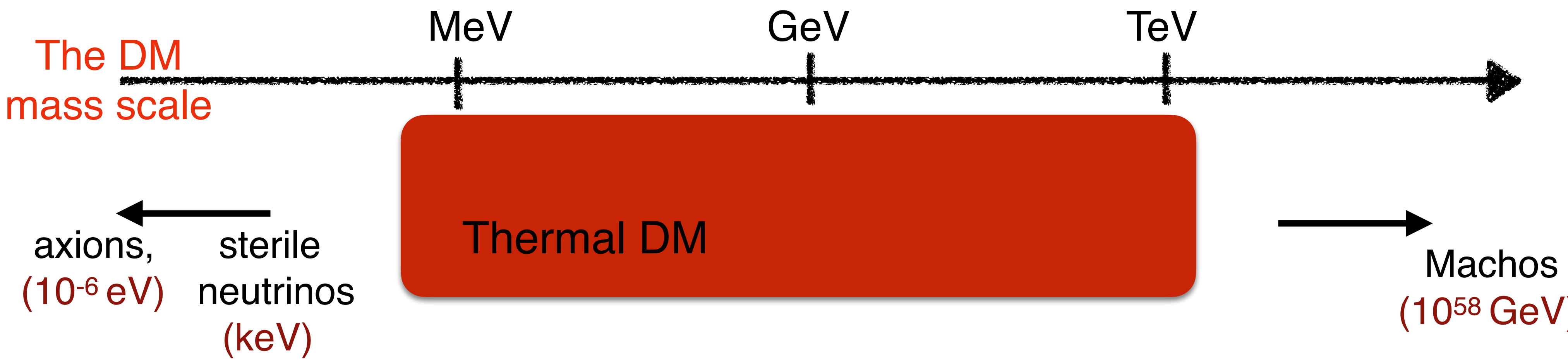
Particles neutral under the SM gauge symmetries



(*) It can be protected by an approximate symmetry

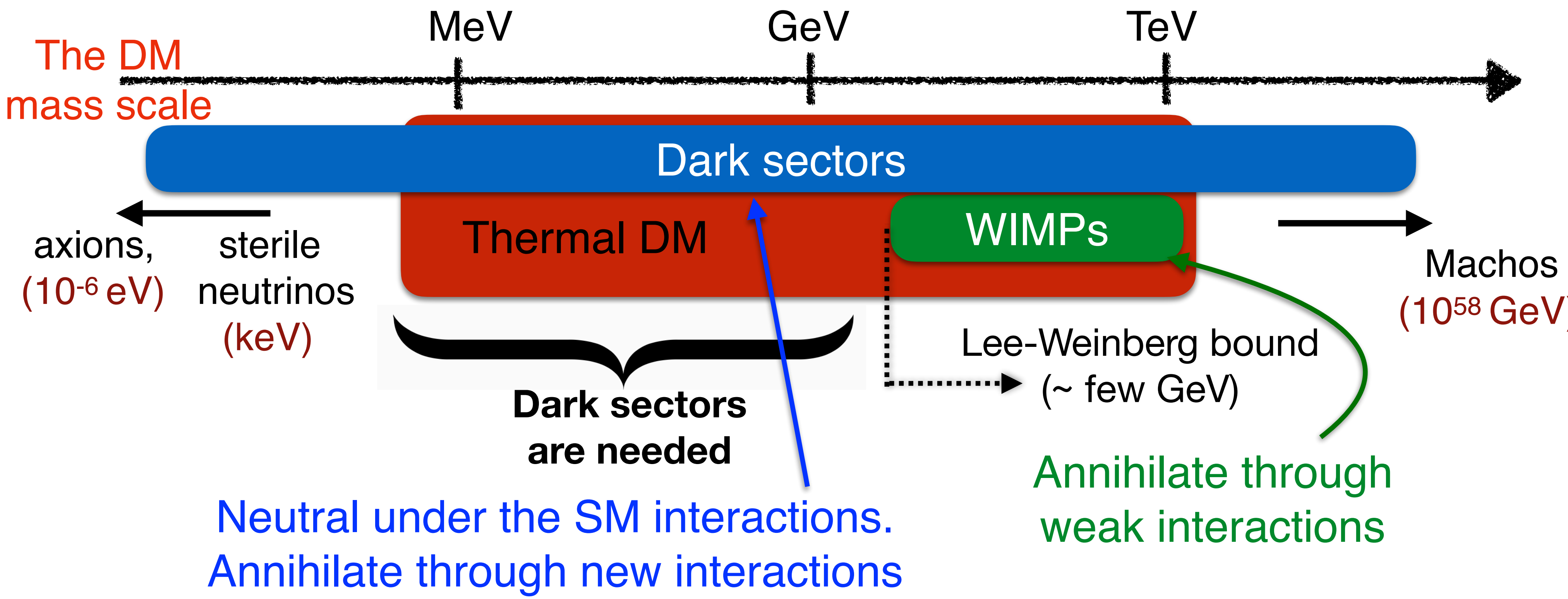
Why a dark sector?...

The Dark Matter scale



The dark matter scale is **unknown**.
Completely different search strategies depending on the mass of dark matter

The Dark Matter scale



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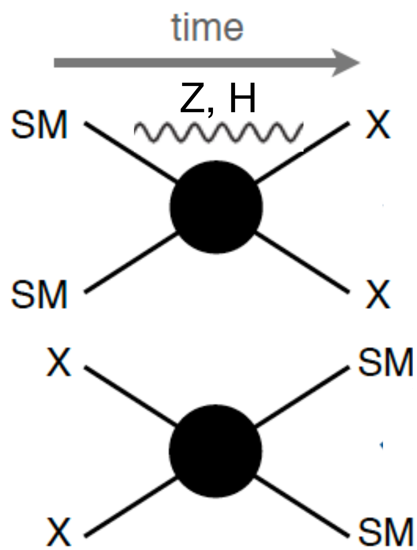
Completely different search strategies depending on the mass of dark matter

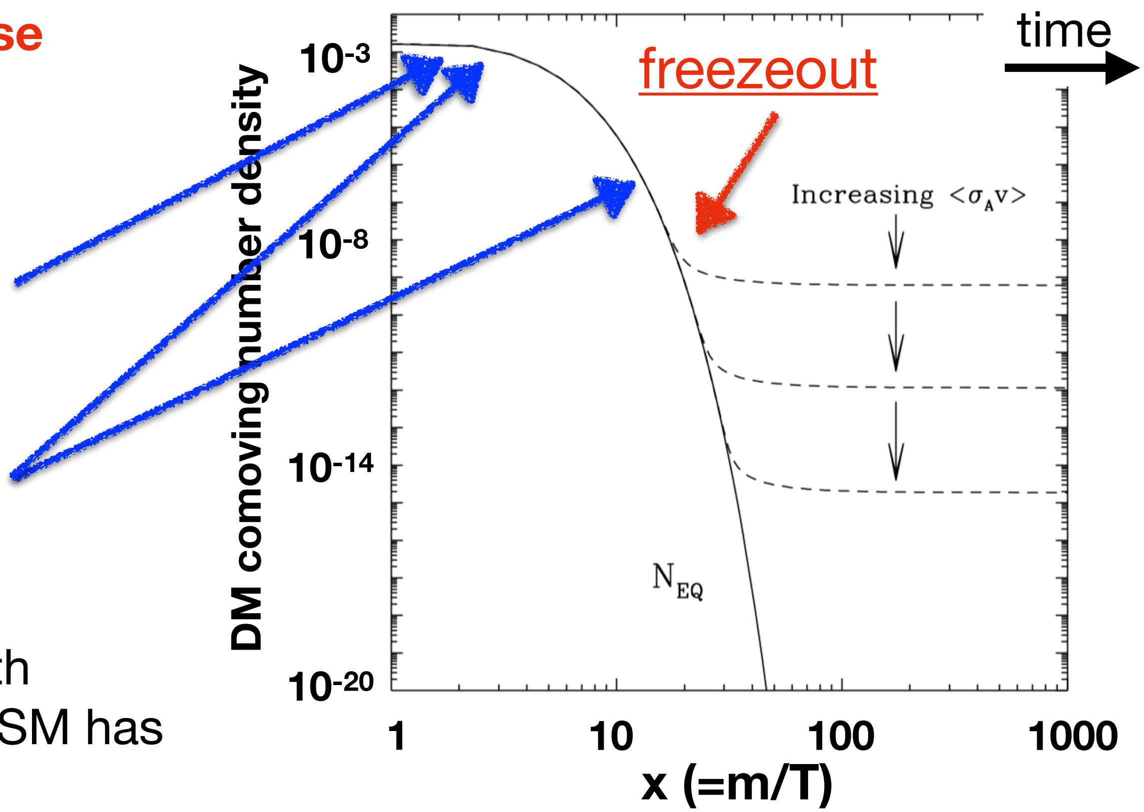
Today we will focus on dark matter with a mass in **~(MeV, GeV)**

The WIMP miracle

(Weakly Interacting Massive Particles)

Thermal in the early universe





DM at ~the electroweak scale with ~electroweak couplings with the SM has the measured relic abundance

The WIMP miracle
(Weakly Interacting Massive Particles)

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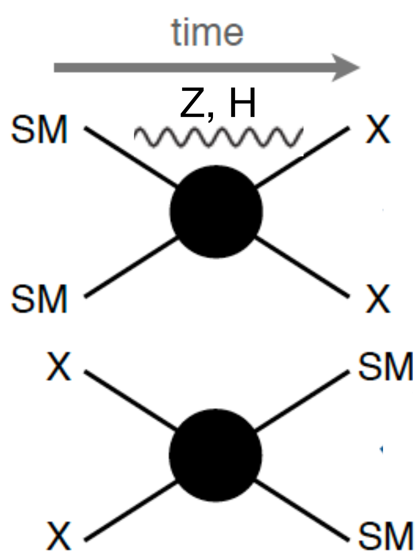
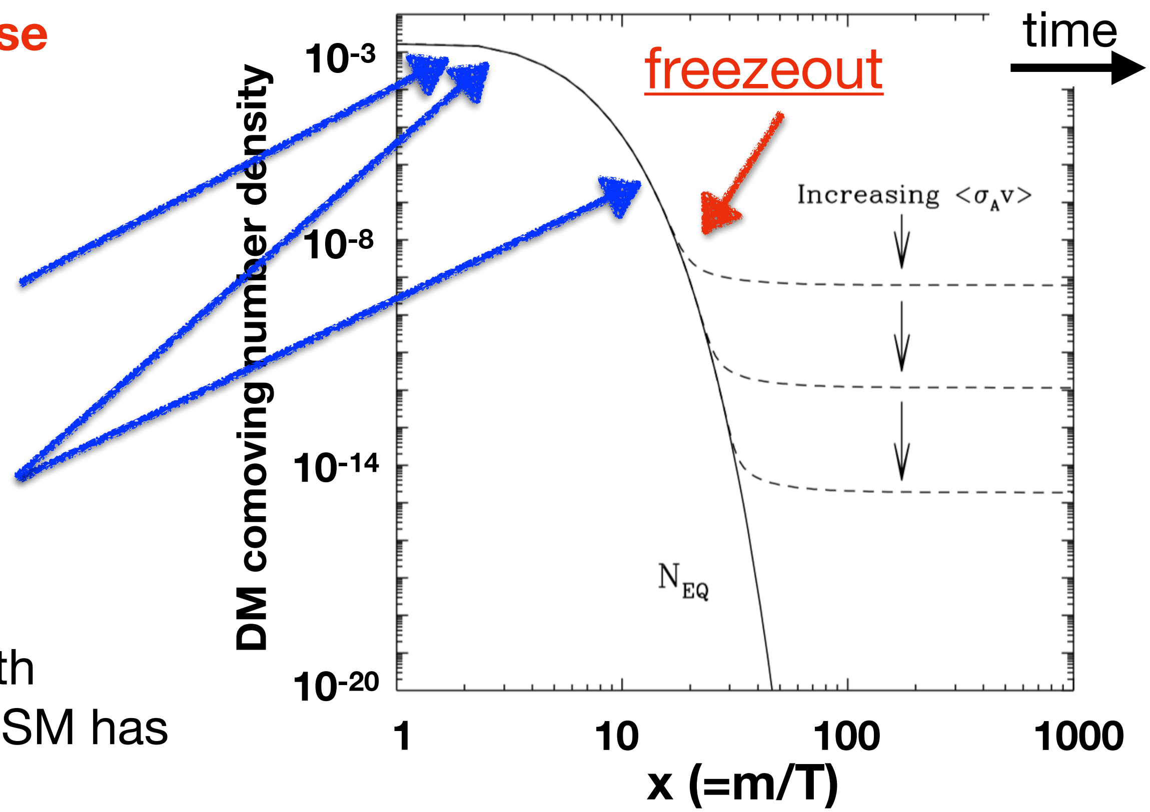
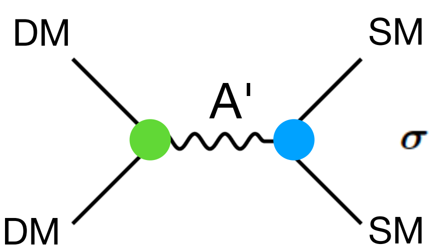




