Overview of dark sectors

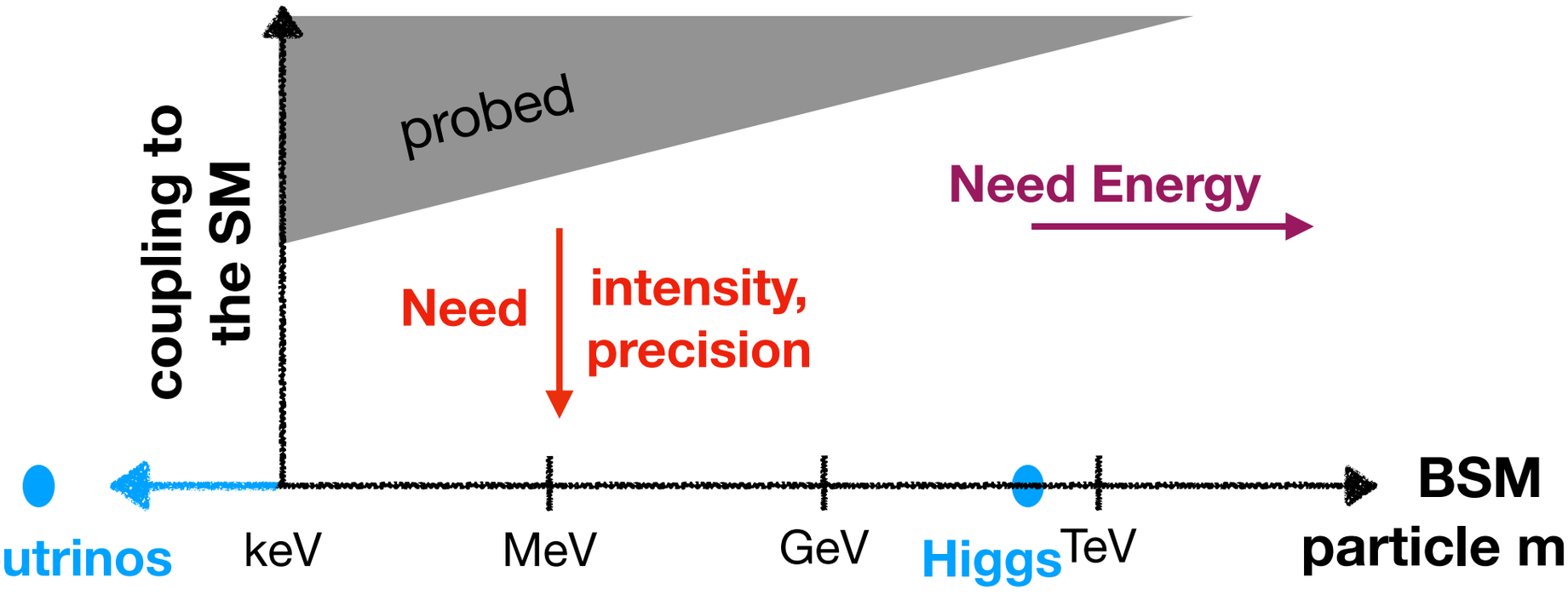
Stefania Gori
UC Santa Cruz



HPS collaboration meeting

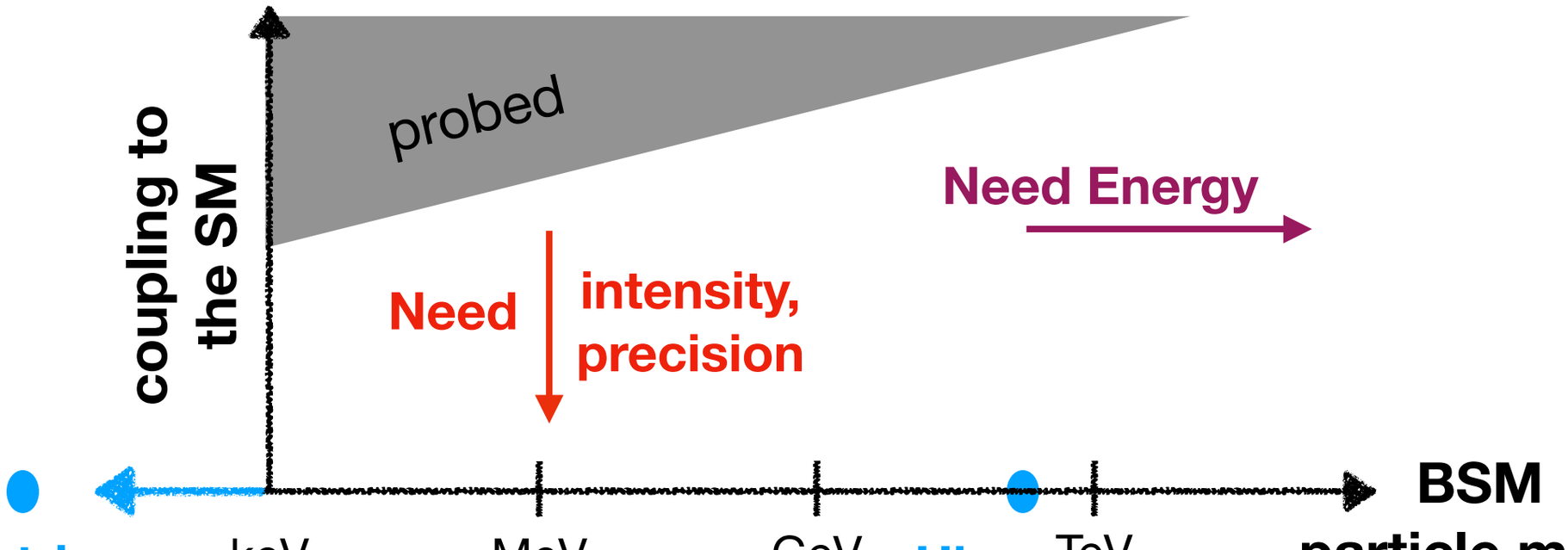
Jefferson Lab,
October 19, 2026

The quest for new physics



We do not know what will be the next New Physics (NP) scale.

The quest for new physics



We do not know what will be the next New Physics (NP) scale.

➡ **Search as broadly as possible.**

Accelerator experiments have access to NP scales in the range of few TeV and below.
Enormous progress in the exploration has been made in the past several years. Numerous gaps still to cover.

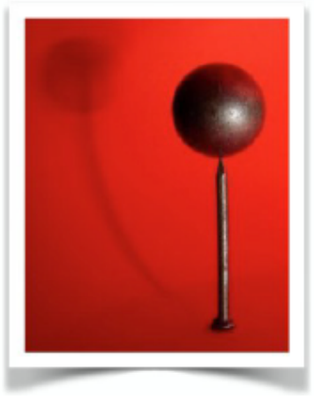
The most hidden particles are "dark sector particles", i.e. those particles that are not charged under the Standard Model (SM) gauge symmetries.

"Portals":

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$yHLN$
Axion	$\frac{1}{f_a} F_{\mu\nu} \tilde{F}_{\mu\nu} a$

Theoretical guidance

No guaranteed discovery but…

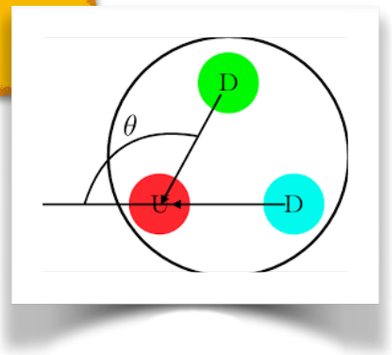


Naturalness problem

dark scalars
(twin Higgs, SUSY)

Strong CP problem

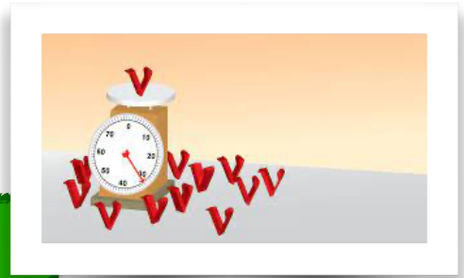
axions



dark photons

Nature of Dark Matter





Neutrino masses

sterile neutrinos

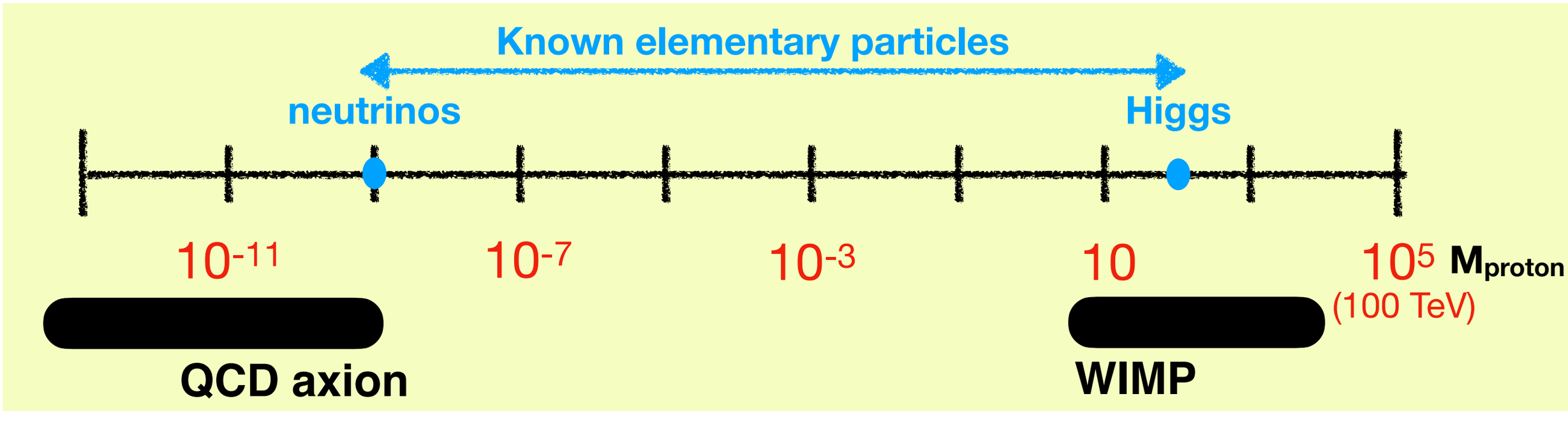
Baryon anti-baryon asymmetry



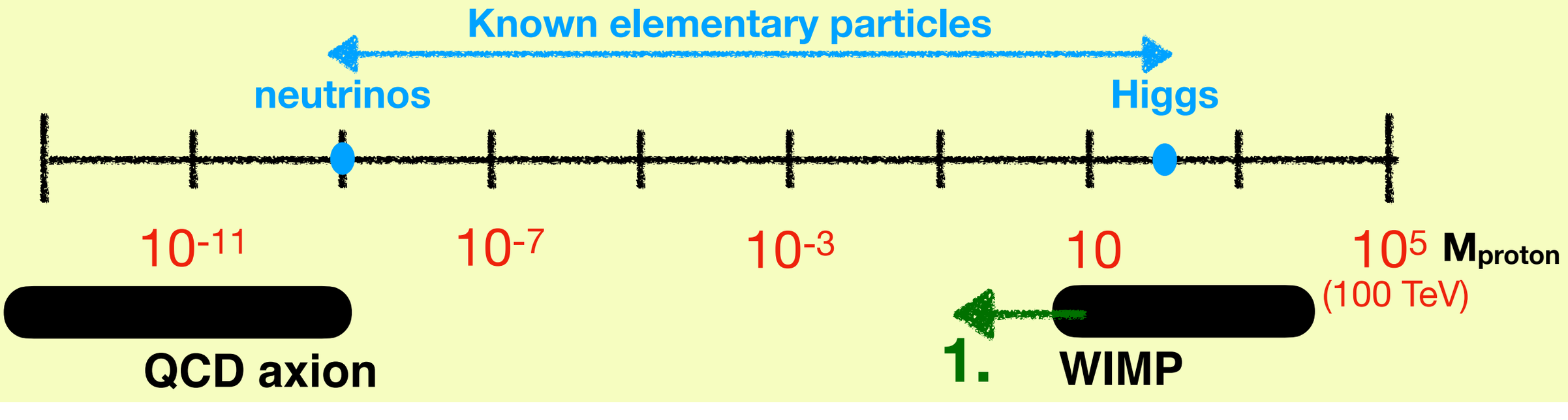
dark scalars, axions

In this talk, we will focus on the connection with Dark Matter and the strong CP problem

A case for sub-GeV dark particles

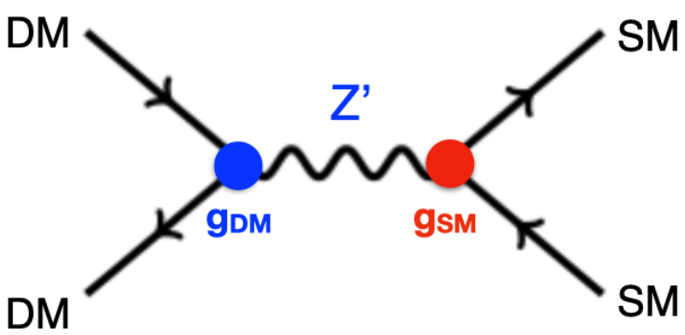


A case for sub-GeV dark particles



1. WIMP is a beautiful and predictive framework.

Can we extend it to lower masses?

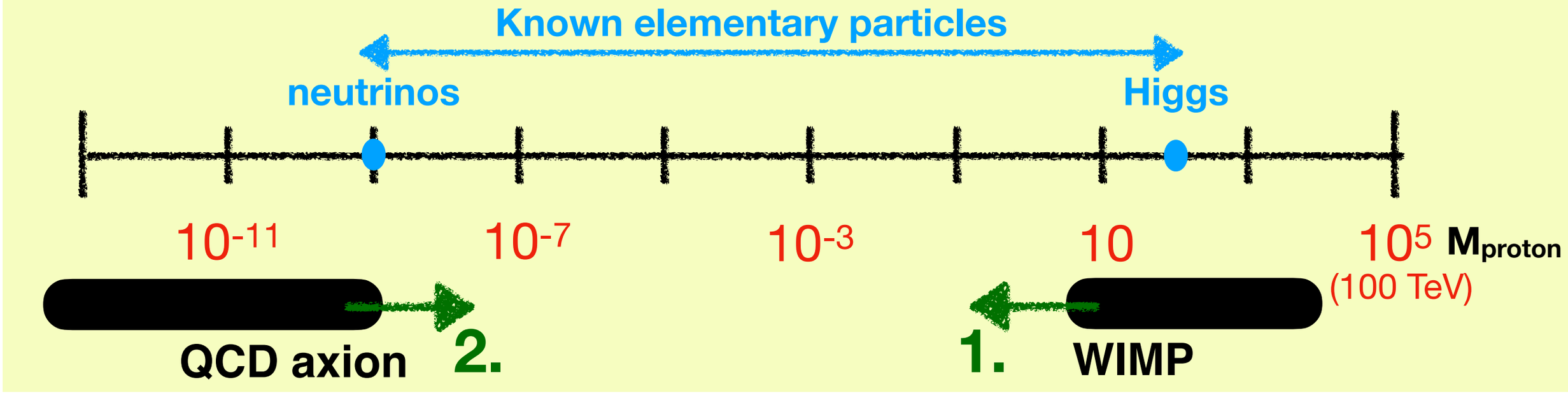


for the measured relic abundance

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

Lee Weinberg bound: $m_{DM} \geq$ O(1 GeV),
or **existence of a "Dark Sector"**
(in addition to Dark Matter)

A case for sub-GeV dark particles

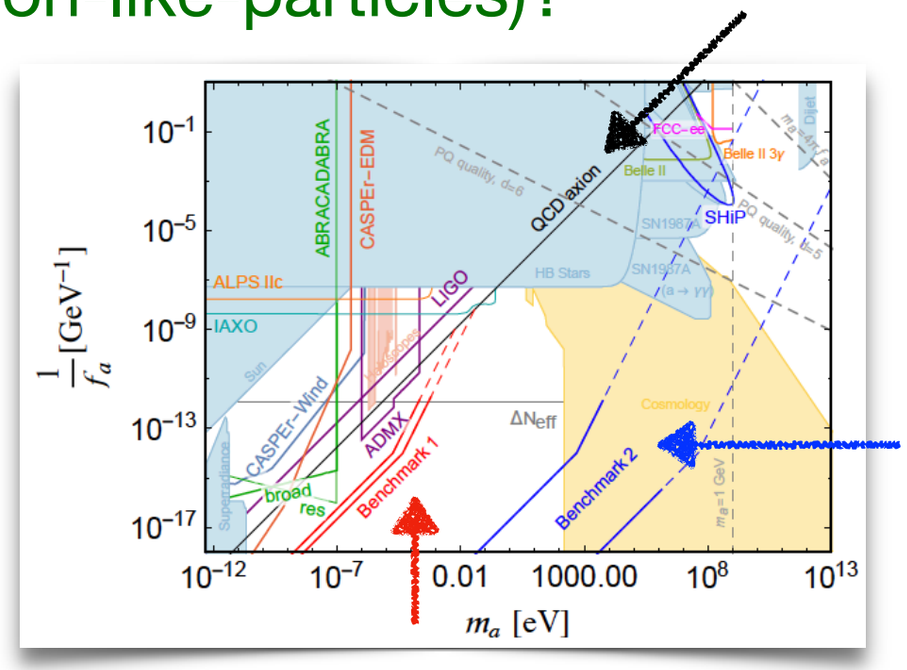


2. Can the strong CP problem be addressed by **heavier axions** (or axion-like-particles)?

Yes, extended QCD sectors can do that.
(e.g., Agrawal, Howe, 1710.04213;
Foster, Kumar, Safdi, Soreq, 2208.10504, …)

Axion quality problem generically alleviated for heavy axions:

if PQ symmetry broken by dimension D operators at Λ_{UV}: $\delta\bar{\theta} \sim \frac{f_a^{D-2}}{m_a^2 \Lambda_{UV}^{D-4}}$





Models

1. Minimal non-secluded
2. (Slightly) non-minimal: inelastic Dark Matter
3. Minimal secluded

Pheno

- Searches for the dark mediator particle
- Complementarity with DM bounds

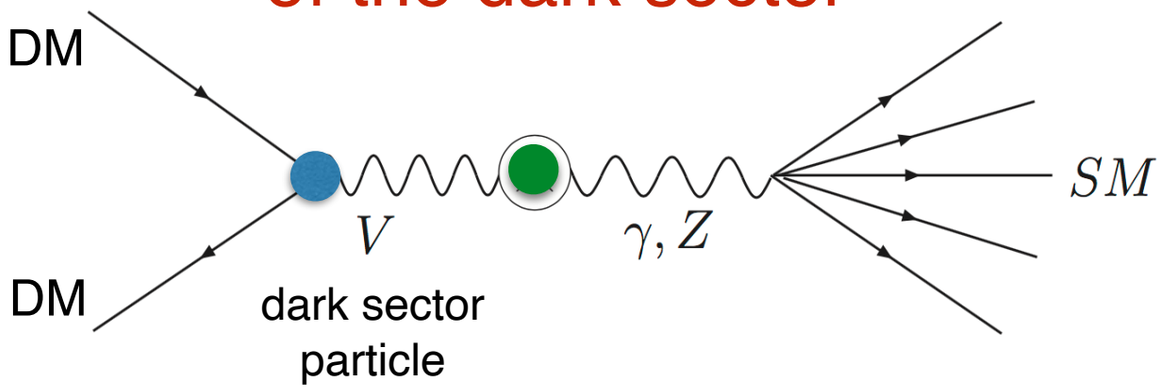
We will focus on DM models mediated by a dark photon or an axion/ALP

1.

Minimal non-secluded DM models

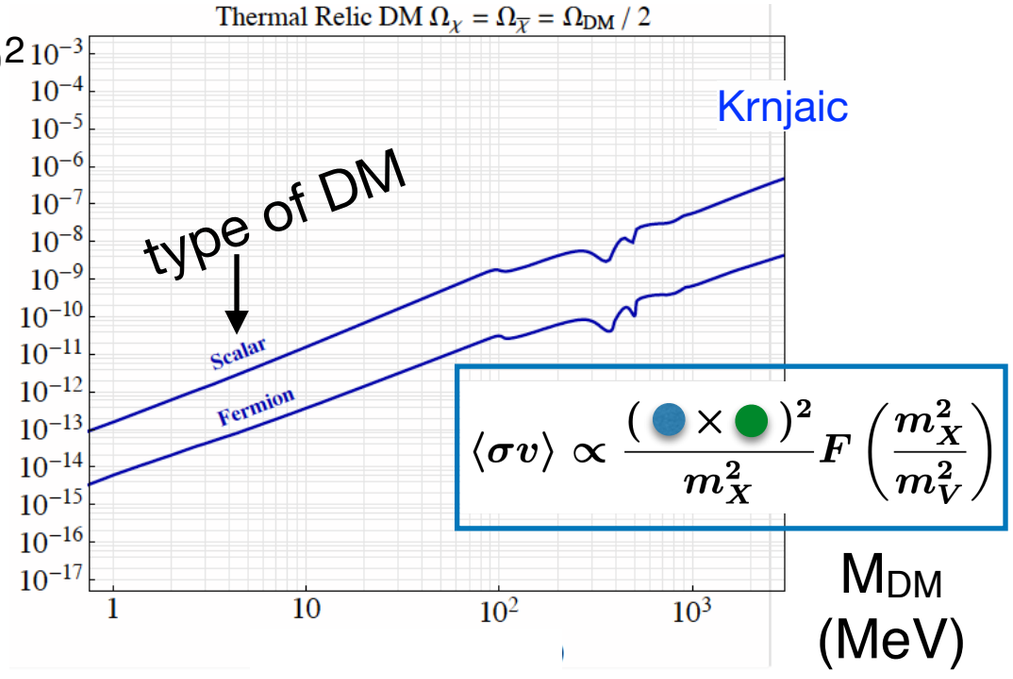
Familiar thermal freeze-out mechanism

DM is the lightest state
of the dark sector



Relic abundance regulated by ●, ●

(● X ●)^2

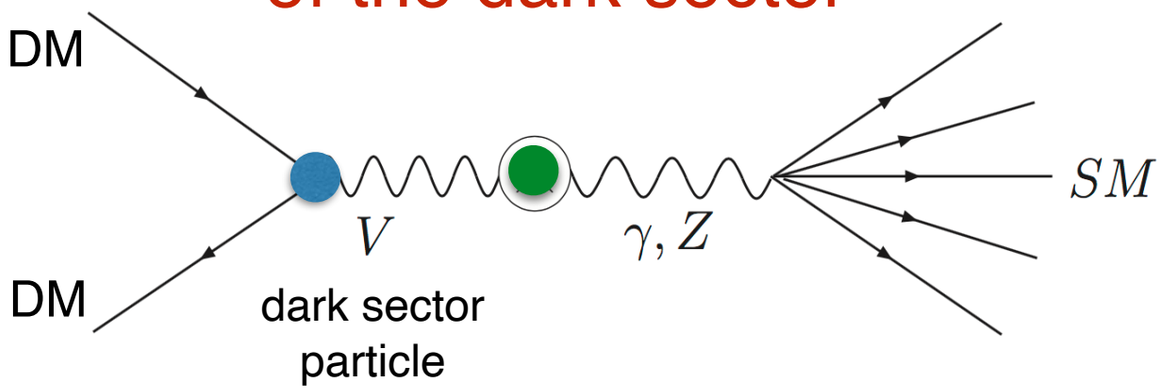


1.

Minimal non-secluded DM models

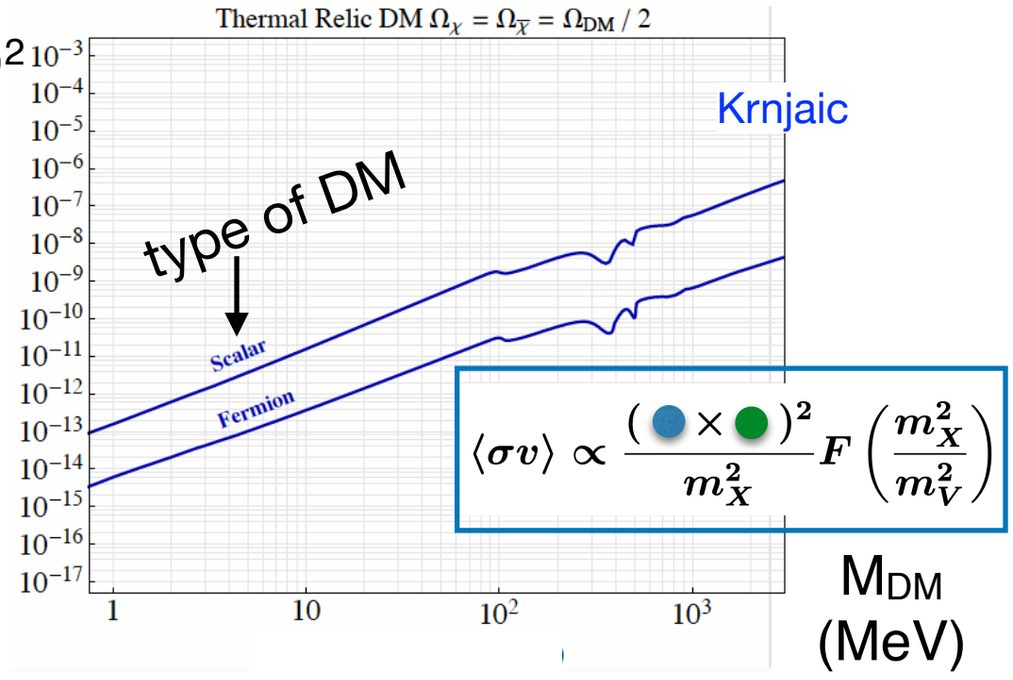
Familiar thermal freeze-out mechanism

DM is the lightest state
of the dark sector



Relic abundance regulated by ●, ●

(● X ●)^2



Phenomenology:

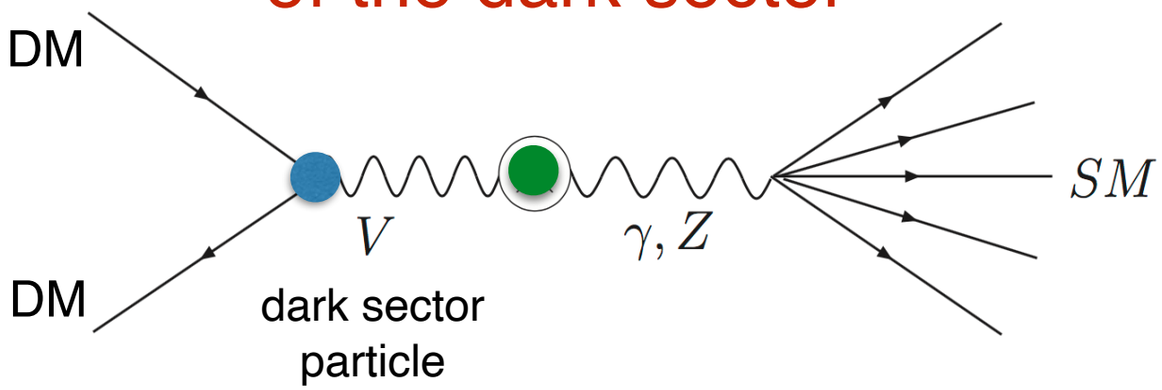
The mediator will generically decay to DM ➡ Invisible signatures for high energy colliders, Belle II, NA62, fixed target experiments, …

1.