DM at ~the electroweak scale with ~electroweak couplings with the SM has the measured relic abundance

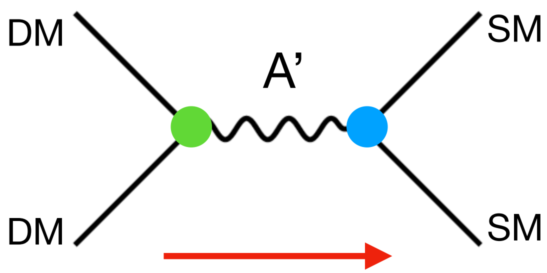
Generalization: freeze-out for DM particles with a mass **below the few GeV scale.**



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

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

Probing DM at accelerators & at direct detection experiments



Sets the relic abundance

$$\sigma \propto \frac{y}{m_{\rm DM}^2},$$

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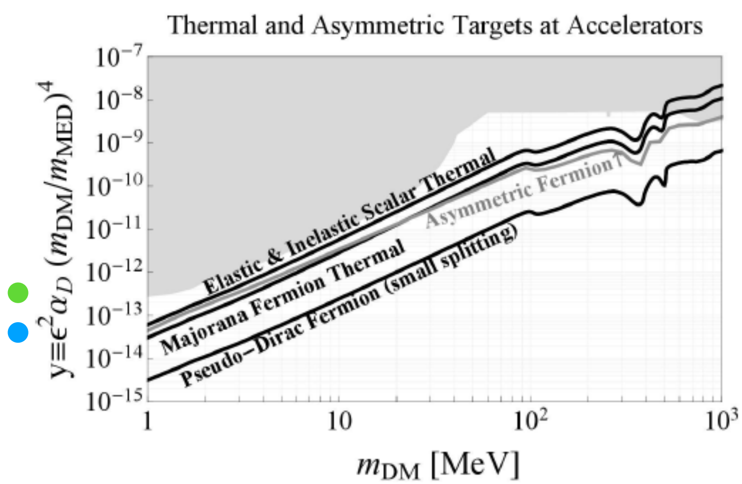

 Battaglieri et al., 1707.04591

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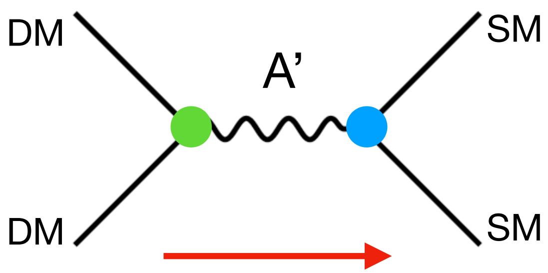

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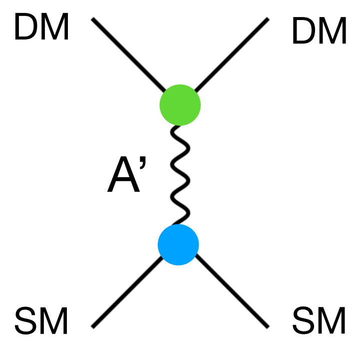
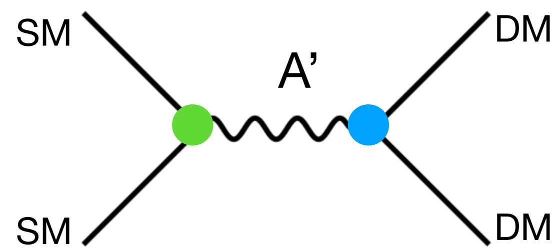


Direct detection
(see G. Blockinger talk today)



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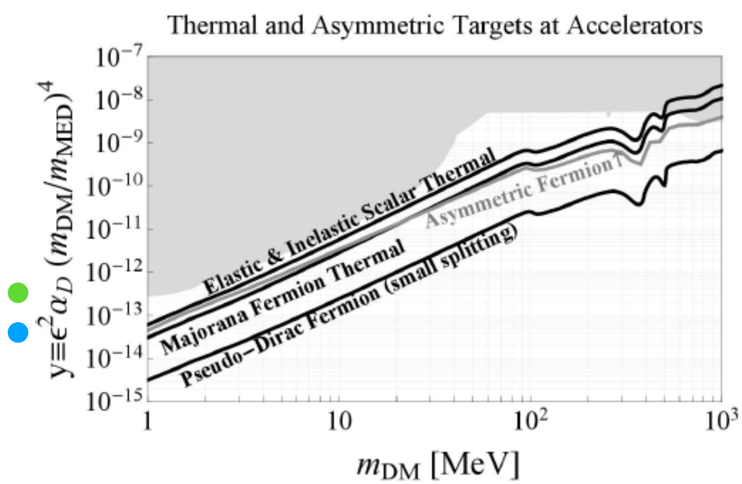

S.Gori

Battaglieri et al., 1707.04591

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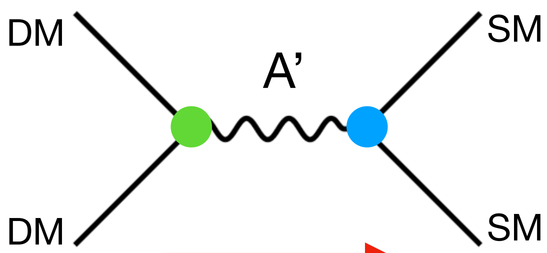

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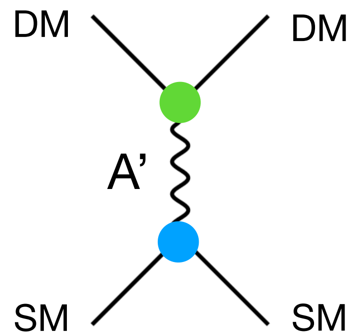

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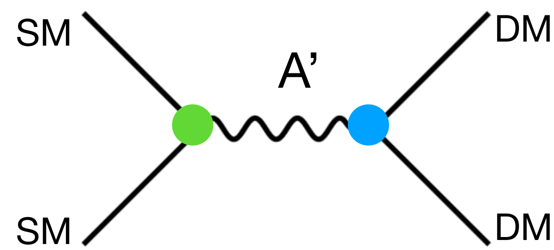

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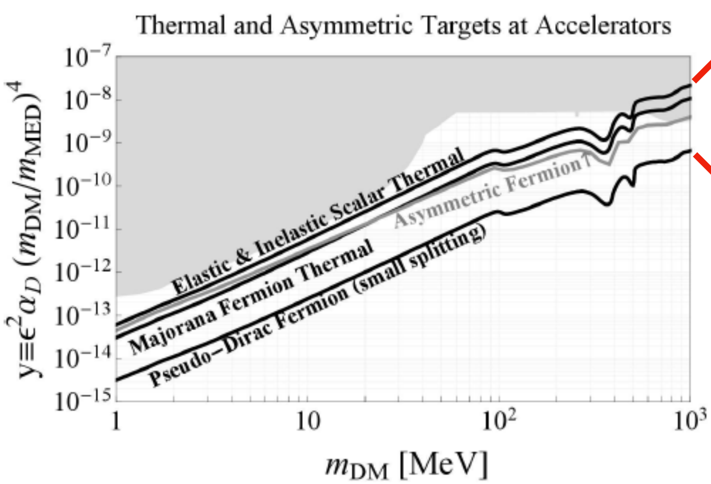

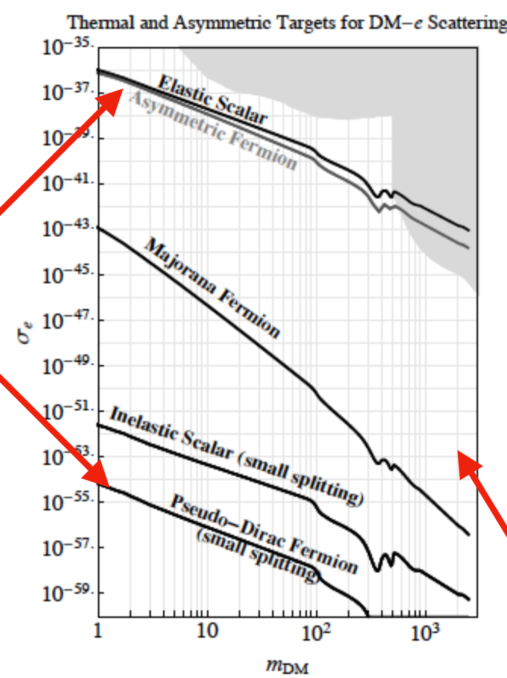

Accelerator production recreates the kinematic conditions of the early universe (**DM is relativistic**).

It is ~ unaffected by the nature of DM.

non-relativistic scattering

Battaglieri et al., 1707.04591

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
- Theories for the generation of neutrino masses

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

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

← simple set of requirements

(*) some studies go beyond this assumption

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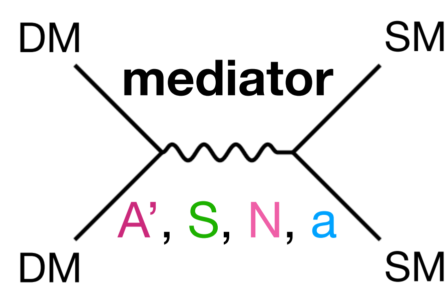
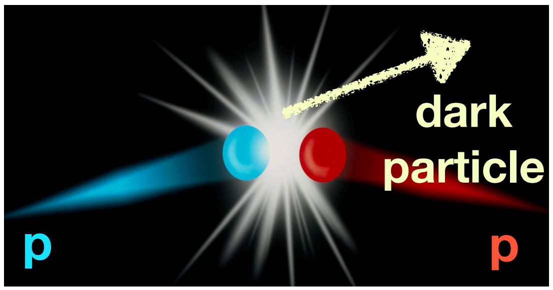
Dark sector portals

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



A broad program of searches at accelerator experiments

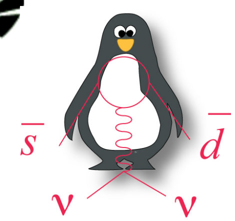
The LHC



Novel search strategies are needed!

Important role covered by the Higgs

Flavor-factories



Unique access to dark sectors!