Minimal non-secluded DM models

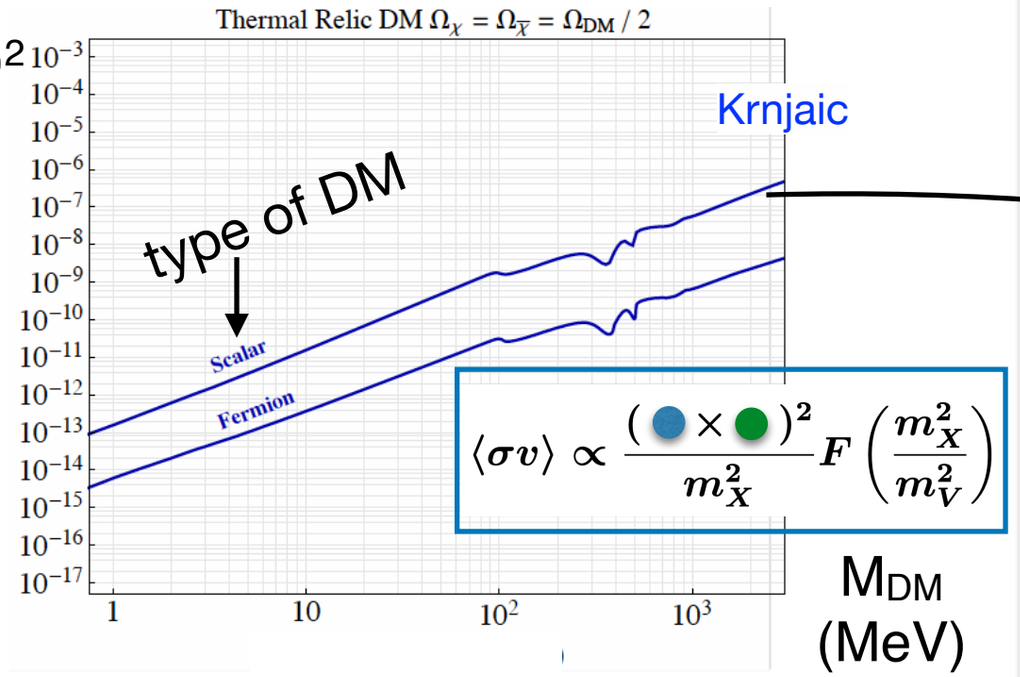
Familiar thermal freeze-out mechanism

DM is the lightest state
of the dark sector



Relic abundance regulated by ●, ●

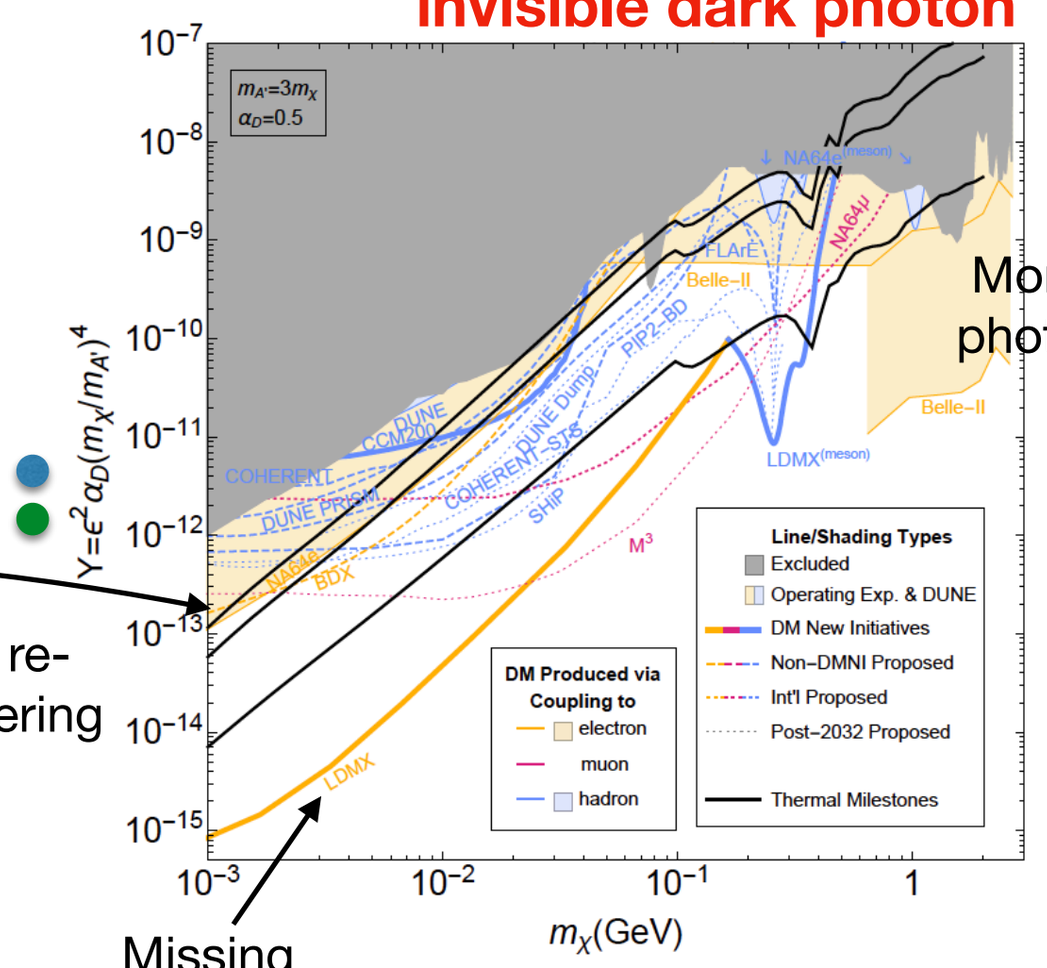
$(● \times ●)^2$



Phenomenology:

The mediator will generically decay to DM ➡ Invisible signatures for high energy colliders, Belle II, NA62, fixed target experiments, …

invisible dark photon



Mono photon

DM re-scattering

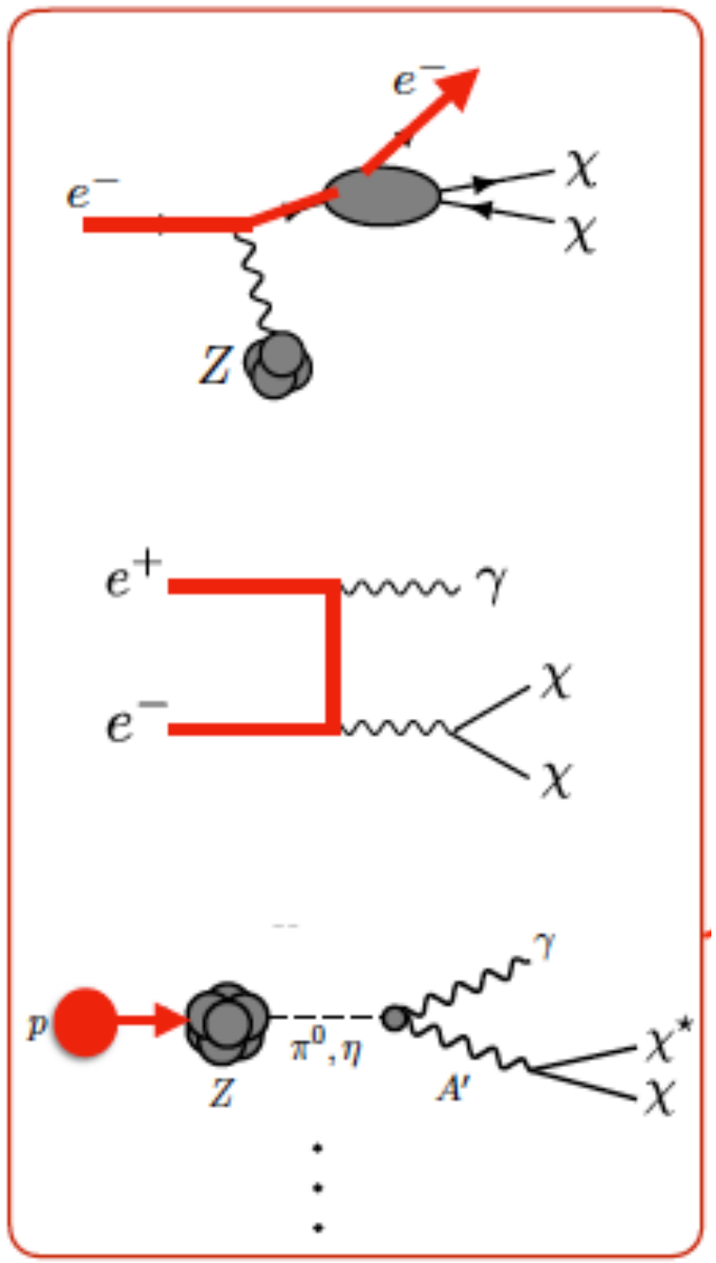
Missing momentum

Krnjaic, Toro et al, 2207.00597

1.

From snowmass: DM production at fixed targets

https://arxiv.org/abs/2207.00597

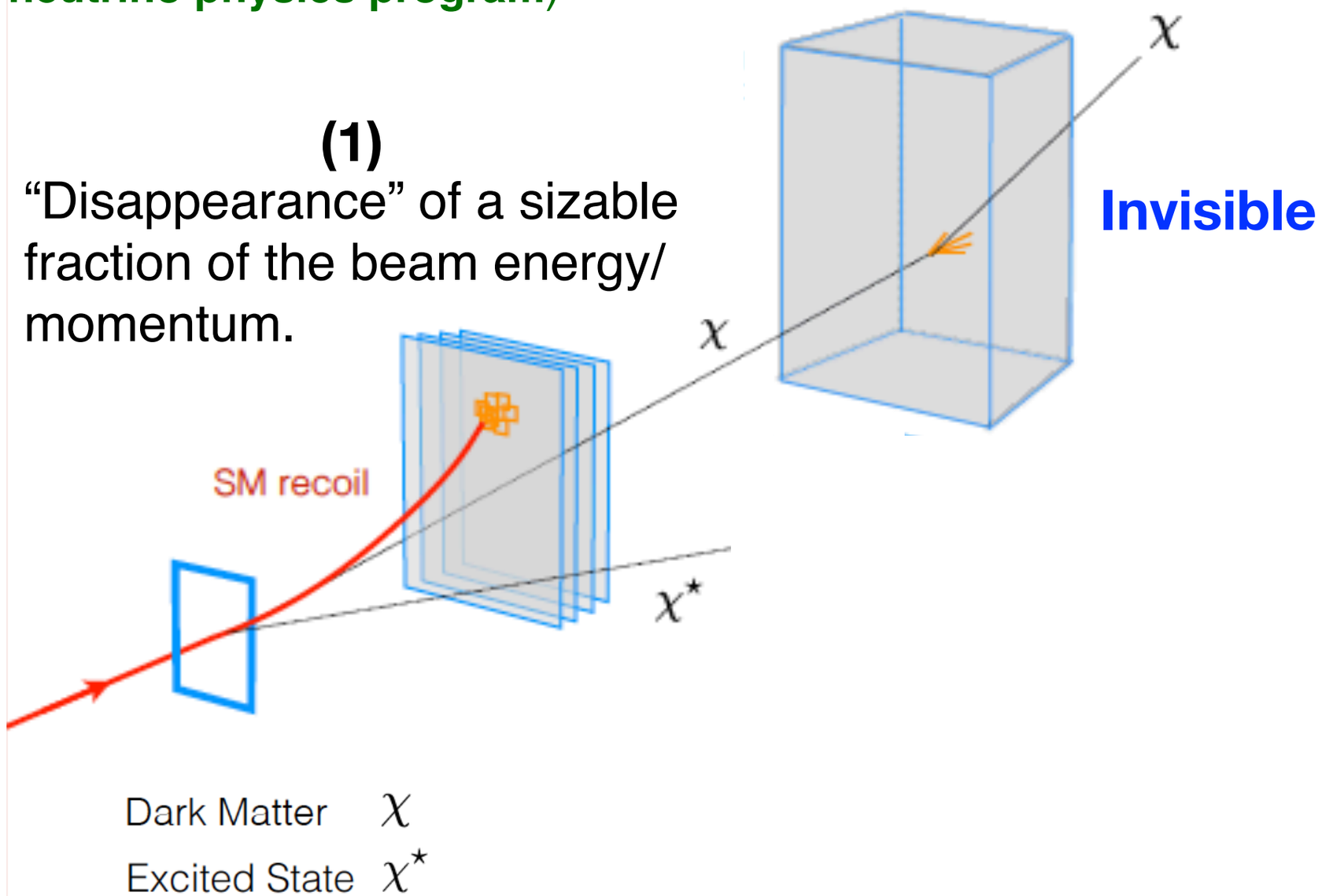


(proton beam: synergistic with the accelerator-based **neutrino physics program**)

Detection of DM scattering in forward detectors. **(2)**

(1)

"Disappearance" of a sizable fraction of the beam energy/ momentum.



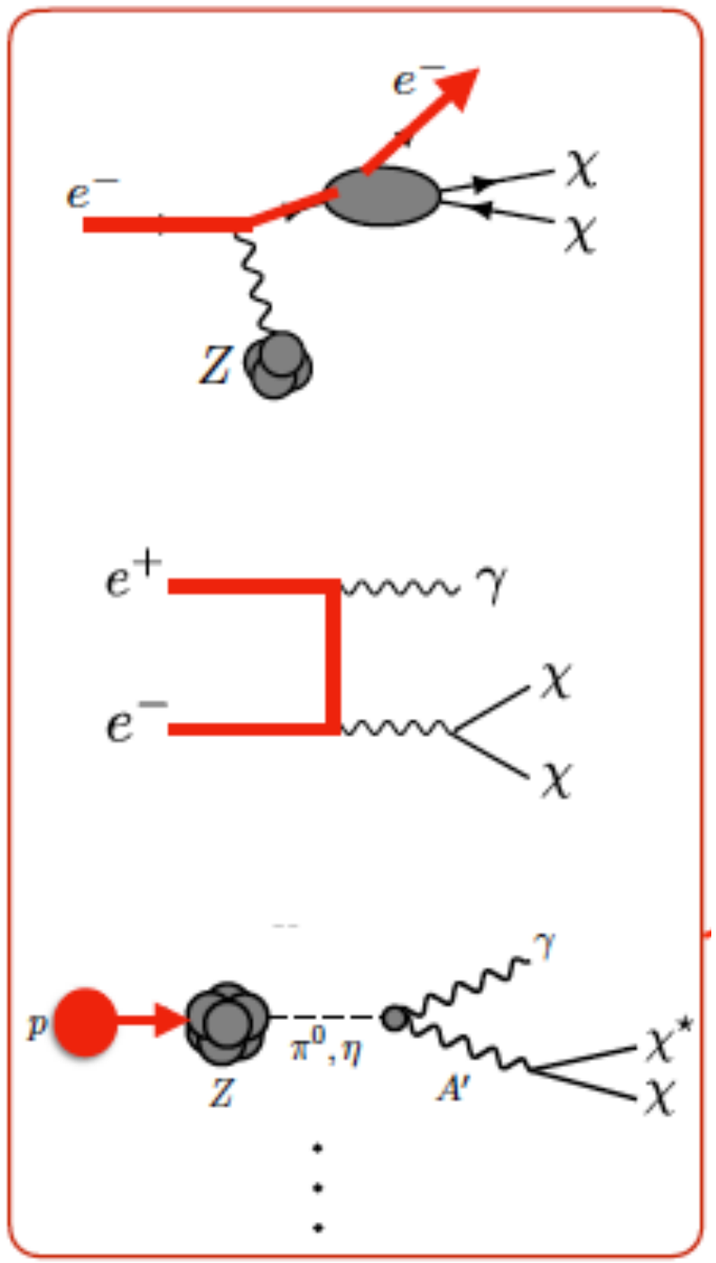
Invisible

Synergy with auxiliary detectors at collider experiments

1.

From snowmass: DM production at fixed targets

https://arxiv.org/abs/2207.00597

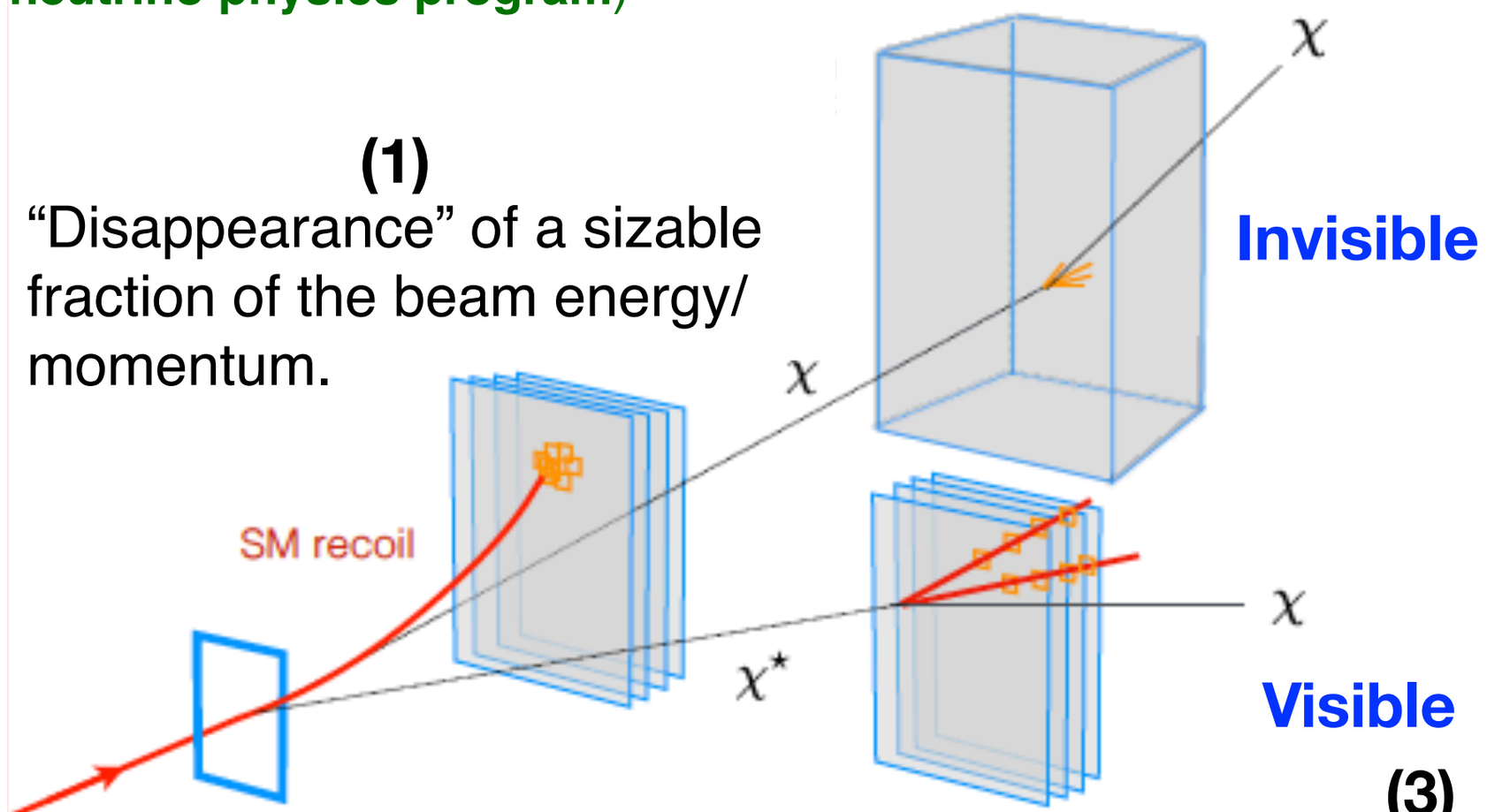


(proton beam: synergistic with the accelerator-based **neutrino physics program**)

(1)

"Disappearance" of a sizable fraction of the beam energy/ momentum.