Fixed target experiments (including neutrino experiments)

Beam (high intensity) **Dump/shield** **Decay volume** **Detector**

Both **visible** and **invisible** **searches**

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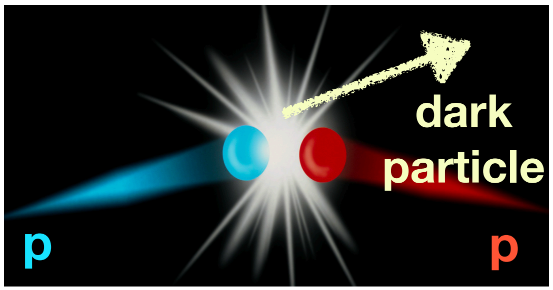

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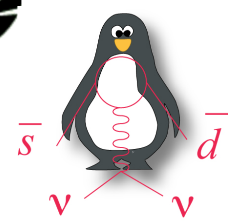

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A large community effort

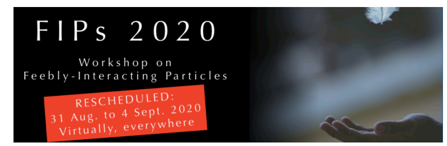
The worldwide search for Dark Sectors has involved hundreds of scientists, new models, many new analyses & experiments in last few years

Vibrant theory + experimental community

Dark Interactions Workshop, BNL, 2014

Dark sectors workshop, SLAC, 2016

Cosmic Visions community workshop 2017.
Community report:
Battaglieri et al., 1707.04591



International effort:

- The Physics Beyond Colliders Study Group at CERN, https://pbc.web.cern.ch

- In the US, 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

- In the US, Snowmass process 2020-2022.
Rare Frontier 6 topical group (SG, M. Williams, https://snowmass21.org/rare/dark)

Note on theory uncertainties

Several production and decay processes have large theoretical uncertainties

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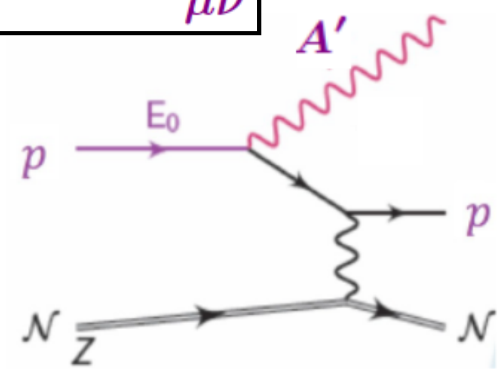
A couple of examples:

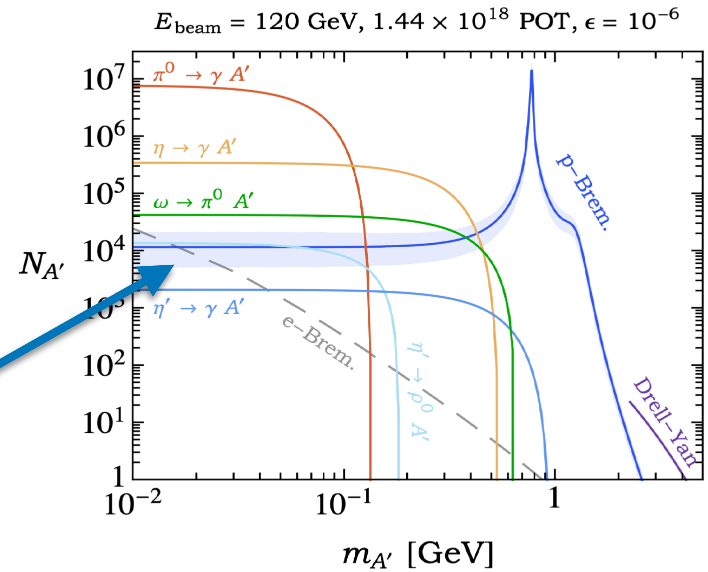
1. Bremsstrahlung production of a dark photon at fixed target experiments

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



Weizsaecker-Williams approximation

Berlin, SG, Schuster, Toro, 1804.00661



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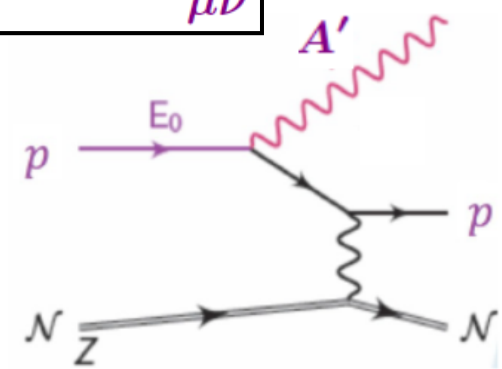

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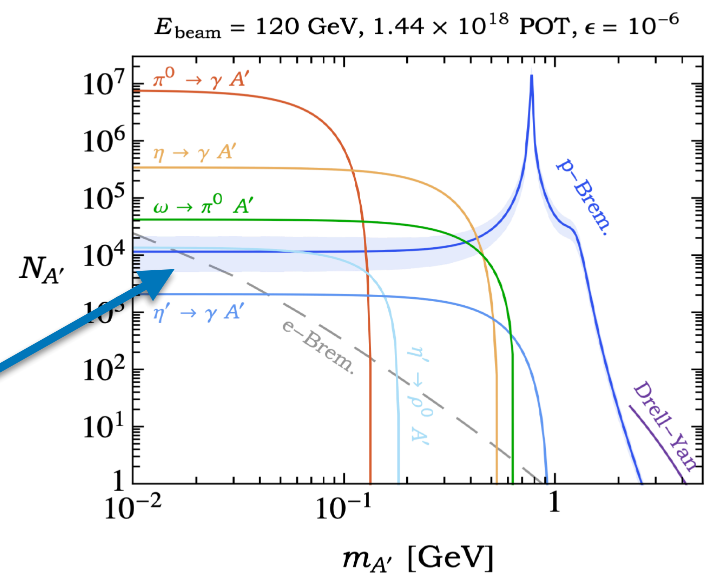


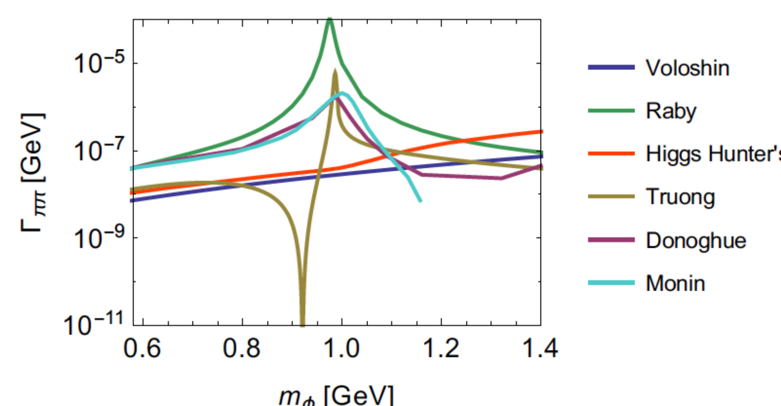
2. Dark scalar decays and life time

$$\kappa |H|^2 |S|^2$$

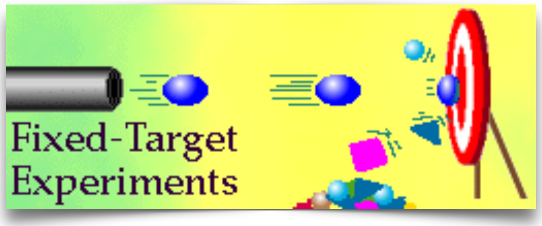
for example, the width into pions:

$$S \to \mu^+\mu^-,\ \pi^+\pi^-, KK, \ldots$$

Winkler. 1809.01876

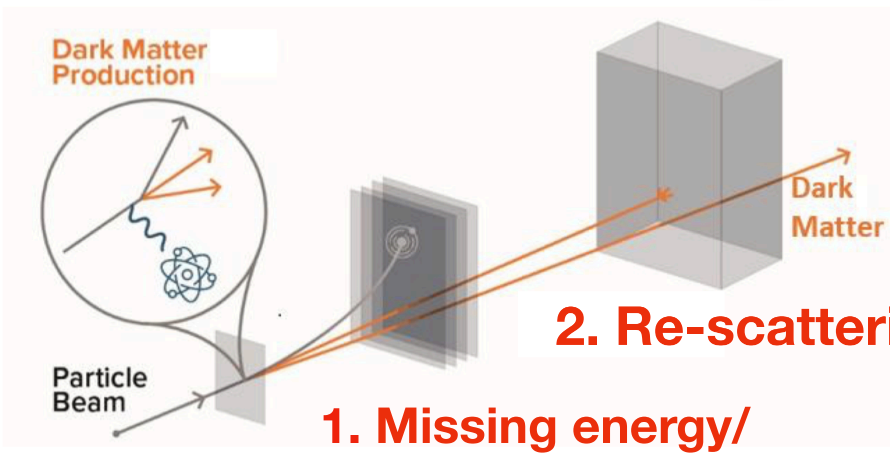


Dark sectors from colliding beam(s)



DM at fixed targets & B-factories

Fixed target



2. Re-scattering

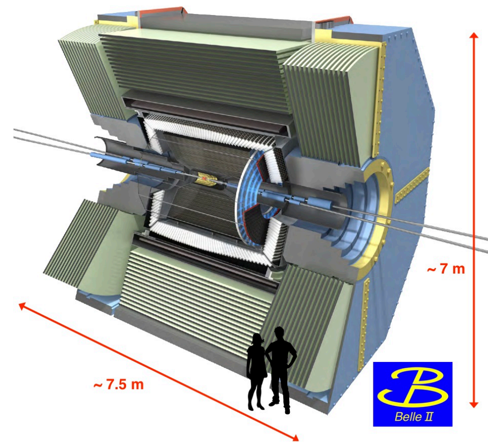
1. Missing energy/ momentum

1. Present:
   e$^-$ beam for the **NA64** experiment,
   Proposed:
   e$^-$ beam for the **LDMX** experiment,
   e$^+$ beam for the **POKER** experiment,
   μ$^-$ beam for the **M^3** experiment

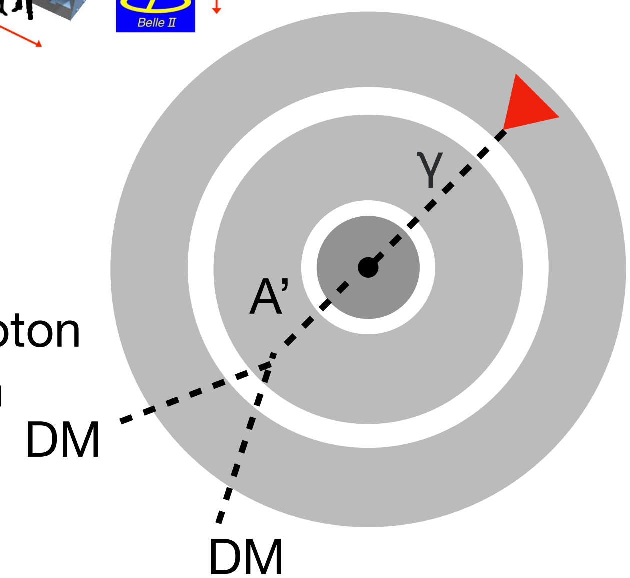
2. Neutrino experiments!