Detection of DM scattering in forward detectors. **(2)**



Invisible

Visible

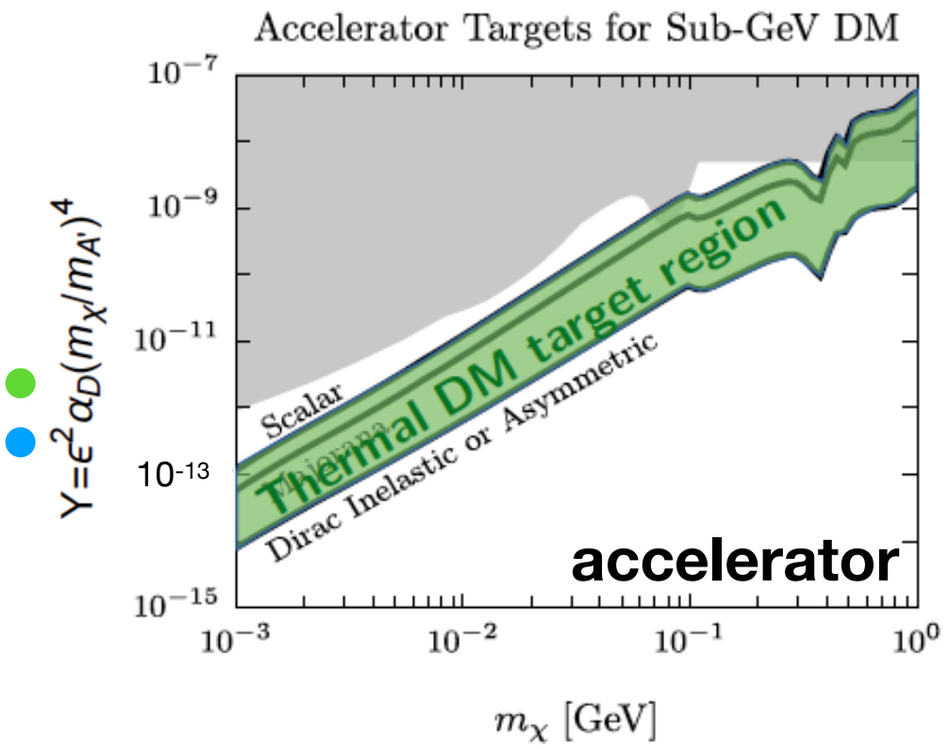
(3)

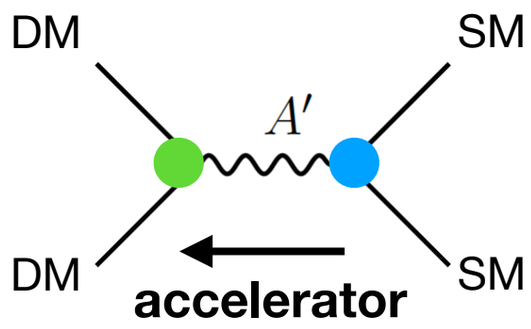
Production of an unstable dark sector particle and detection of its SM decay products.

Synergy with auxiliary detectors at collider experiments

1.

Complementarity with DM direct detection





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

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

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

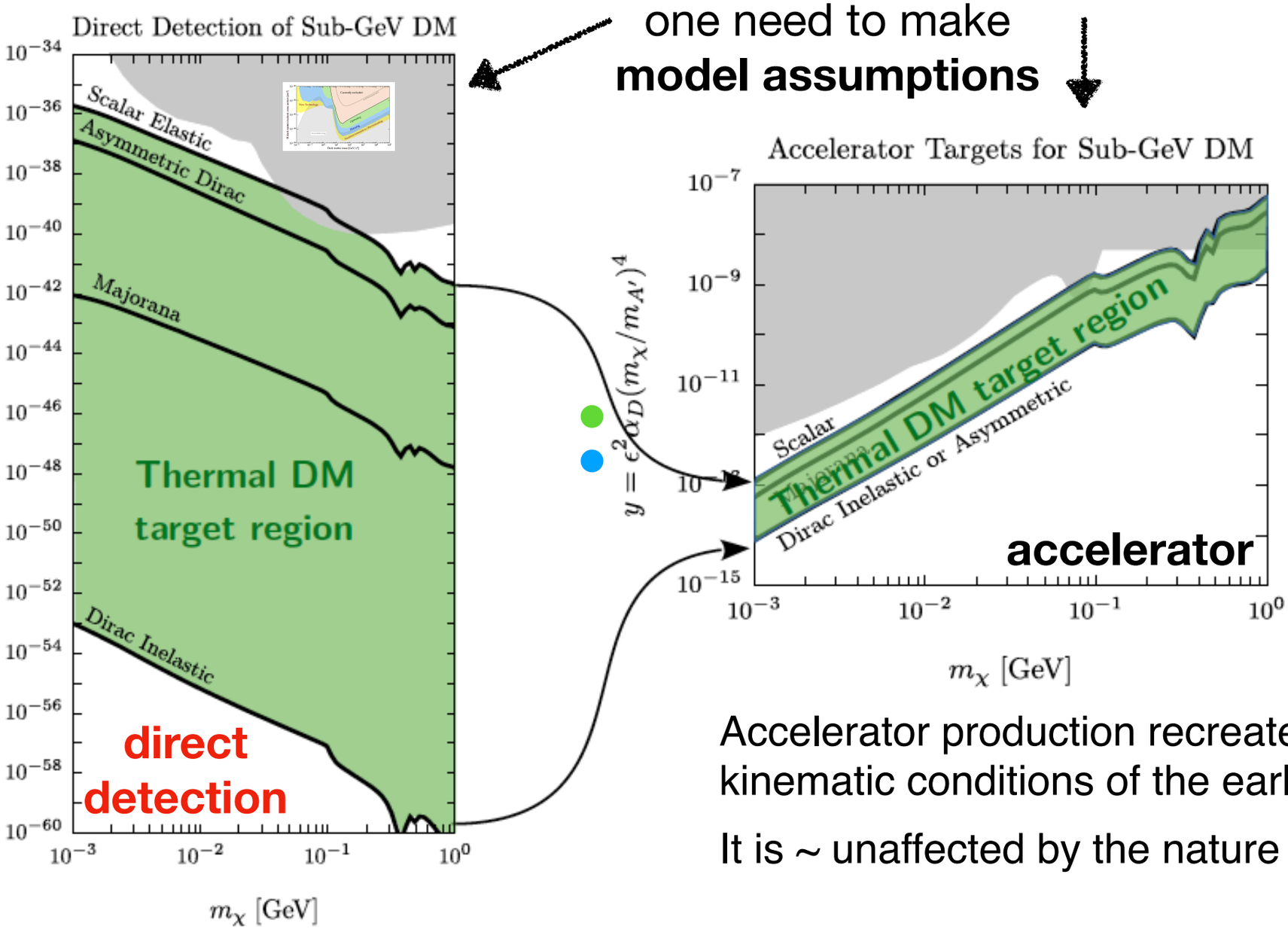
Accelerator production recreates the kinematic conditions of the early universe.

It is ~ unaffected by the nature of DM

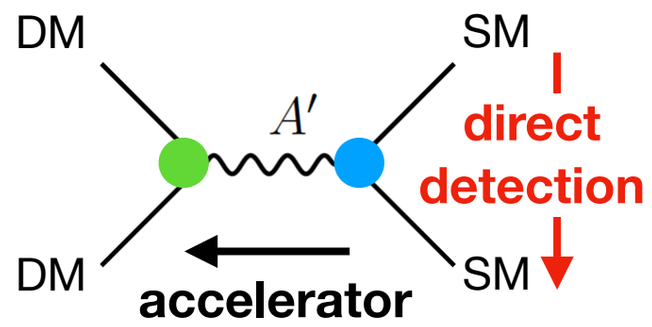
1.

Complementarity with DM direct detection

To connect these two probes,
one need to make
model assumptions



scattering with electrons



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

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

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

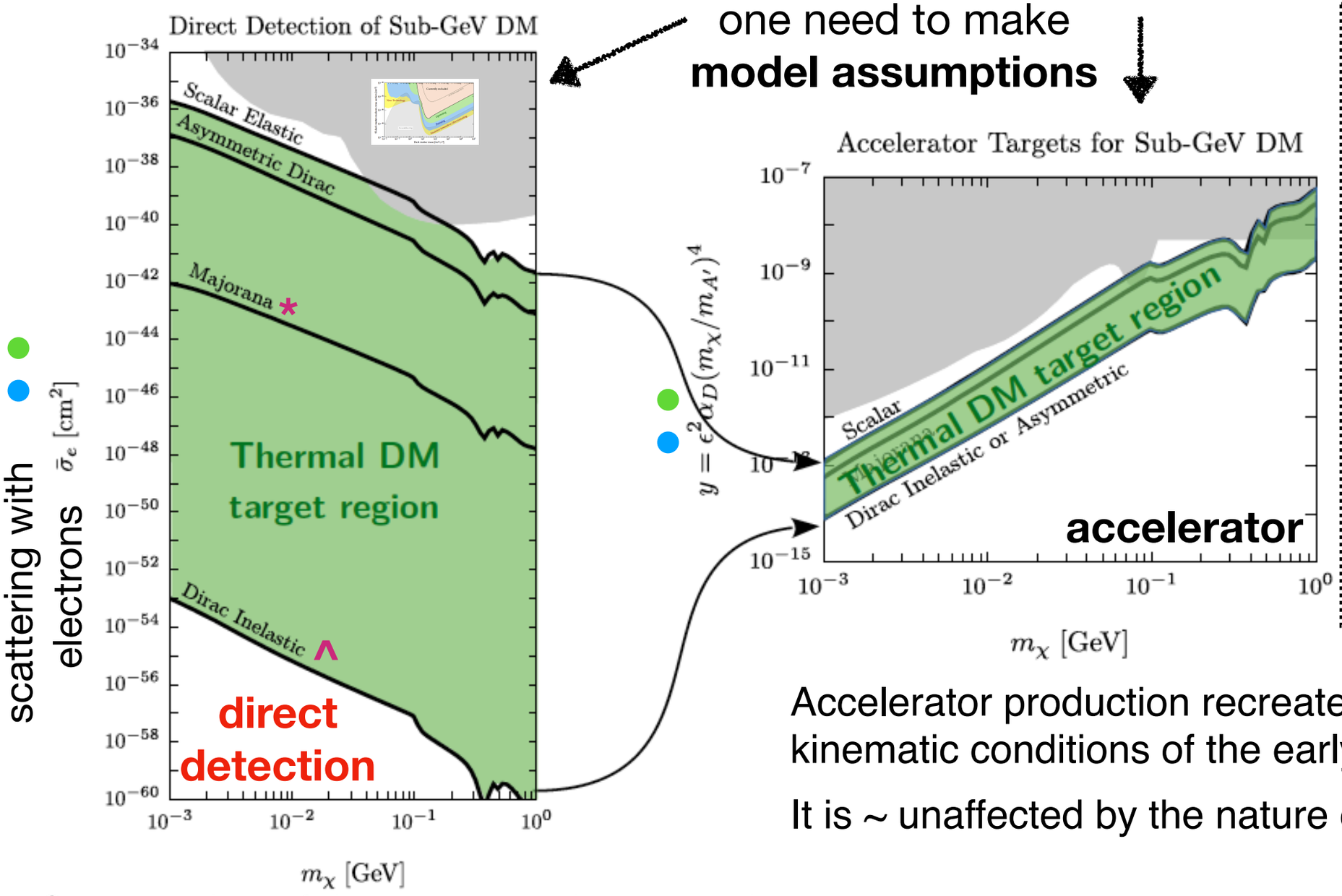
Accelerator production recreates the kinematic conditions of the early universe.

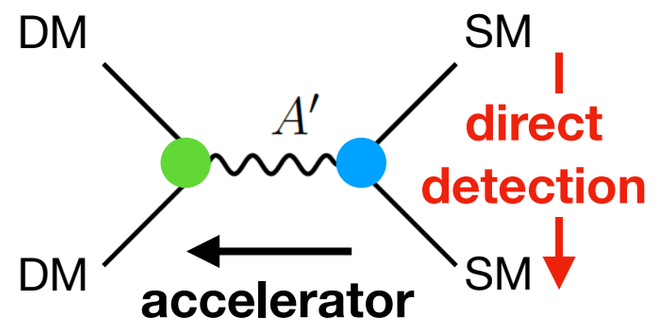
It is ~ unaffected by the nature of DM

1.

Complementarity with DM direct detection

To connect these two probes,
one need to make
model assumptions





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

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

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

Accelerator production recreates the kinematic conditions of the early universe.

It is ~ unaffected by the nature of DM

Suppression of the cross section can arise:

* small DM velocity (Majorana DM*)
* phase space + loops (inelastic DM^)

Direct detection can also be enhanced in different models (e.g., DM candidates with Coulombic interactions)

1.

Several other minimal non-secluded models

* $L_\mu - L_\tau$ mediated
* B-3L_τ mediated
* B mediated

* Higgs-mixed scalar mediated
* Muon-philic scalar mediated
* Neutrino-philic scalar mediated

* Axion mediated (see later in the talk)

* Sterile neutrino mediated (t-channel and s-channel)

* Millicharged particles

Benchmarks

The breadth of ideas for experiments within this program is important for several reasons.

* In the case of discovery the ability to measure dark sector masses and interaction strengths

* More in general, probe generalizations of thermal freeze-out, such as

- those where a mediator does not couple to electrons but preferentially to μ and/or τ leptons or baryons.

- Models where meta-stable particles in the dark sector play important roles in DM cosmology and enable new discovery techniques (next)

Messages

2.

Non-minimal non-secluded DM models

Several interesting examples of non-minimal dark matter - dark sector models:

Strongly interacting DM, Asymmetric DM, **Inelastic DM***, …

* Tucker-Smith, Weiner, 0101138
Gained renewed interest following the LZ event

2.