talk by A. de Roeck on Thursday

B-factories



e.g.
mono-photon
search

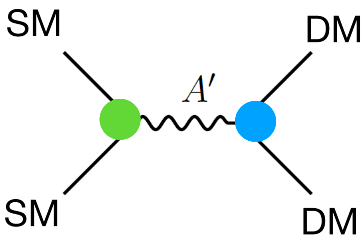


Missing energy

DM at fixed targets & B-factories

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

A’→XX

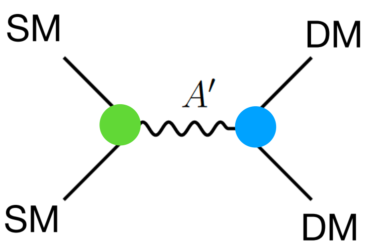


Dark photon mediated DM

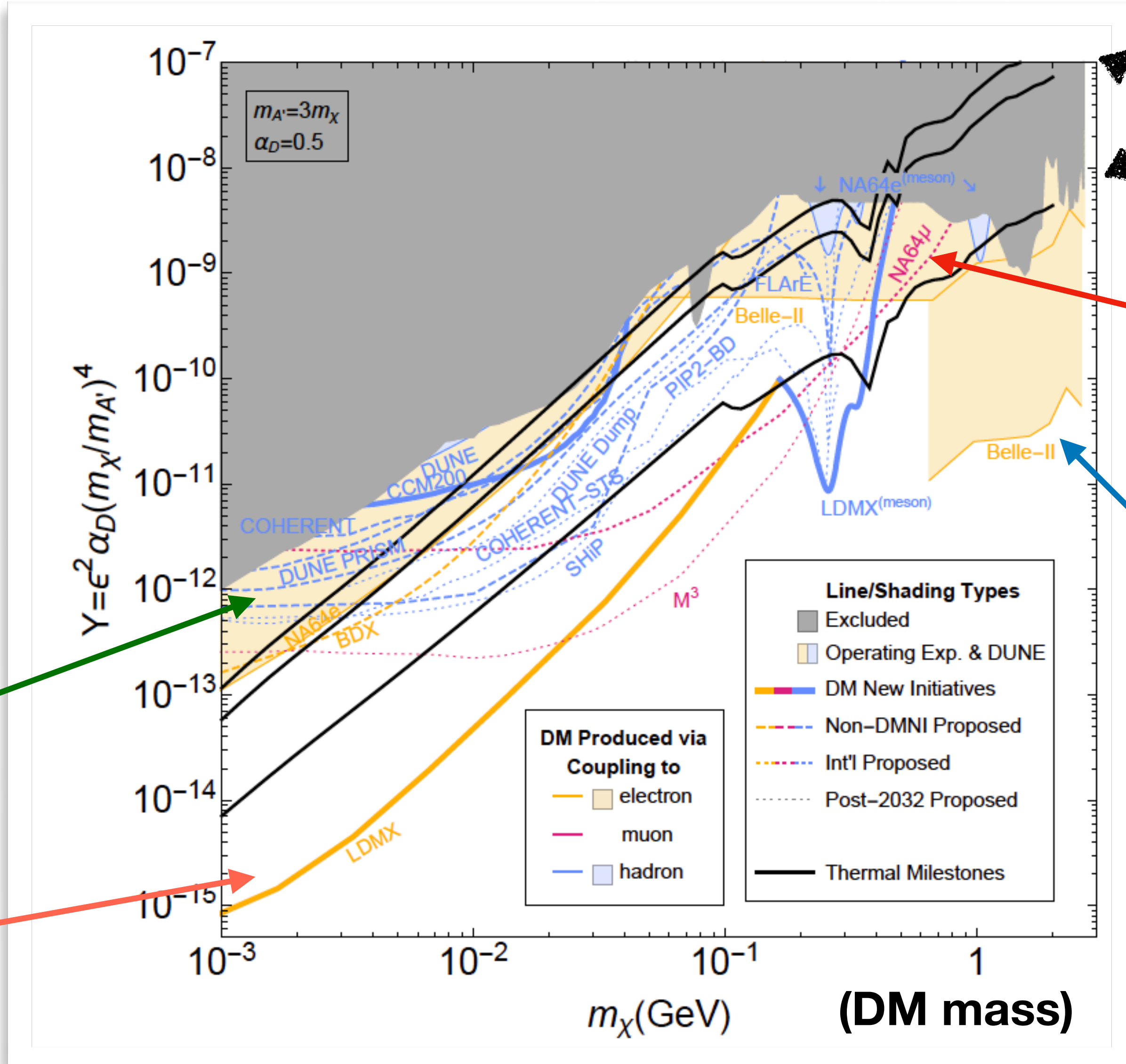
DM at fixed targets & B-factories

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

A'→XX



Dark photon mediated DM



(DM mass)

benchmarks for thermal DM

Missing energy (fixed-target)

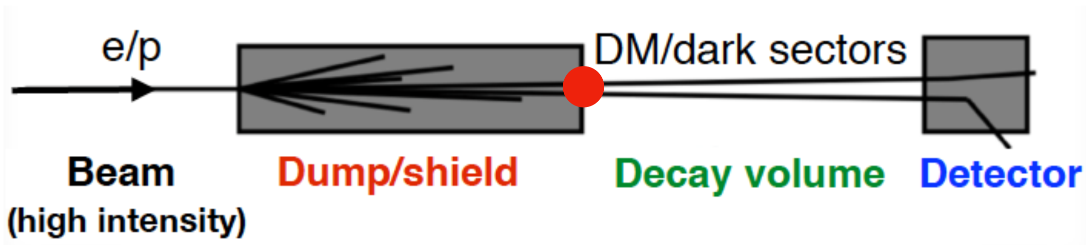
mono-photon (B-factories)

Re-scattering (neutrino experiments)

Missing momentum (fixed-target)

RF6 Snowmass topical group, SG, M.Williams et al.

Visible dark sectors at fixed-targets & B-factories



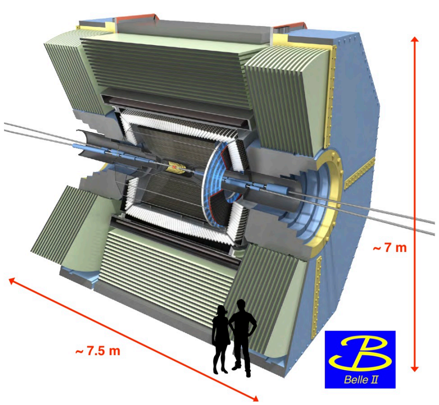
Low background experiments
(depending on the size of the dump)

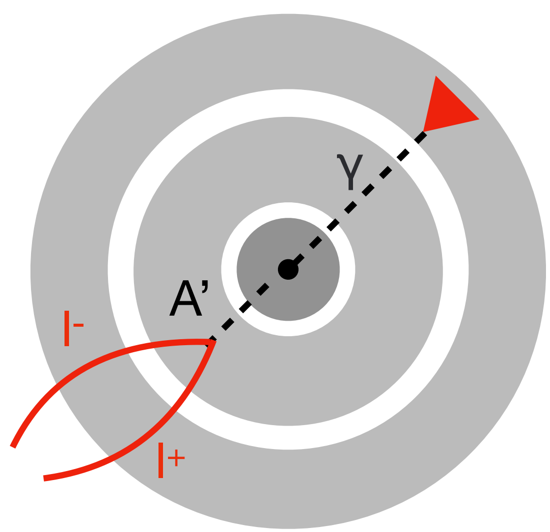
p beam for the SeaQuest/DarkQuest experiment at Fermilab
p beam for the NA62, KLEVER experiments at CERN
p beam for the SHiP experiments at CERN
e- beam for the HPS experiment at JLAB
e- beam for the DarkLight experiment at TRIUMF
e-/e+ beams for future e^+e^- colliders (ILC, CLIC, …)

Running experiments

Future experiments

Initial studies





Visible dark sectors at fixed-targets

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

$A' \to \ell^+ \ell^-$

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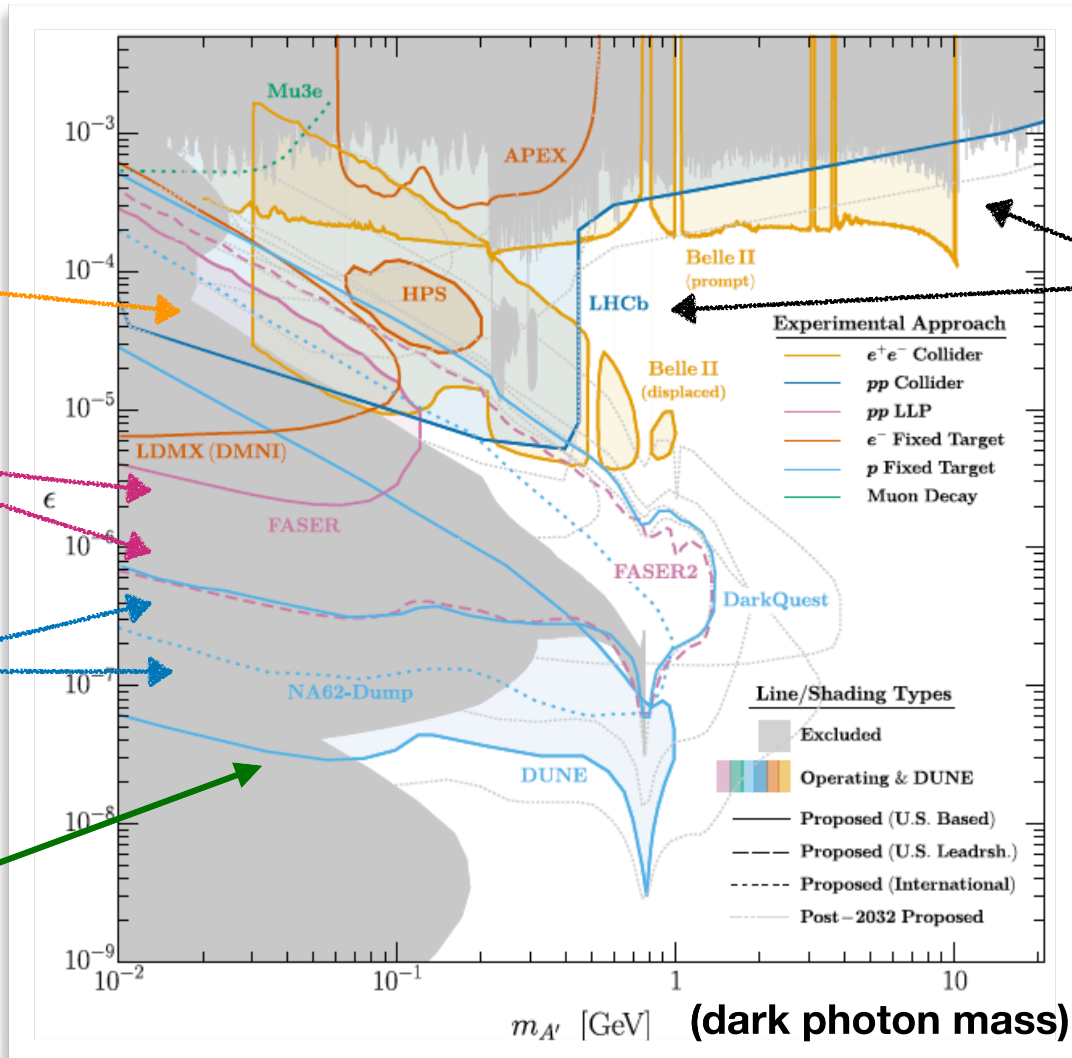
electron fixed-target

forward detectors

proton fixed-target

Neutrino experiments



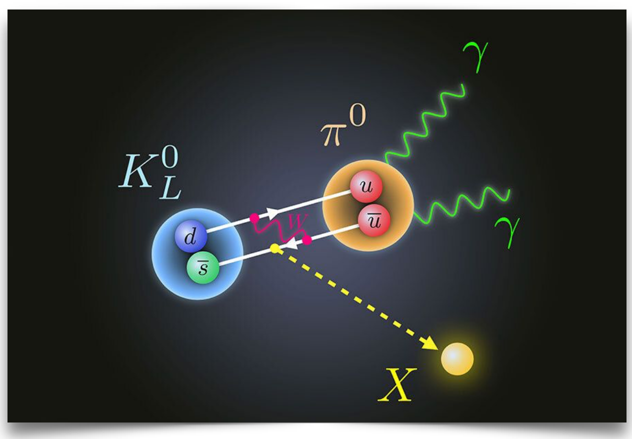
(dark photon mass)

Colliders

$$e^+e^- \to \gamma A' \to \gamma(\ell^+\ell^-)$$
$$pp \to X A' \to X(\mu^+\mu^-),$$
$$D^* \to D A' \to D(e^+e^-)$$

RF6 Snowmass topical group, SG, M.Williams et al.

Dark sectors from meson decays



Huge statistics of mesons at flavor factories

A big jump in luminosity is expected in the coming years

	Past/Present	Future
Pion-factories	**PIENU experiment** at TRIUMF: **PIBETA experiment** at PSI: $\sim 10^{11}$ pi$^+$	**PIONEER experiment** at PSI (phase 1 approved. Data in ~2028(?)): $\sim 10^{12}$ pi$^+$
Kaon-factories	**E949** at BNL: $\sim 10^{12}$ K^+ (decay at rest experiment); **E391** at KEK: $\sim 10^{12}$ K_L	**NA62** at CERN: $\sim 10^{13}$ K^+ by the end of its run (decay in flight experiment); **KOTO** at JPARC: $\sim 10^{14}$ K_L by the end of its run
Charm-factories	**CLEO** at Cornell: $\sim 10^{7}$ J/Psi	**BESIII** at BEPC II: $\sim 10^{10}$ J/Psi talk by A. Pathak on Monday
B-factories	**LHCb:** more than ~ 10^{12} b quarks produced so far; **Belle**: $\sim 10^{9}$ BB-pairs were produced.	**LHCb:** ~40 times more b quarks will be produced by the end of the LHC; **Belle-II:** ~50 times more BB-pairs will be produced. talk by L. Polat on Tuesday

ALPs at pion experiments

Generically, ALP models predict the ALP mixing with the SM π^0

$$\pi^+ \to a e^+ \nu$$

Recast previous pion experiments to probe the ALP parameter space:

Altmannshofer, SG, Robinson,1909.00005

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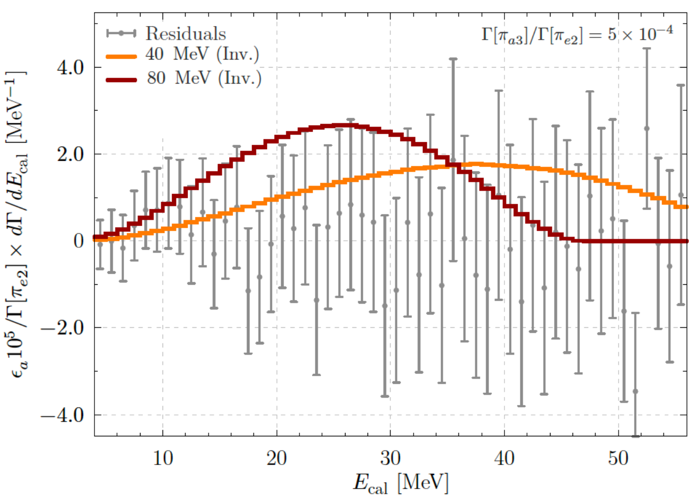
PIENU

Most accurate measurement of $\pi^+ \to e^+ \nu$

Measurement of the e^+ spectrum. The spectrum is affected by the ALP:

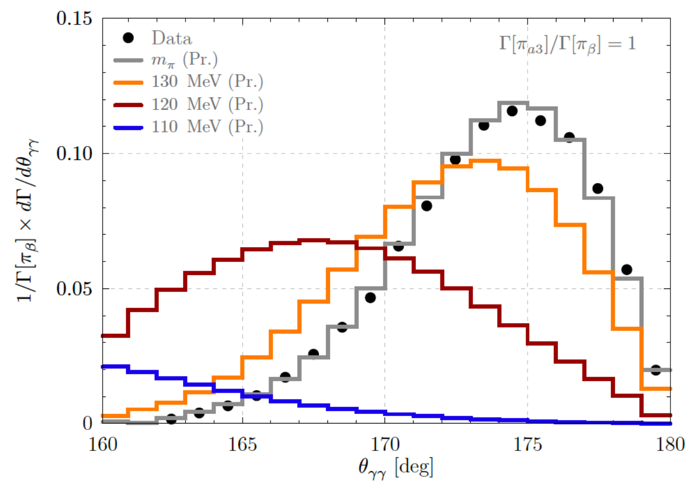


PIBETA

Most accurate measurement of $\pi^+ \to \pi^0 e^+ \nu$

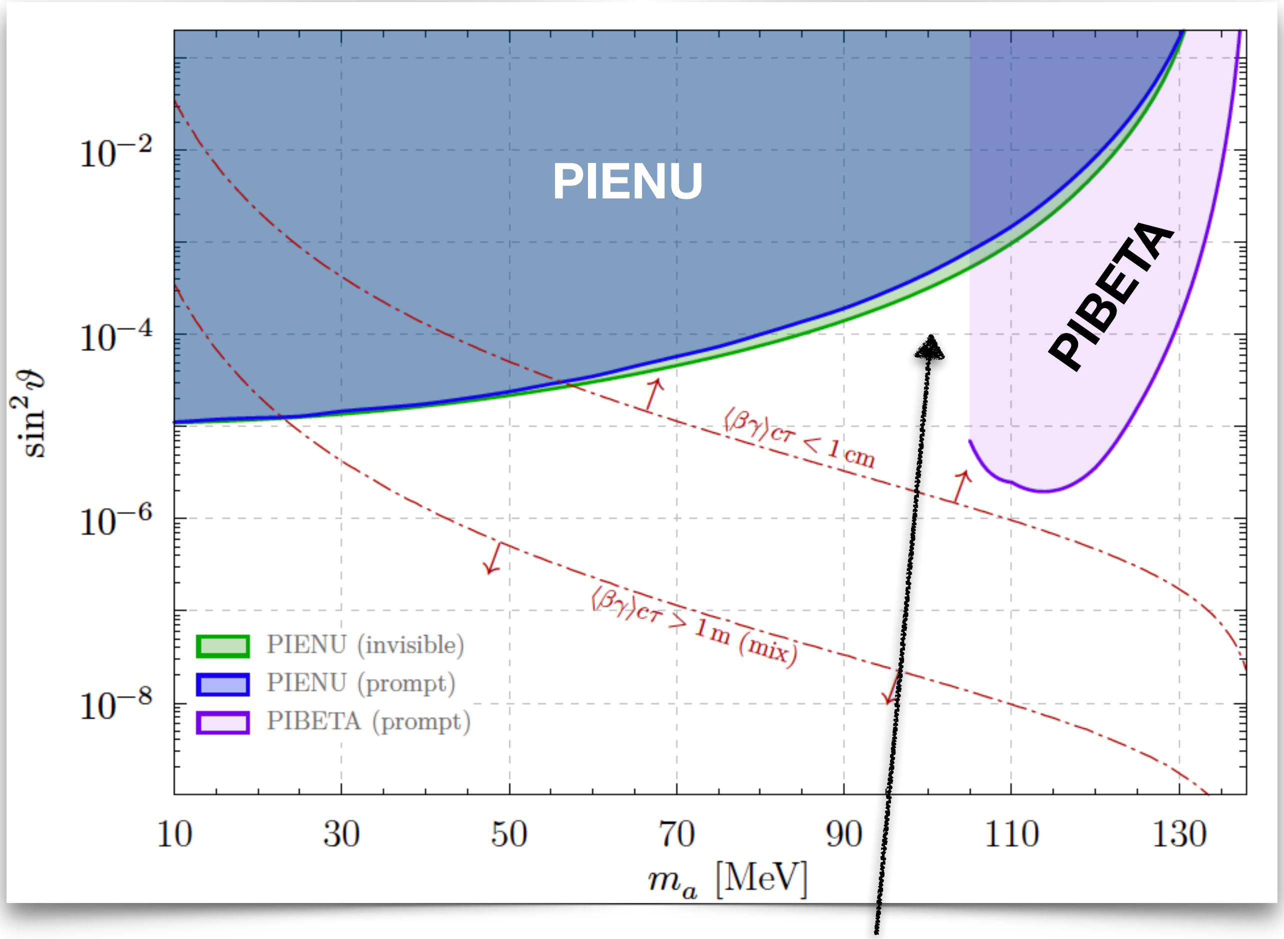
Measurement of the photon spectrum. This spectrum is affected by the ALP

$a \to \gamma\gamma$



Constraining ALP parameter space

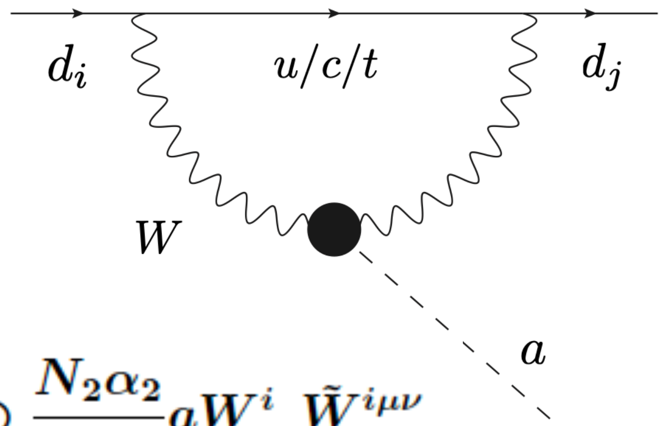
Altmannshofer, SG, Robinson,1909.00005



Possibility to go to lower masses
at future experiments
(data at smaller angles!)

Reach at PIONEER?

ALPs from FCNC processes

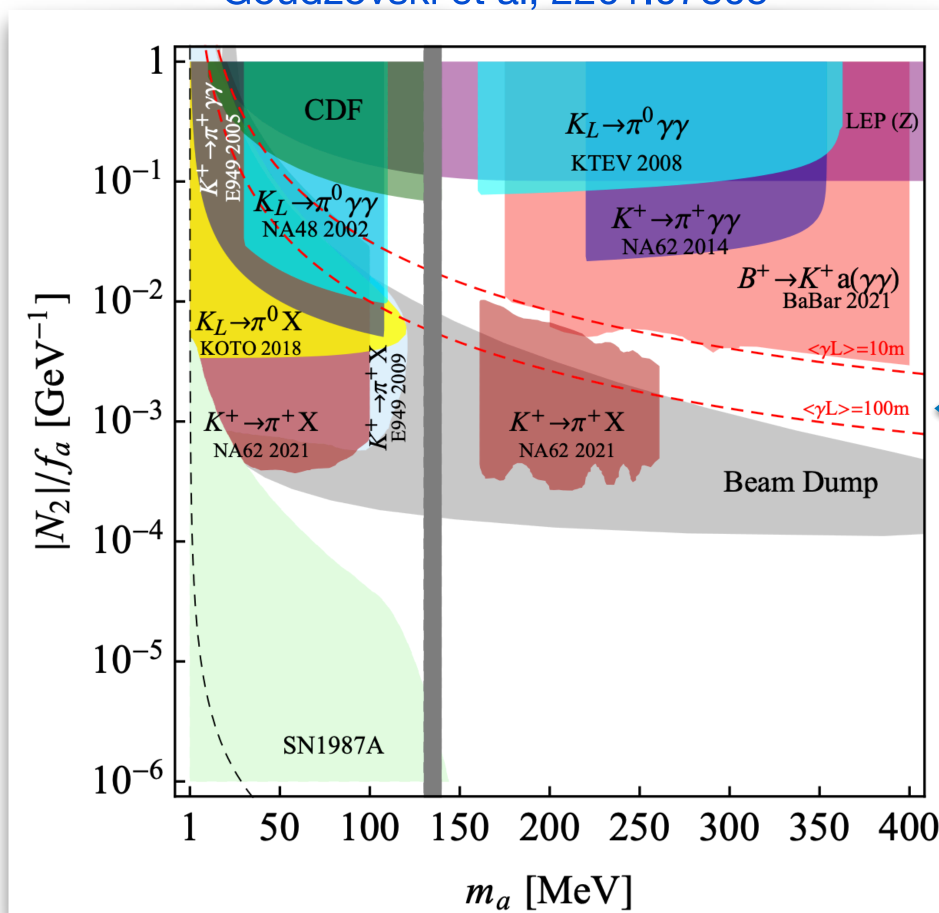


$$\mathcal{L} \supset \frac{N_2 \alpha_2}{8\pi f_a} a W^i_{\mu\nu} \tilde{W}^{i\mu\nu}$$