Non-minimal non-secluded DM models

Several interesting examples of non-minimal dark matter - dark sector models:
Strongly interacting DM, Asymmetric DM, **Inelastic DM***, …

* Tucker-Smith, Weiner, 0101138
Gained renewed interest following the LZ event

Example model: dark photon mediated

$$-\mathcal{L} \supset m_D \eta\xi + \frac{1}{2}\delta_\eta \eta^2 + \frac{1}{2}\delta_\xi \xi^2 + \text{h.c.}$$

2-component Weyl spinors with opposite charge under a new U(1)'

2.

Non-minimal non-secluded DM models

Several interesting examples of non-minimal dark matter - dark sector models:
Strongly interacting DM, Asymmetric DM, **Inelastic DM***, …

* Tucker-Smith, Weiner, 0101138
Gained renewed interest following the LZ event

Example model: dark photon mediated

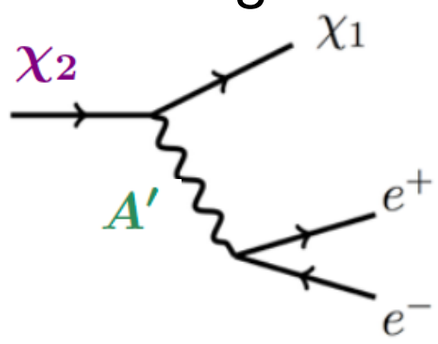
$$-\mathcal{L} \supset m_D \eta\xi + \frac{1}{2}\delta_\eta \eta^2 + \frac{1}{2}\delta_\xi \xi^2 + \text{h.c.}$$

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

(mass eigenstates)

2-component Weyl spinors with opposite charge under a new U(1)'

Dark matter can undergo thermal freeze-out:
X_1 X_2 → SM



2.

Non-minimal non-secluded DM models

Several interesting examples of non-minimal dark matter - dark sector models:
Strongly interacting DM, Asymmetric DM, **Inelastic DM***, …

* Tucker-Smith, Weiner, 0101138
Gained renewed interest following the LZ event

Example model: dark photon mediated

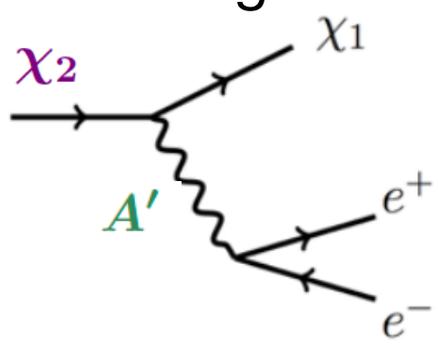
$$-\mathcal{L} \supset m_D \eta\xi + \frac{1}{2}\delta_\eta \eta^2 + \frac{1}{2}\delta_\xi \xi^2 + \text{h.c.}$$

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

(mass eigenstates)

2-component Weyl spinors with opposite charge under a new U(1)'

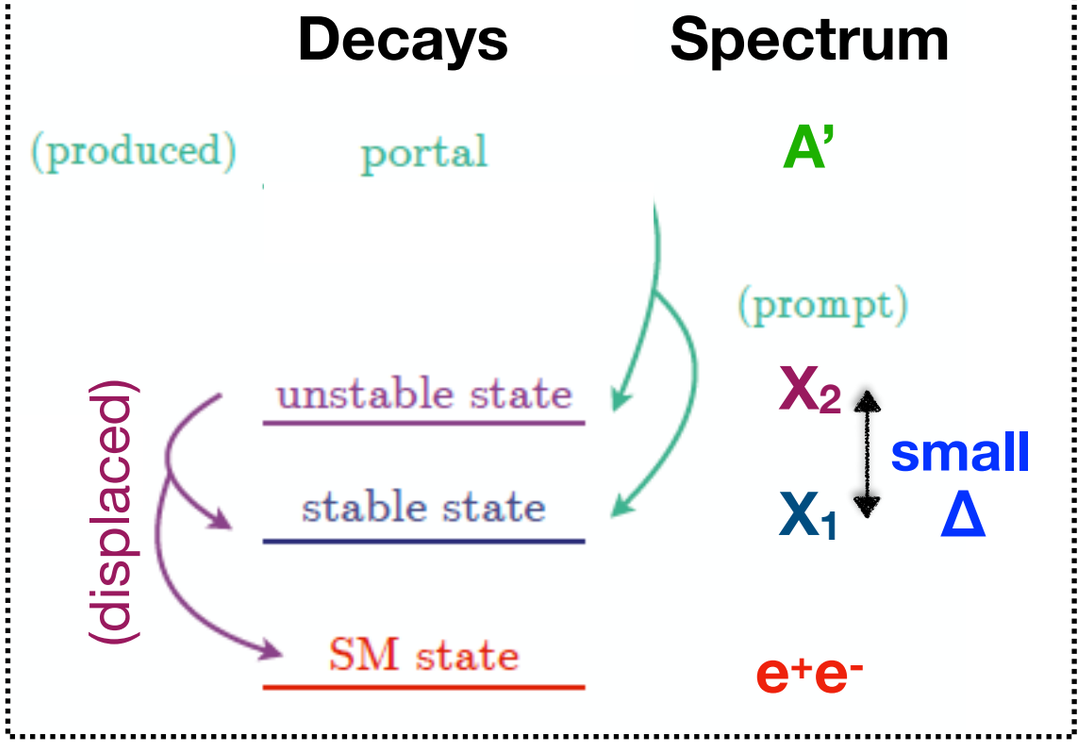
Dark matter can undergo thermal freeze-out:
X_1 X_2 → SM



Accelerator experiments can produce the dark photon with the decay

$$pp \to A' \to \chi_2 \chi_1, \; \chi_2 \to e^+ e^- \chi_1$$

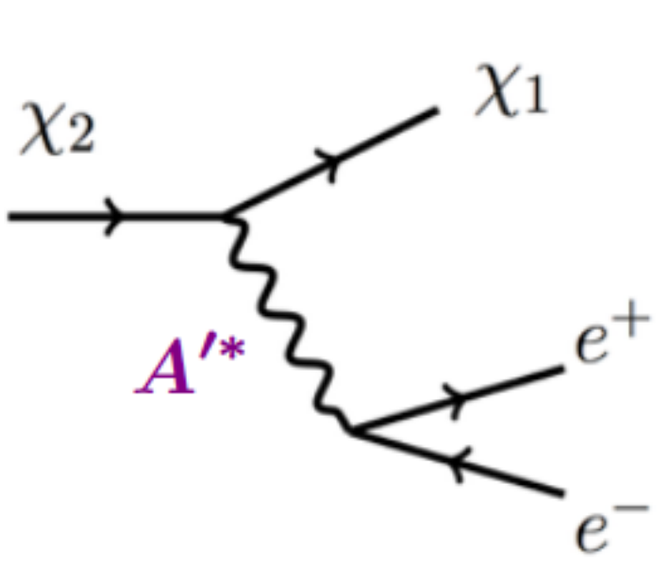
$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) = \frac{4\epsilon^2 \alpha_{\text{em}} \, \alpha_D \, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

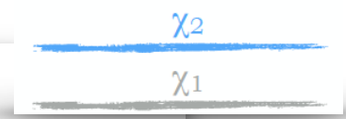


$$\Delta \equiv \frac{m_2 - m_1}{m_1} \simeq \frac{\delta_\eta + \delta_\xi}{m_D} \ll 1$$

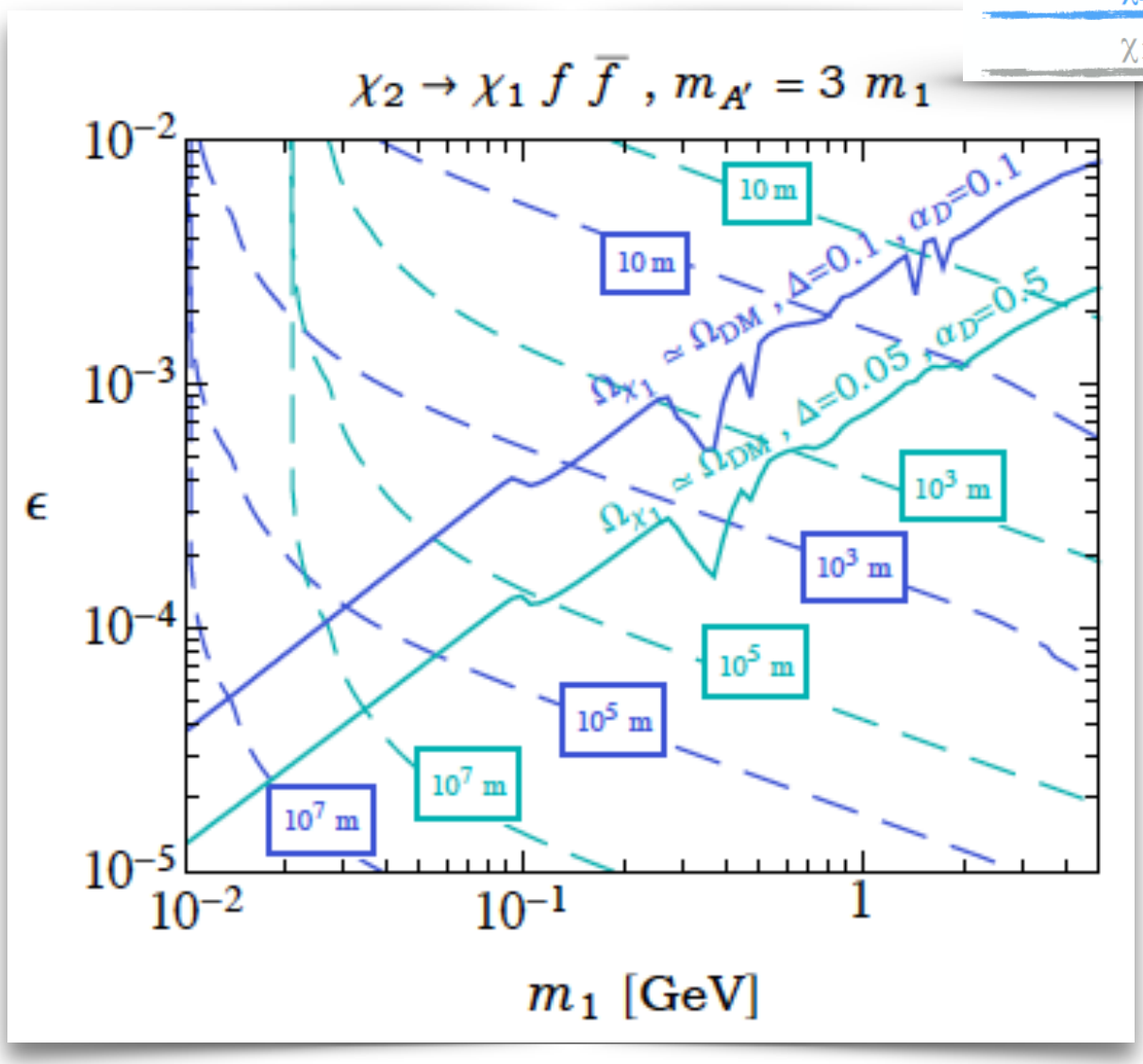
2.

A (generically) long-lived DM excited state





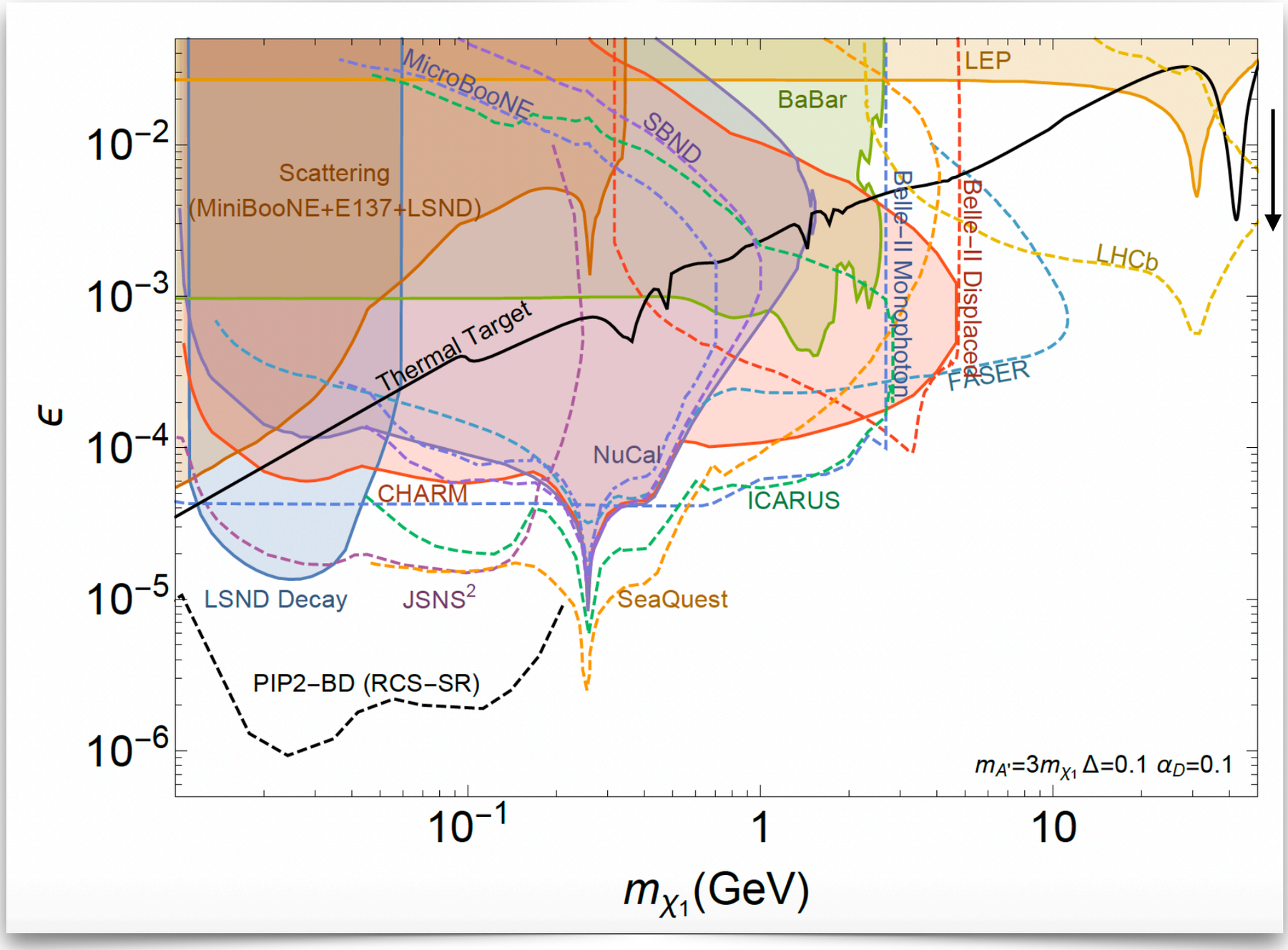
Berlin, SG, Schuster, Toro, 1804.00661



χ_2 life-time for two different mass splittings

2.

Searching for IDMs

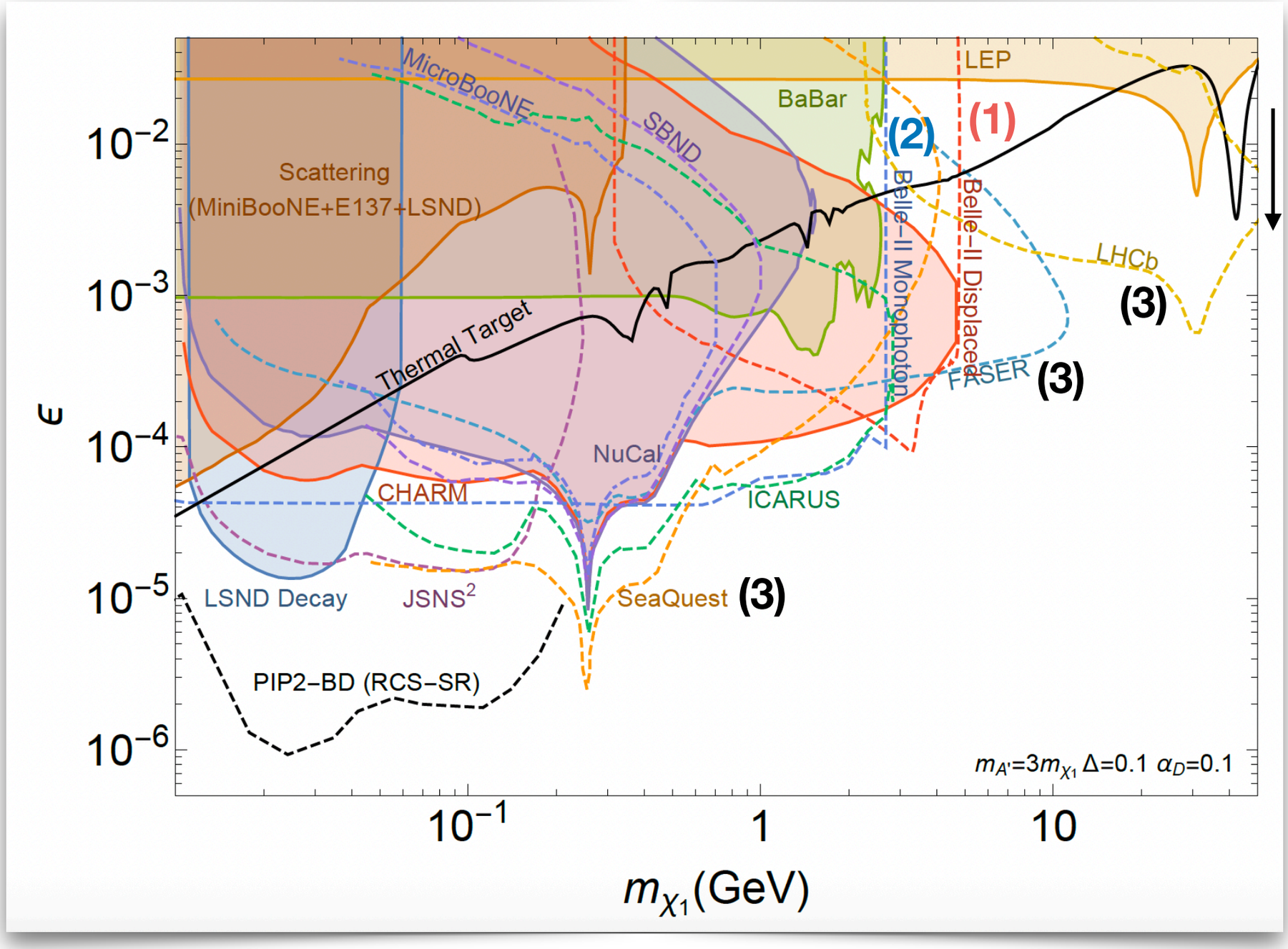


Thermal target moves down for smaller mass splittings

Krnjaic, Toro et al, 2207.00597

2.

Searching for IDMs



Krnjaic, Toro et al, 2207.00597

Thermal target moves down for smaller mass splittings

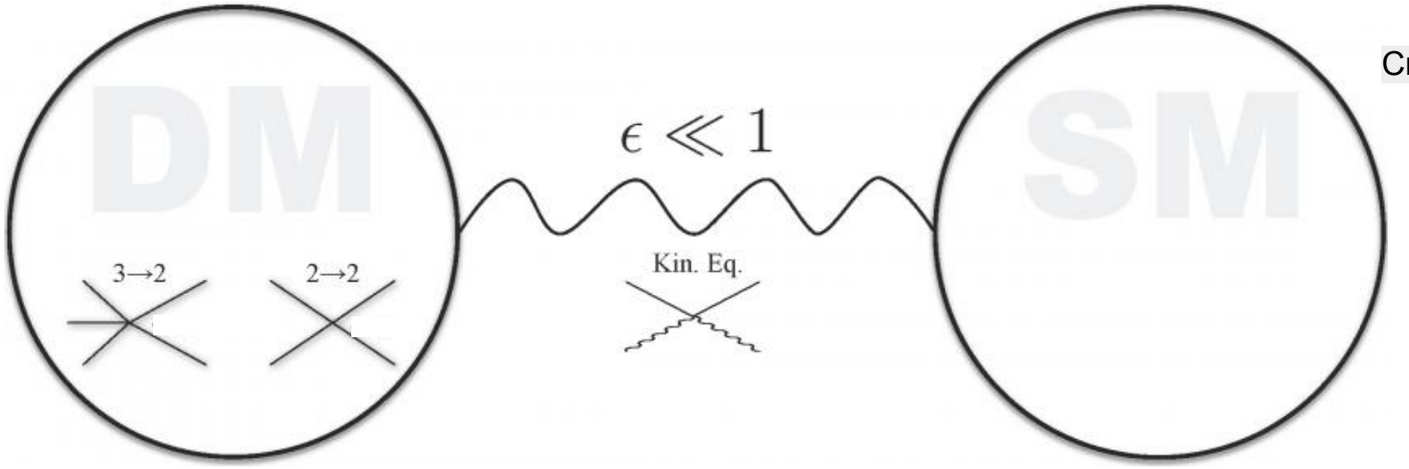
$e^+e^- \to \gamma A',\ A' \to \chi_2\chi_1,$
$\chi_2 \to \chi_1 \mathrm{SM\ SM}$
displaced
Duerr et al, 2012.08595 **(1)**

$e^+e^- \to \gamma A',\ A' \to \mathrm{inv}$
Kou et al., 1808.10567 **(2)**

$pp \to A',\ A' \to \chi_2\chi_1,$
$\chi_2 \to \chi_1 \mathrm{SM\ SM}$
displaced **(3)**

2.

Strongly interacting massive particle DM



Credit: Hochberg, Y et al. (2014)

confining SU(3)'
gauge symmetry with N_f=3

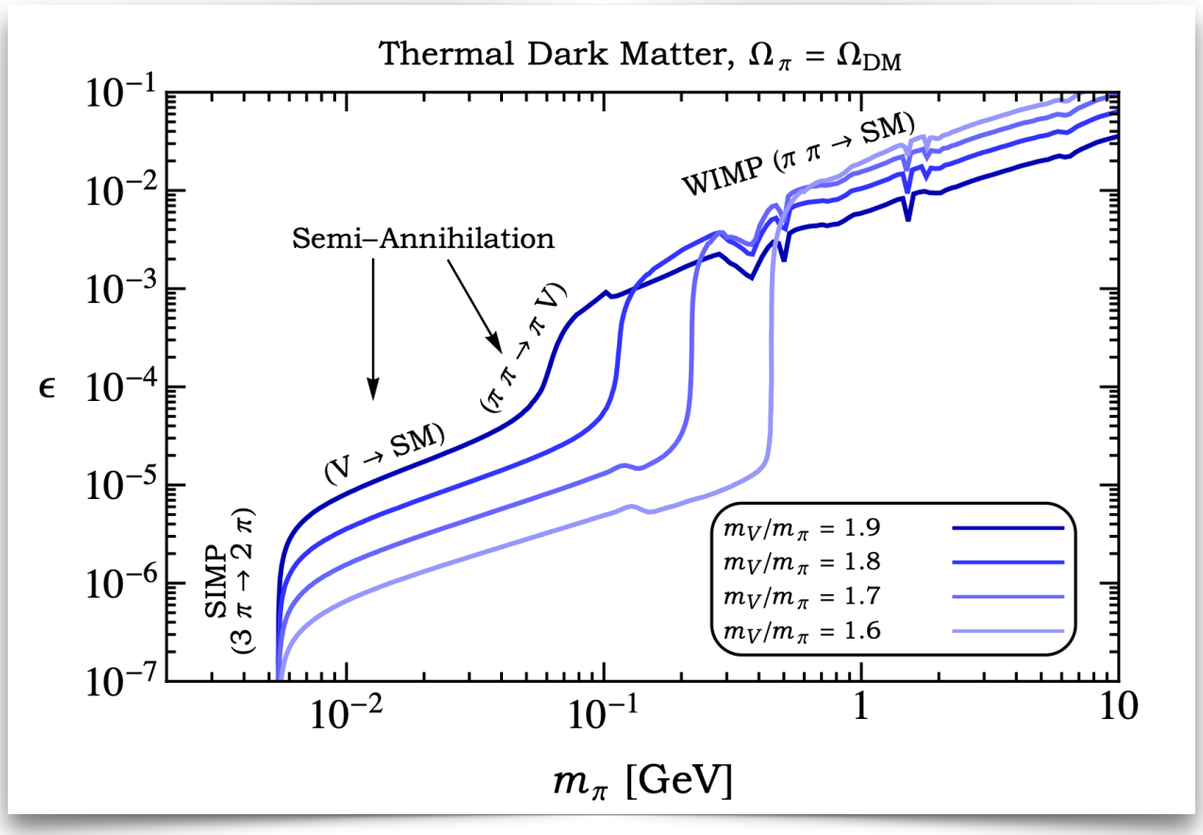
Dark pions and dark vector mesons

Light
They can be DM!

They are expected to have a mass close to the pion mass

They have an impact on the cosmological depletion of DM:

$$\begin{cases} 3\pi_D \to 2\pi_D & \text{annihilation} \\ \pi_D\pi_D \to V_D\pi_D & \text{semi-annihilation} \end{cases}$$



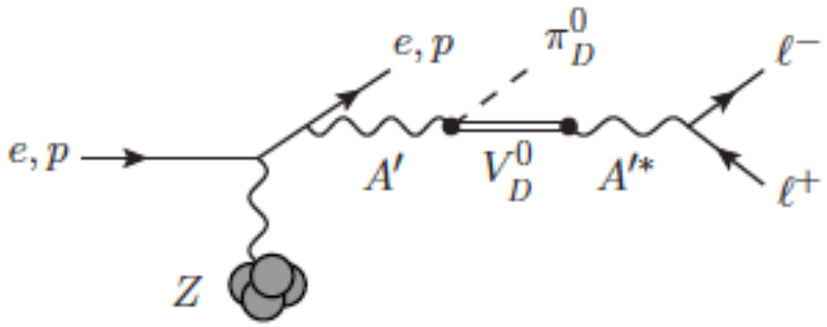
Berlin, Blinov, SG, Schuster, Toro, 1801.05805

2.

Visible signatures from SIMPs

The additional dark states will lead to a richer phenomenology

For example:

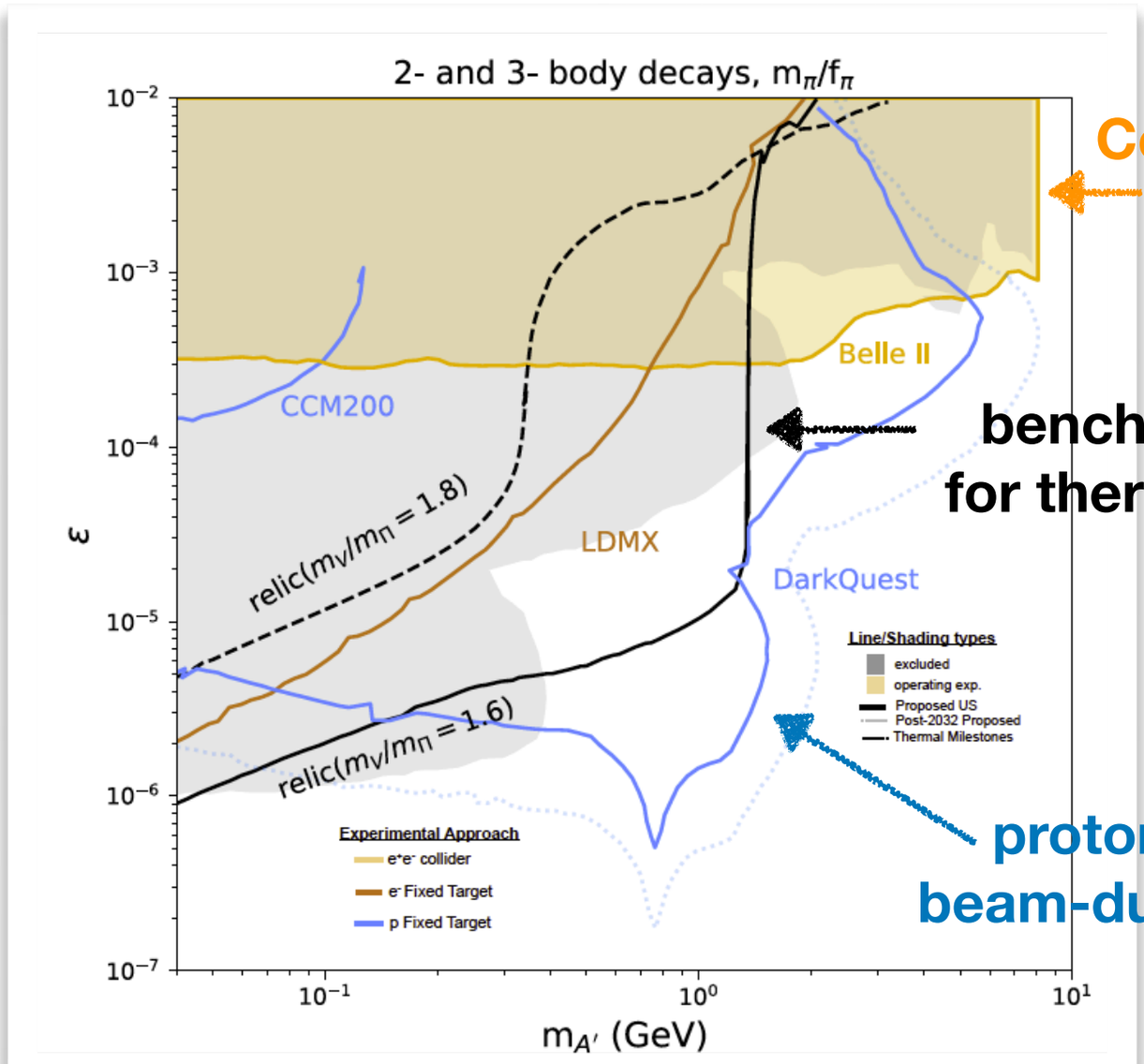


generically long-lived

$A' \to V_D \pi_D$, ← DM state

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

or $V_D^\pm \to A'^* \to \pi_D^\pm e^+ e^-$



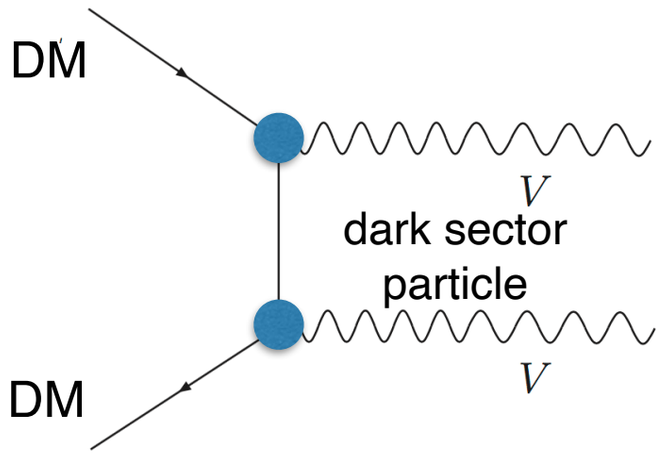
3.