Izaguirre et al., 1611.09355

$$B \to K a, \ B \to K^* a,$$
$$K^+ \to \pi^+ a, K_L \to \pi^0 a$$

Goudzovski et al, 2201.07805

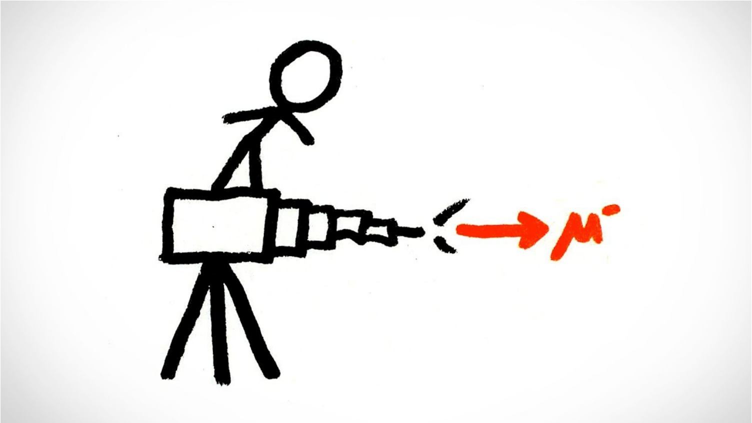


What about…

Belle II: $B \to K^{(*)} a, \ a \to \gamma\gamma,$
$B \to K^{(*)} a, \ a \to \text{inv}$

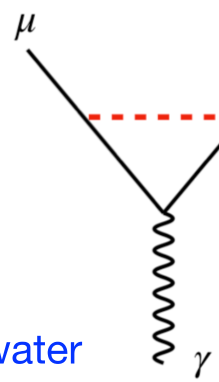
KOTO: $K_L \to \pi^0 a, \ a \to \gamma\gamma$

Dark sectors from (secondary) muon beams



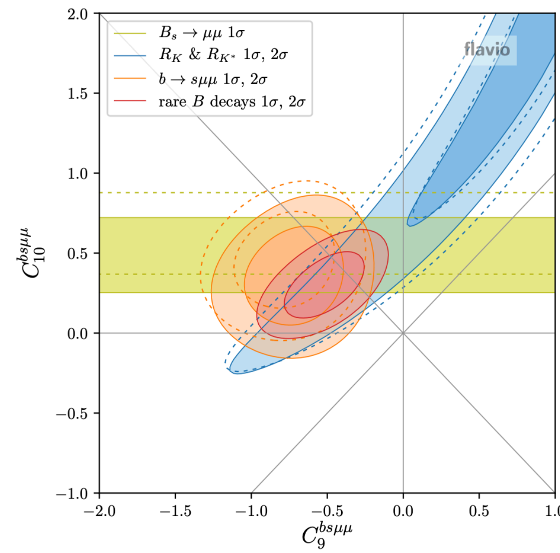
New Physics coupled mainly to muons?

Several anomalies in data can be addressed via New Physics coupled to muons:



(see G. Onderwater talk today)

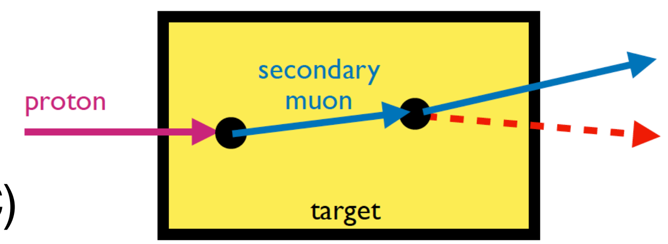
(g-2)$_\mu$



R_K, R_{K^*}, P_5', …

Altmannshofer, Stangl, 2103.13370

* Proton fixed-target experiments produce a large number of muons (secondary muon beams)



* Many muons at B-factories
* Low energy muon beams (PSI, Fermilab, JPARC)

* Proposal for
- Fermilab muon fixed target experiments
- high energy muon colliders

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

Only a very small set of dark sector models can address the $(g-2)_\mu$ anomaly.

All models based on minimal portal interactions have been already fully probed in the last few years.

Can we fully probe a light explanation of $(g-2)_\mu$? Flavor specific models

Example

$$g_\mu S \bar{\mu}\mu + \text{h.c.}$$

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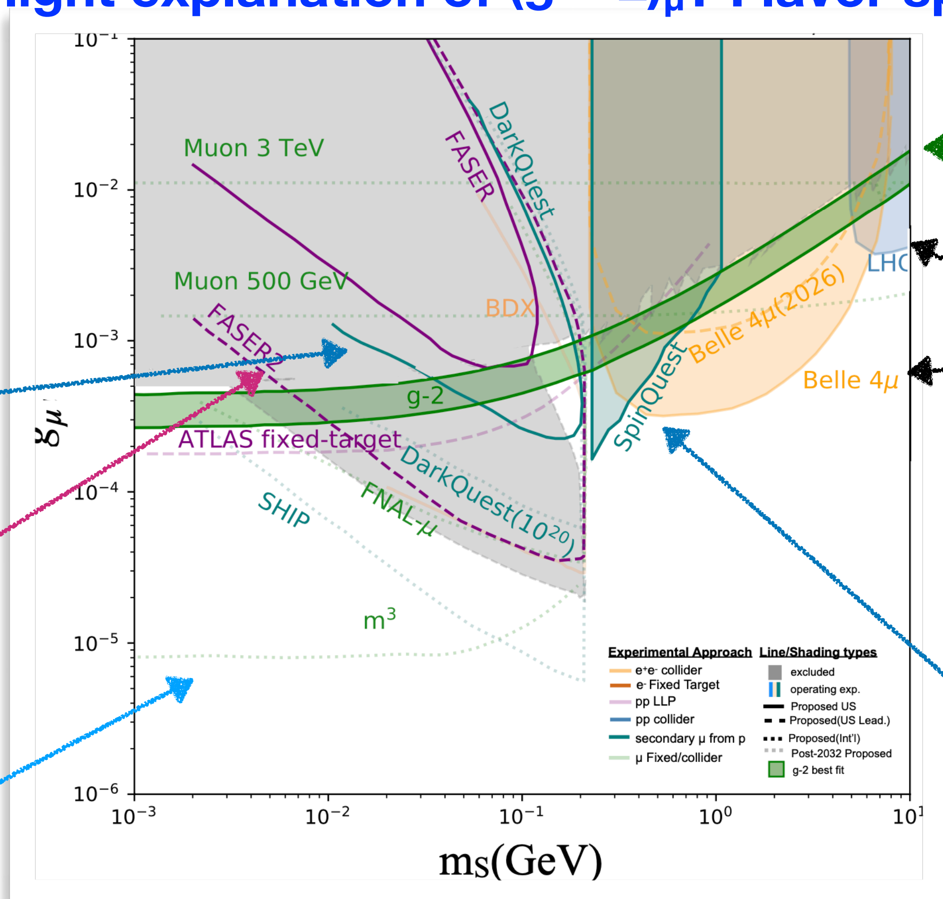


proton beam-dump (secondary muons)

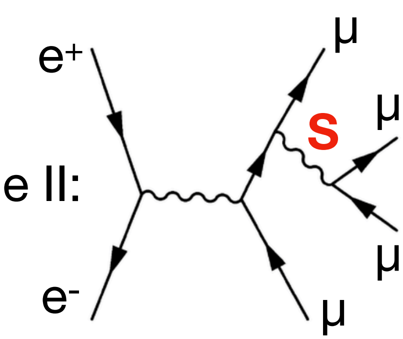
LHC auxiliary detectors

muon fixed-target

$(g-2)_\mu$ region

Colliders

Belle II:



proton beam-dump (secondary muons)

RF6 Snowmass topical group, SG, M.Williams et al.

Take home messages

Dark sector particles in the MeV-GeV range naturally appear in DM models, as well as many well-motivated extensions of the Standard Model.

Unique role of **high-intensity experiments**

Complementarity of fixed target experiments and flavor factories (+ DM direct detection experiments).

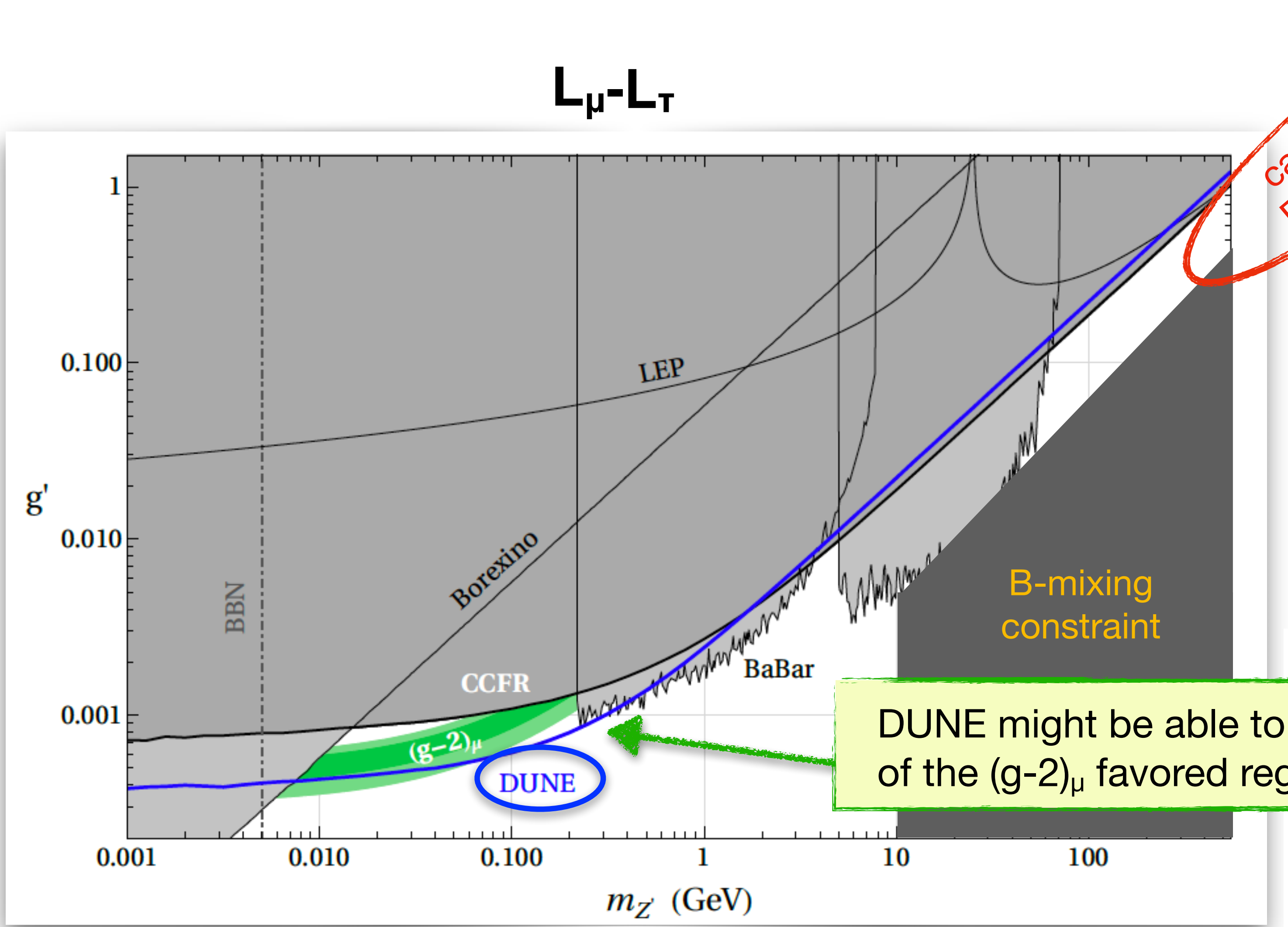
Production of dark sector particles from
- colliding beam(s)
- meson decays

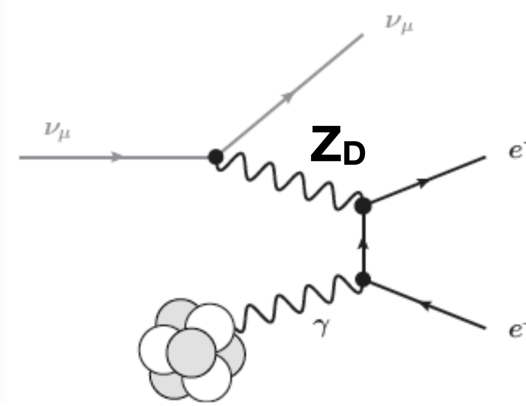
Opportunity of broadly probing thermal DM models and anomaly-motivated models in the coming years.