Minimal secluded DM models

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

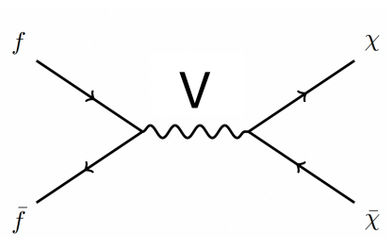
("secluded" case)

Pospelov, Ritz, Voloshin, 0711.4866



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

- **thermal** freeze-out in the dark sector



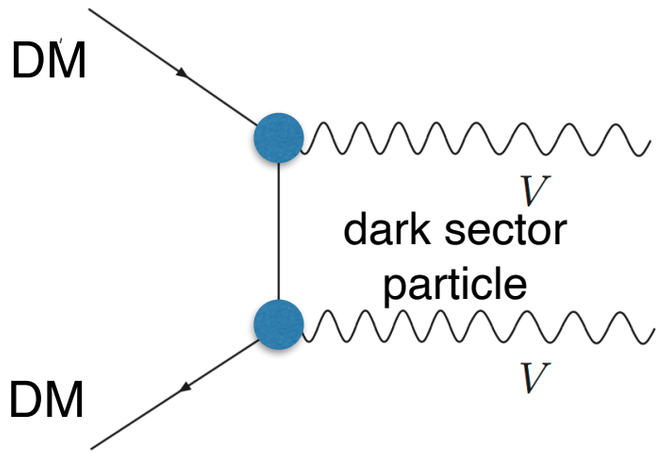
3.

Minimal secluded DM models

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

("secluded" case)

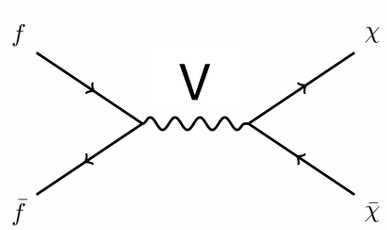
Pospelov, Ritz, Voloshin, 0711.4866



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

Several scenarios are viable:

- thermal freeze-out in the dark sector
- out of equilibrium freeze-out
- freeze-in



It will depend on how large the portal coupling to the SM is

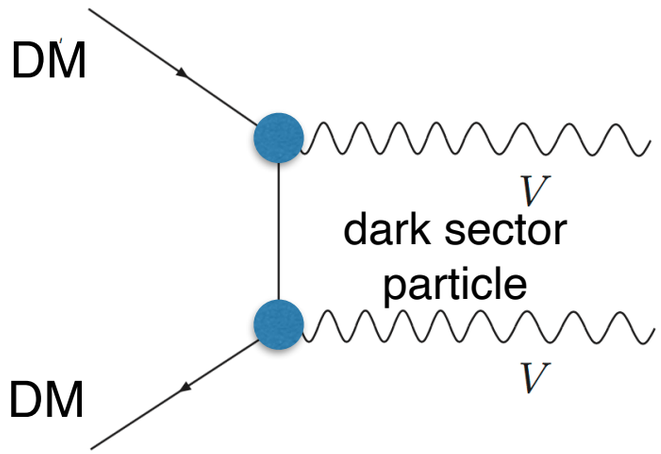
3.

Minimal secluded DM models

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

("secluded" case)

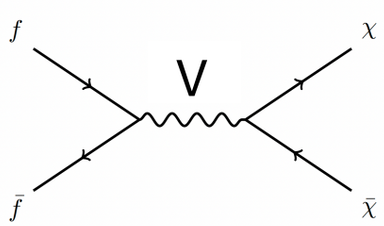
Pospelov, Ritz, Voloshin, 0711.4866



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

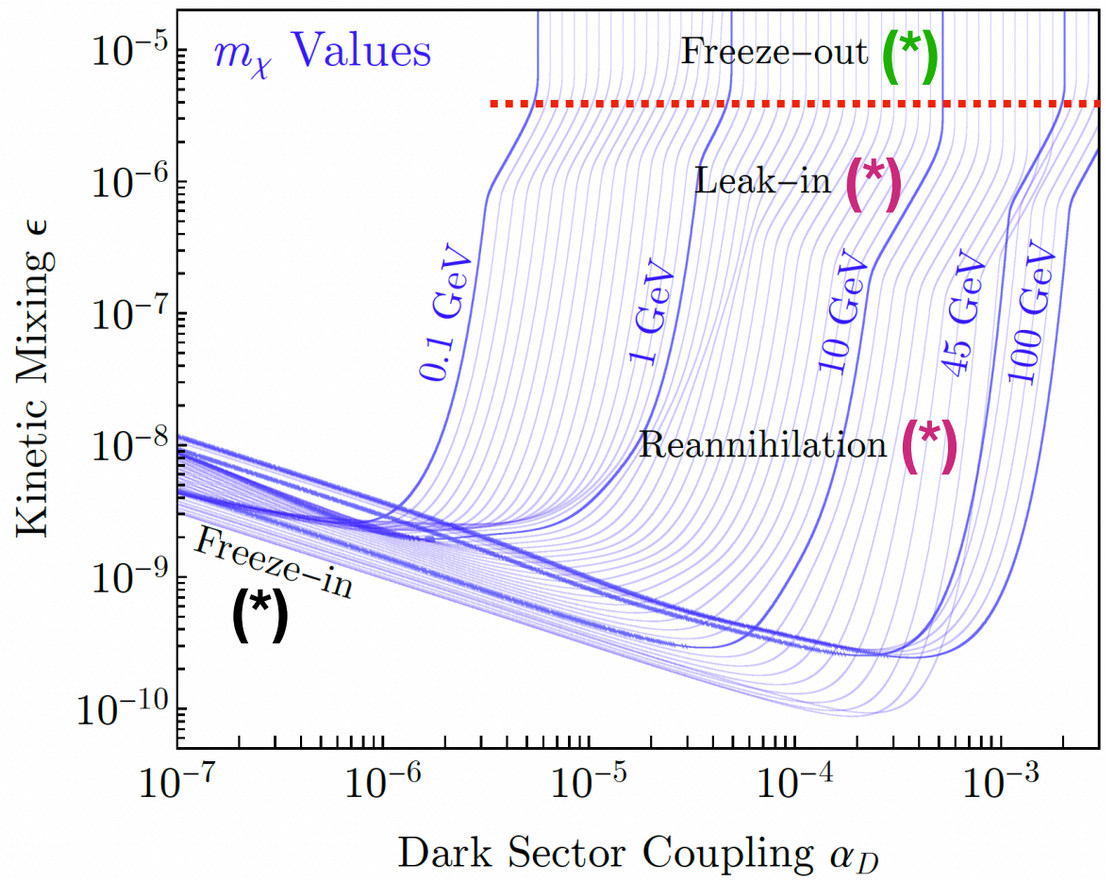
Several scenarios are viable:

- thermal freeze-out in the dark sector (*)
- out of equilibrium freeze-out (*)
- freeze-in (*)



It will depend on how large the portal coupling to the SM is

Alenezi, Cesarotti, SG, Shelton, 2504.00077



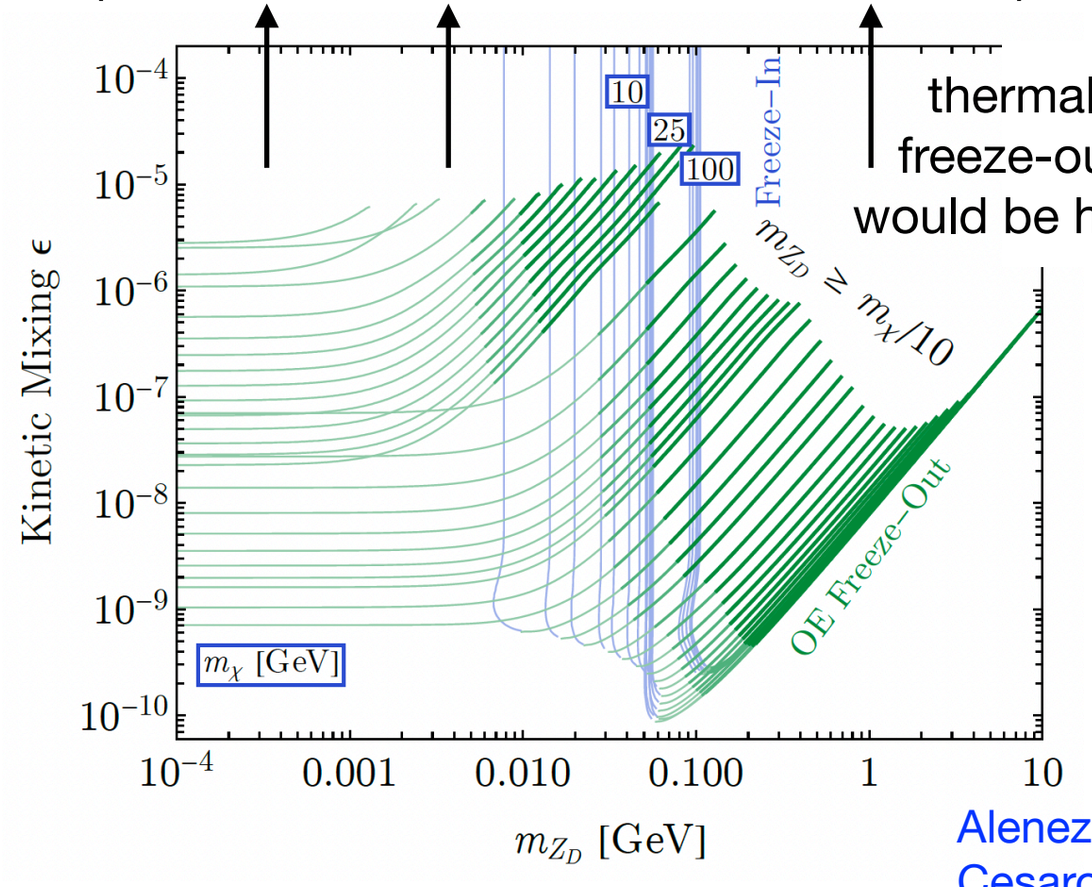
..... "thermalization floor"

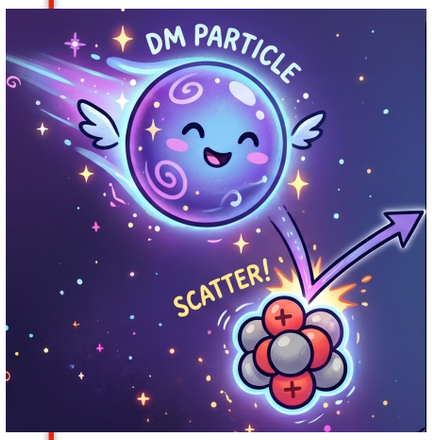
3.

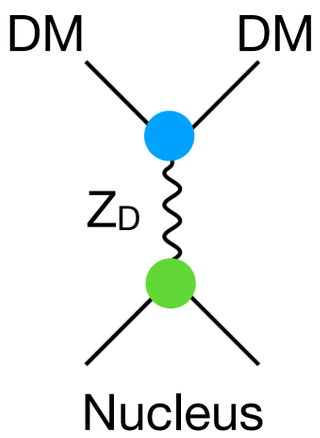
Lots of experimental progress

DM direct detection

(CRESST, DarkSide, XENONnT, LZ)







Only out of equilibrium freeze-out and freeze-in are still viable options.

Alenezi, Cesarotti, SG, Shelton, 2504.00077

Thermal freeze-out is completely probed!

(Caveat, we are assuming $m_{\rm ZD} \lesssim m_\chi/10$)

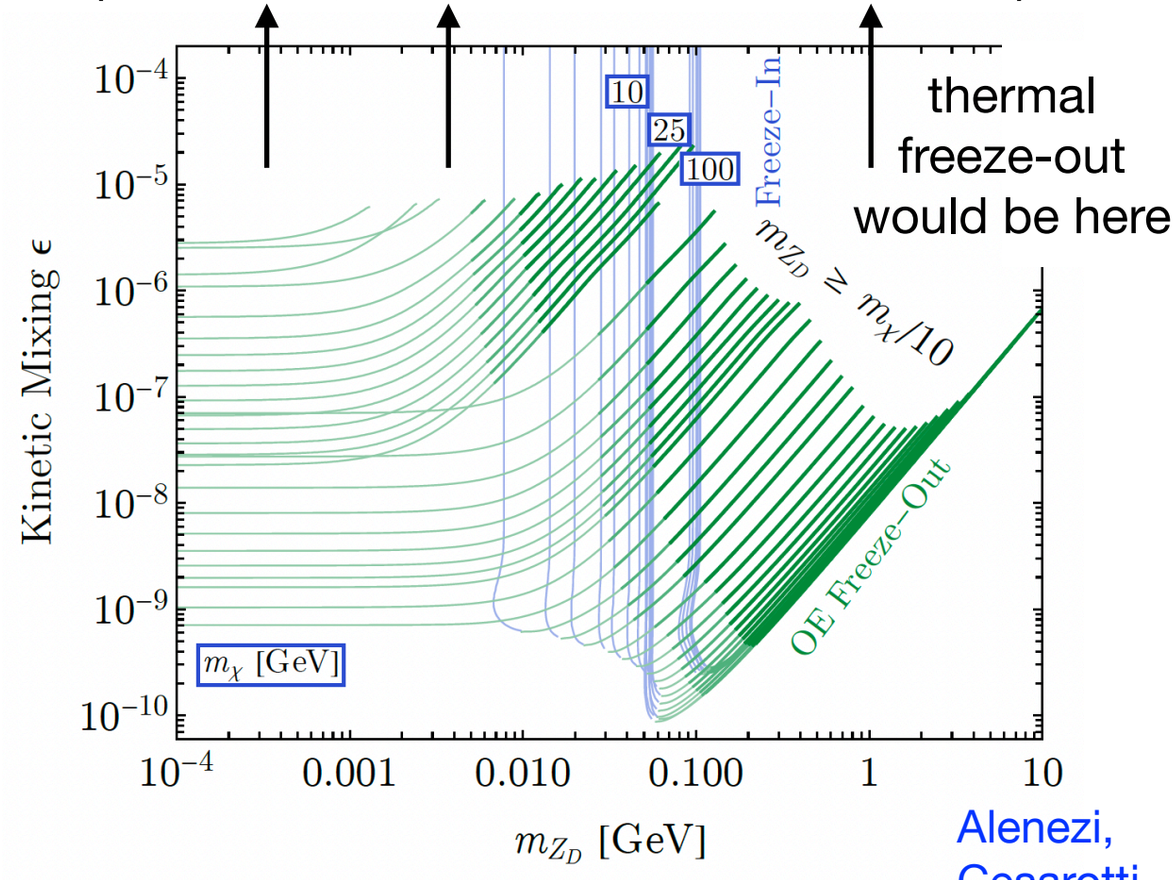
Additional bounds from indirect detection, and in particular CMB

3.