Flavor measurements can shed light on light New Physics (as well as New Physics above the TeV scale).

Backup

Trident production at neutrino experiments



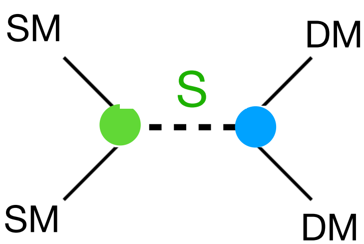


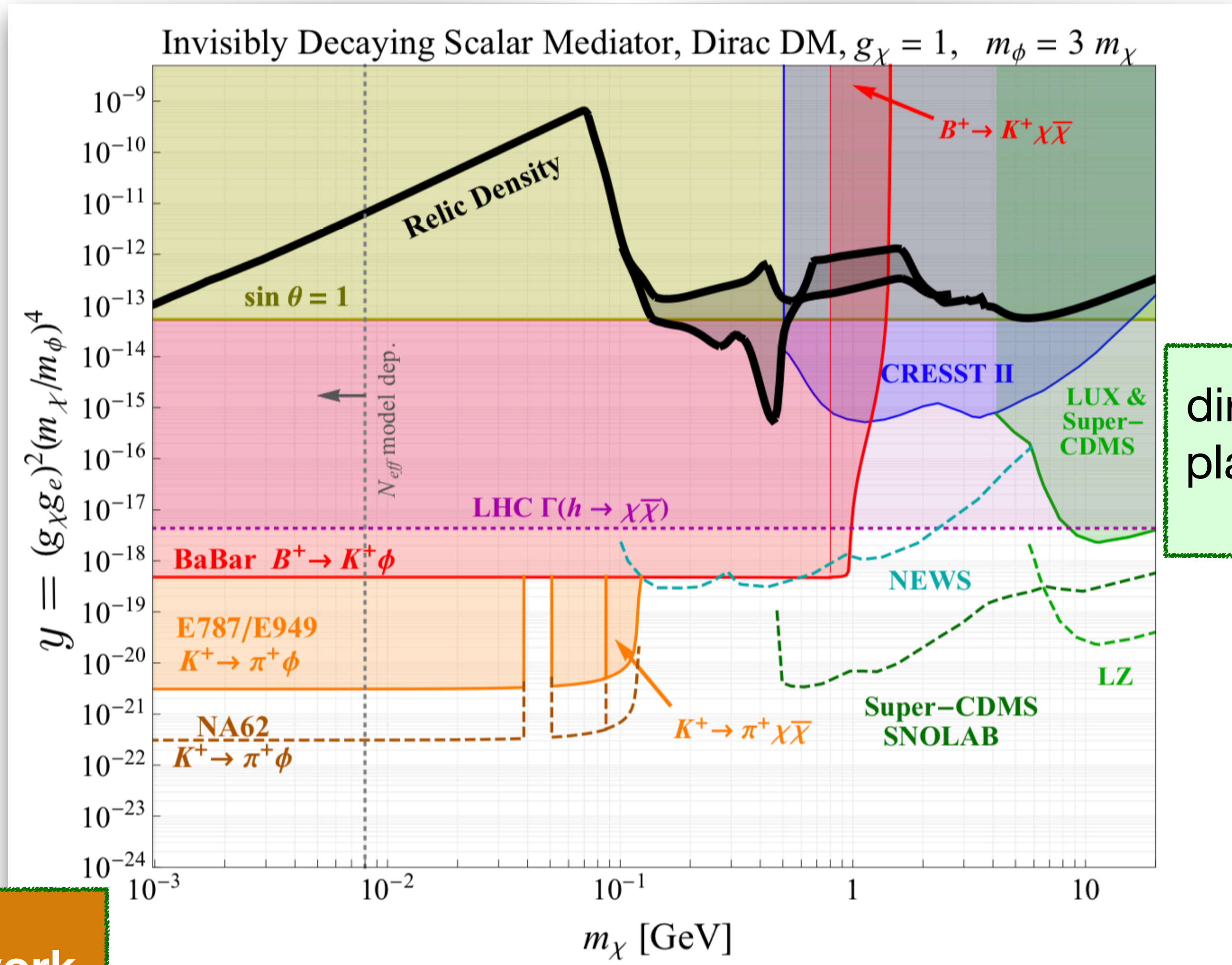
Altmannshofer, SG, Martin-Albo, Sousa, Wallbank 1902.06765

Milestones already achieved (in the last few years)

$\kappa |H|^2 |S|^2$

S→XX





direct detection played a crucial role

Krnjaic, 1512.04119

This DM framework is now fully probed

K → π X , X → γ γ (neutral mode)

SG, Perez, Tobioka, 2005.05170

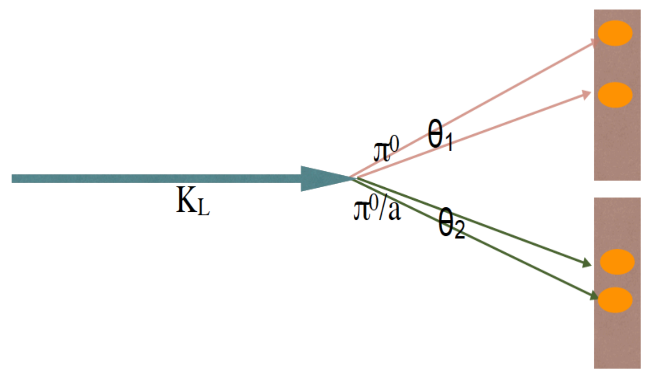
* KTeV analysis for $K_L \to \pi^0 \gamma\gamma$
* Our new proposed search for KOTO: $K_L \to \pi^0 X \to 4\gamma$

Challenges of the search:

- the decay point is unknown
- combinatorics of γγ pairs

Main ingredients :

1. We derive the K_L decay vertex location of the 6 possible di-photon pair combinations, assuming $m^2_{\gamma_i\gamma_j} = m^2_{\pi^0}$



2. Require $m_{4\gamma} \simeq m_{K_L}$ to find a correct pair

Importance of a good vertex resolution! (~5cm) and small energy smearing (~2%)

We simulate the main sources of background:

$K_L \to \pi^0\pi^0, \; K_L \to \pi^0\gamma\gamma$

mainly for $m_a \sim m_{pion}$

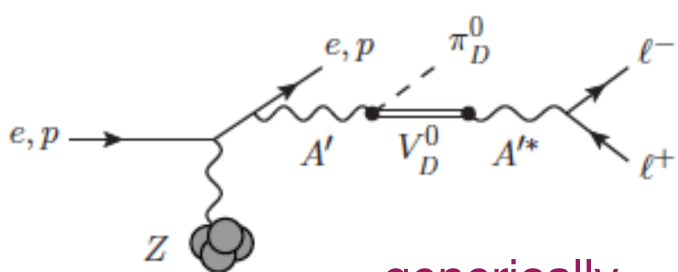
DM in a strongly interacting dark sector

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

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

The additional dark states will lead to a richer phenomenology

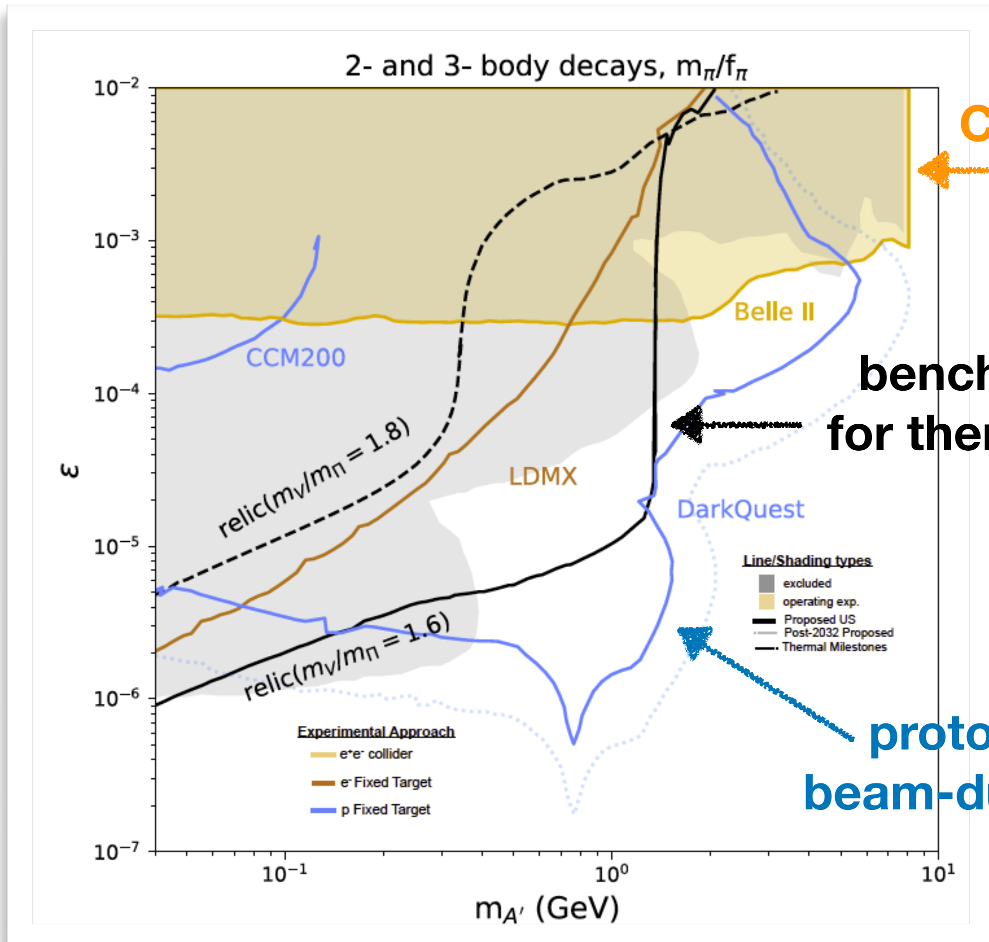
For example:



generically long-lived

$A' \to V_D \pi_D$ ← DM state

$V_D \to A'^* \to e^+e^-$



Colliders

benchmarks for thermal DM

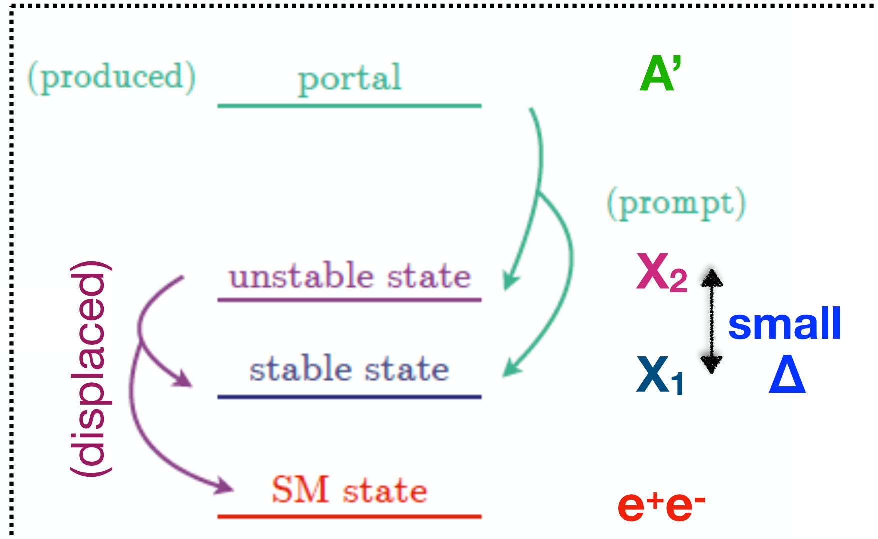
proton beam-dump

DM models with metastable particles

Inelastic Dark Matter

Tucker-Smith, **Weiner**, 0101138

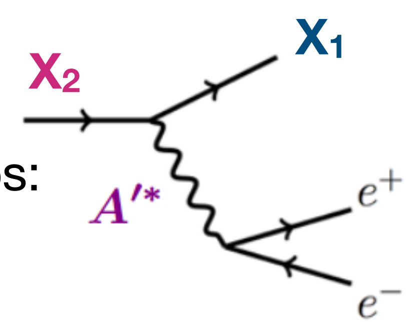
$$\mathcal{L} \supset \frac{i e_D\, m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}} A'_\mu \left(\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1\right)$$



* A non-minimal freeze-out mechanism:

X_1 X_2 → SM

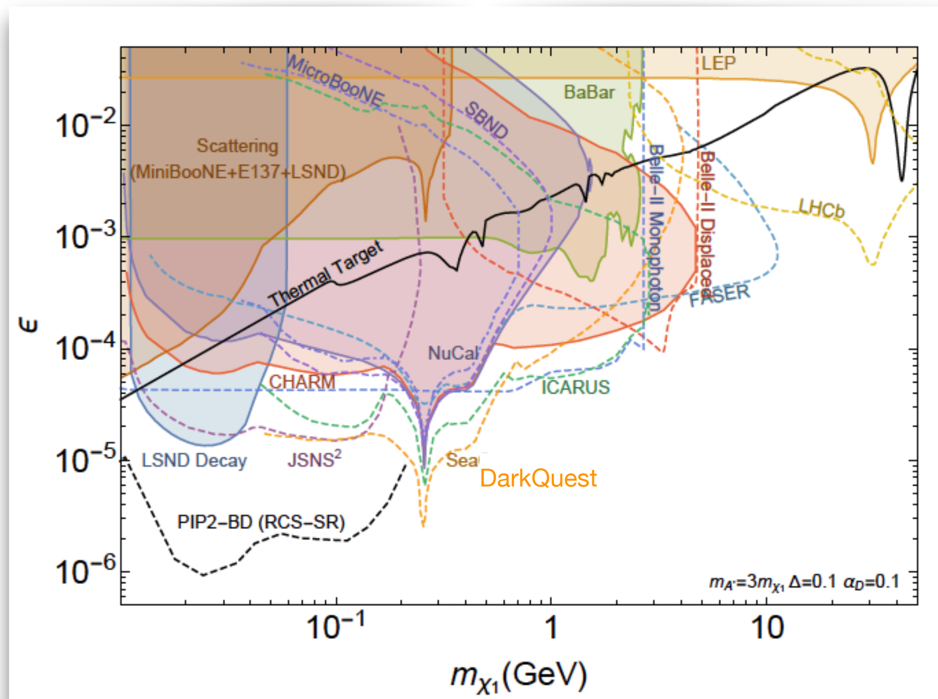
DM **DM excited state**



* Signatures in our labs:

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

- Prompt visible decays
- Long lived particles
- Invisible component

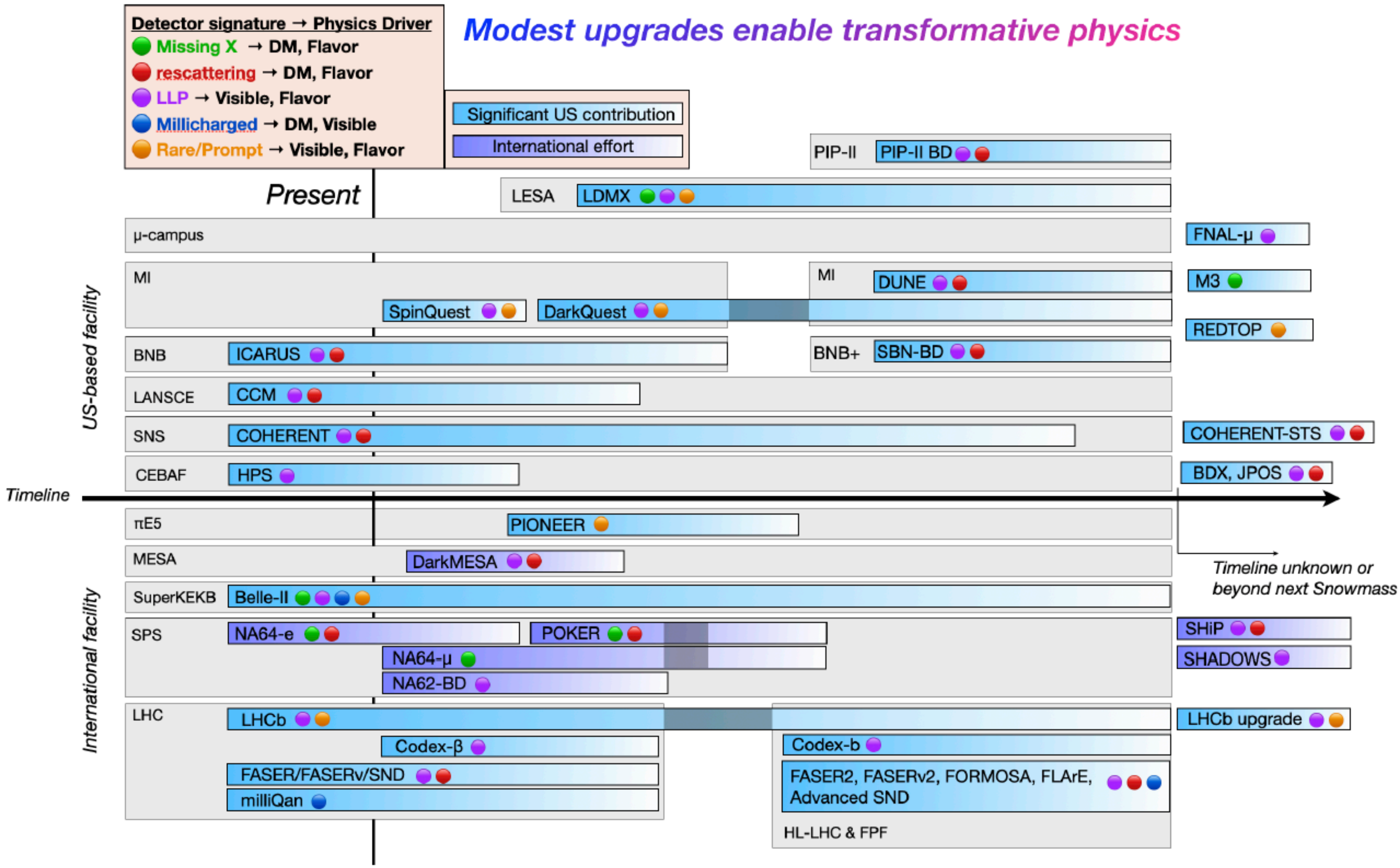


S.Gori

Backup

Experiments/facilities

https://arxiv.org/abs/2206.04220



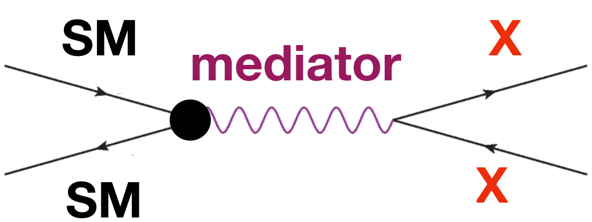
S.Gori

Final states to look for

a. **Invisible, non-SM**

Dark Matter production

Producing stable particles that could be (all or part of) Dark Matter

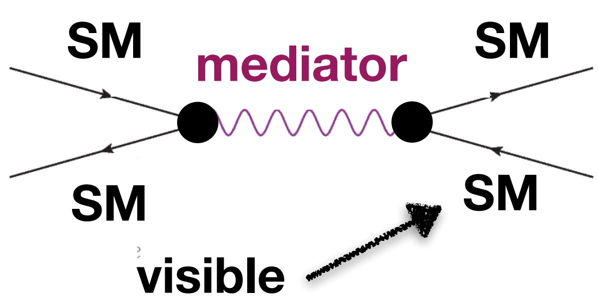


1. Missing energy/ momentum
2. Scattering

b. **Visible, SM**

Production of portal-mediators that decay to SM particles

Systematically exploring the portal coupling to SM particles

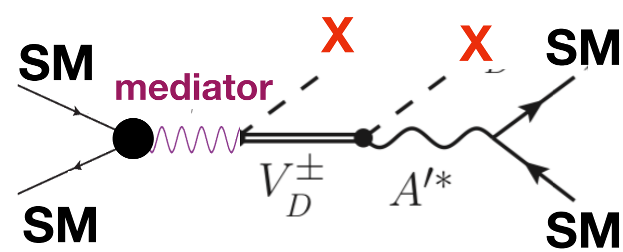


3. Visible decay products

c. **Mixed visible-invisible**

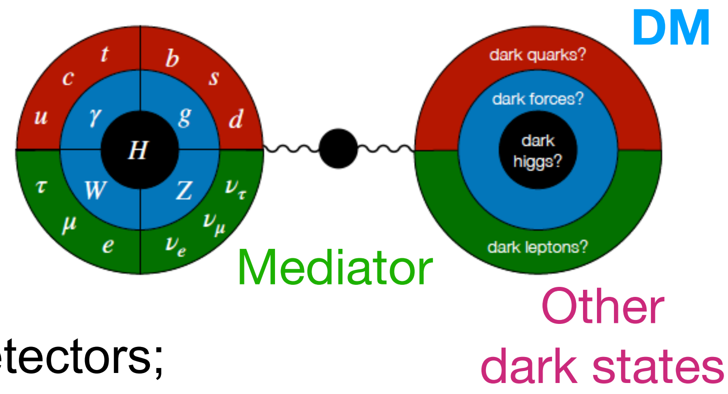
Production of “rich” dark sectors

Testing the structure of the dark sector



1. Missing energy/ momentum
2. Scattering
3. Visible decay products

Experimental techniques



1. Detect dark matter particle production

(i) inferring missing energy, momentum, or mass;

(ii) detecting re-scattering of DM particles in downstream detectors;

(iii) observing semi-visible signatures of metastable dark sector particles.

2. Producing and detecting unstable dark particles: Minimal Portal Interactions

Detect visible decay products of the mediator (prompt or displaced decays).

Mediator produced at (e^+e^-, pp) colliders, meson factories, fixed target experiments

3. Beyond minimal models

(i) Detect visible decay products of the mediator in non-minimal models, e.g. flavor specific couplings (prompt or displaced decays);

(ii) Detect visible or invisible signatures of other dark sector states, e.g. DM excited states

Variations of the invisible dark photon scenario