Lots of experimental progress

DM direct detection

(CRESST, DarkSide, XENONnT, LZ)



Alenezi, Cesarotti, SG, Shelton, 2504.00077

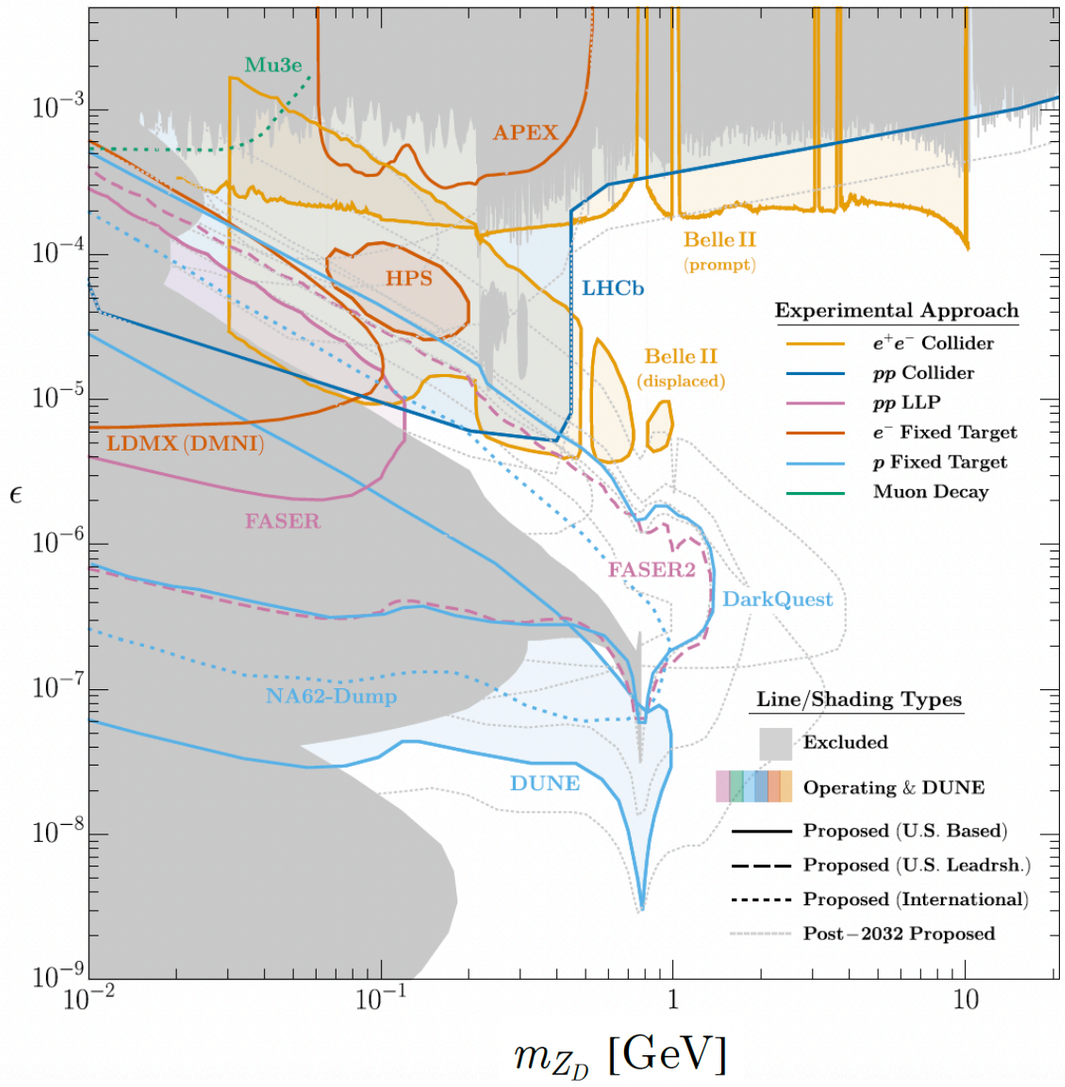
Only out of equilibrium freeze-out and freeze-in are still viable options.

Thermal freeze-out is completely probed!

(Caveat, we are assuming $m_{\rm ZD} \lesssim m_\chi/10$)

Additional bounds from indirect detection, and in particular CMB

Signal to look for at **high-intensity experiments**: long-lived dark photons decaying into SM (e.g., e^+e^-)

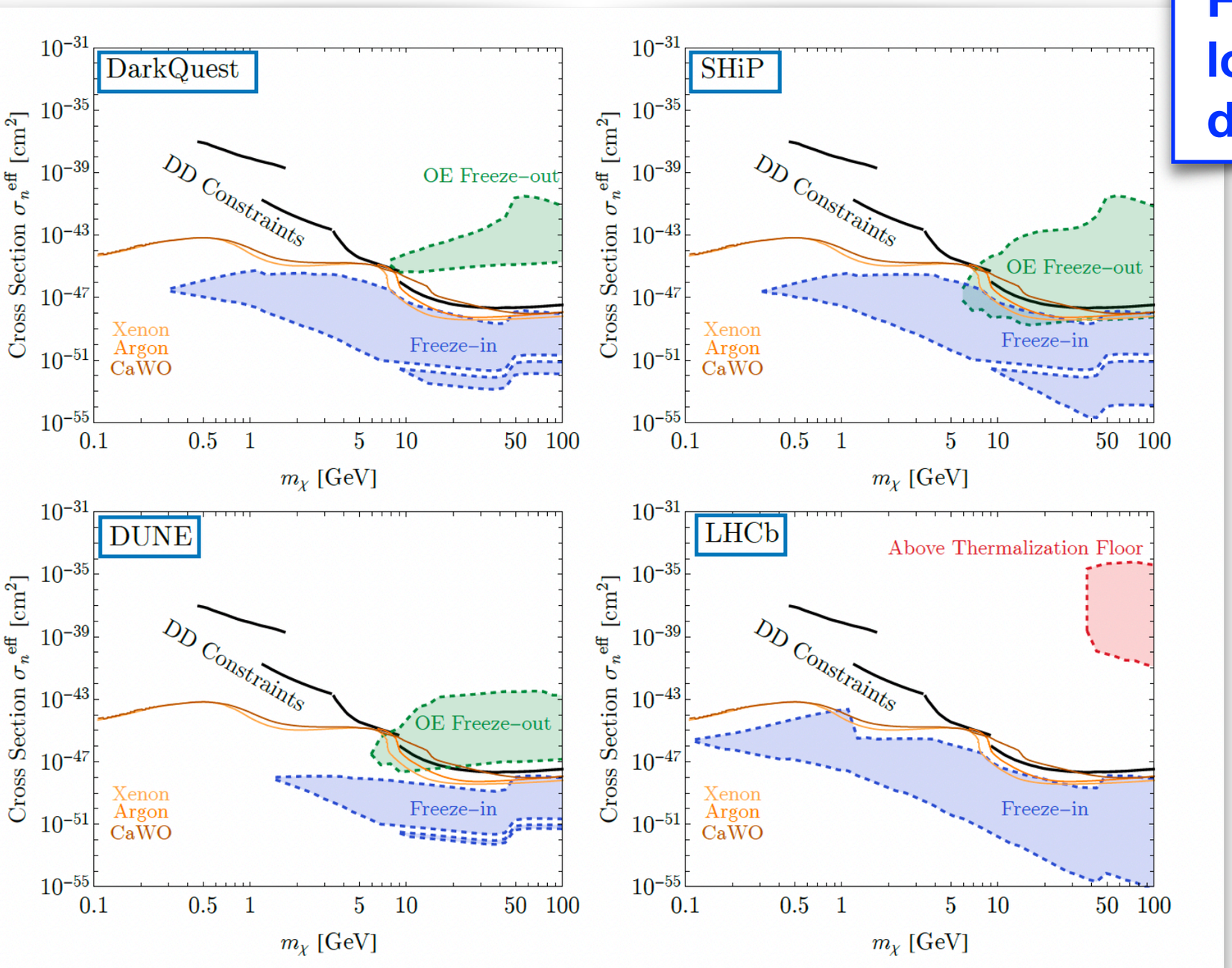


Batell et al., Snowmass report, 2207.06905

3.

Interplay between direct detection and high intensity experiments

Alenezi, Cesarotti, SG, Shelton, 2504.00077



Future searches for long-lived dark photons

Available regions of parameter space that will be probed by DarkQuest, SHiP, DUNE, and LHCb in the coming years

($\alpha_D = \alpha_D(\epsilon)$ fixed by the requirement of correct relic abundance)

Access to direct detection cross sections **below** the neutrino floor/fog!

3.

More challenging scenarios for direct detection

The minimal secluded dark photon - DM model is an ideal playground for studies of complementarity between direct detection (DD) experiments and dark photon searches at accelerator experiments

The dark photon mediates a spin-independent signal at direct detection experiments
Some secluded models are, however, more hidden to direct detection:
axion - mediated DM models ⇨ spin-dependent transitions at DD

The present bounds on the spin-dependent scattering cross sections are **~5-6 orders of magnitude weaker** than for spin-independent interactions

3.

More challenging scenarios for direct detection

The minimal secluded dark photon - DM model is an ideal playground for studies of complementarity between direct detection (DD) experiments and dark photon searches at accelerator experiments

The dark photon mediates a spin-independent signal at direct detection experiments
Some secluded models are, however, more hidden to direct detection:
axion - mediated DM models ⇒ spin-dependent transitions at DD

The present bounds on the spin-dependent scattering cross sections are **~5-6 orders of magnitude weaker** than for spin-independent interactions

Let's take an axion (or axion-like-particle, ALP) coupled to gluons:

$$\mathcal{L} \supset c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \Rightarrow \begin{cases} \mathcal{L}_\phi &= \phi\left[g_\chi\bar{\chi}\chi + g_p\bar{p}\gamma^5 p + g_n\bar{n}\gamma^5 n\right] \\ \mathcal{L}_a &= a\left[g_\chi\bar{\chi}\gamma_5\chi + g_p\bar{p}\gamma^5 p + g_n\bar{n}\gamma^5 n\right] \end{cases}$$

Two different types of couplings with DM

$$\mathcal{H}_\phi = -\frac{g_\chi g_p}{m_p}\frac{\mathrm{q}\cdot \mathbf{S}_p}{\mathrm{q}^2+m_\phi^2}e^{i\mathrm{q}\cdot\mathrm{r}}$$

$$\mathcal{H}_a = -\frac{g_\chi g_p}{m_p m_\chi}\frac{(\mathrm{q}\cdot \mathbf{J}_\chi)(\mathrm{q}\cdot \mathbf{S}_p)}{\mathrm{q}^2+m_a^2}e^{i\mathrm{q}\cdot\mathrm{r}}$$

velocity suppression

additional **velocity suppression**

$$\mathcal{H} = -\frac{g_\chi g_p}{q_0^2+m_{\mathrm{med}}^2}F_{\mathrm{med}}(\mathrm{q})\,\mathcal{O}\left(\mathbf{J}_\chi,\mathrm{q}\right)\cdot\mathbf{S}_p\,e^{i\mathrm{q}\cdot\mathrm{r}}$$

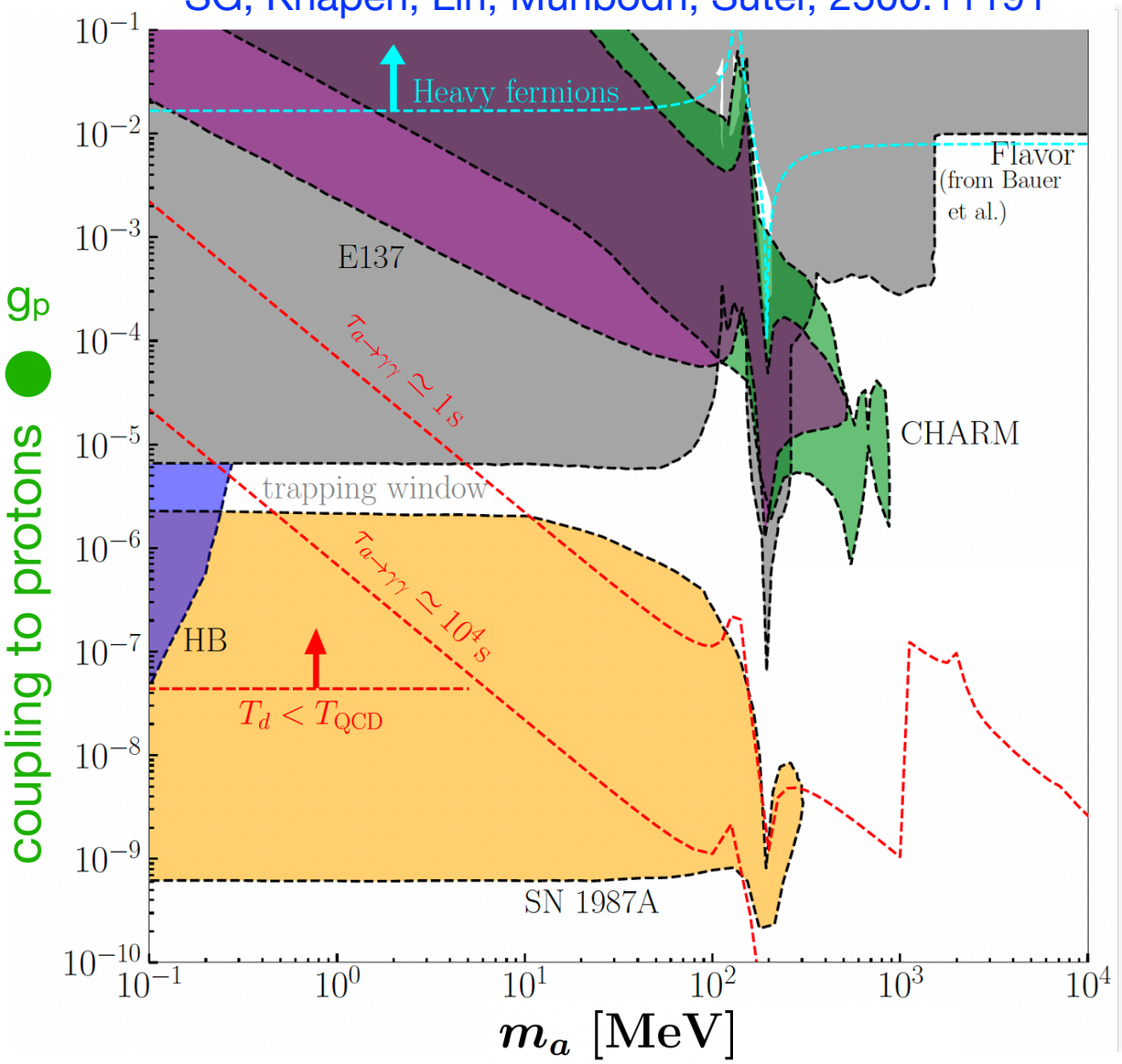
$$F_{\mathrm{med}}(\mathrm{q}) = \frac{q_0^2+m_{\mathrm{med}}^2}{q^2+m_{\mathrm{med}}^2}$$

$q_0 = m_\chi v_0$,
$v_0 = 220$ km/s

3.

Bounds on the ALP mediator

SG, Knapen, Lin, Munbodh, Suter, 2506.11191

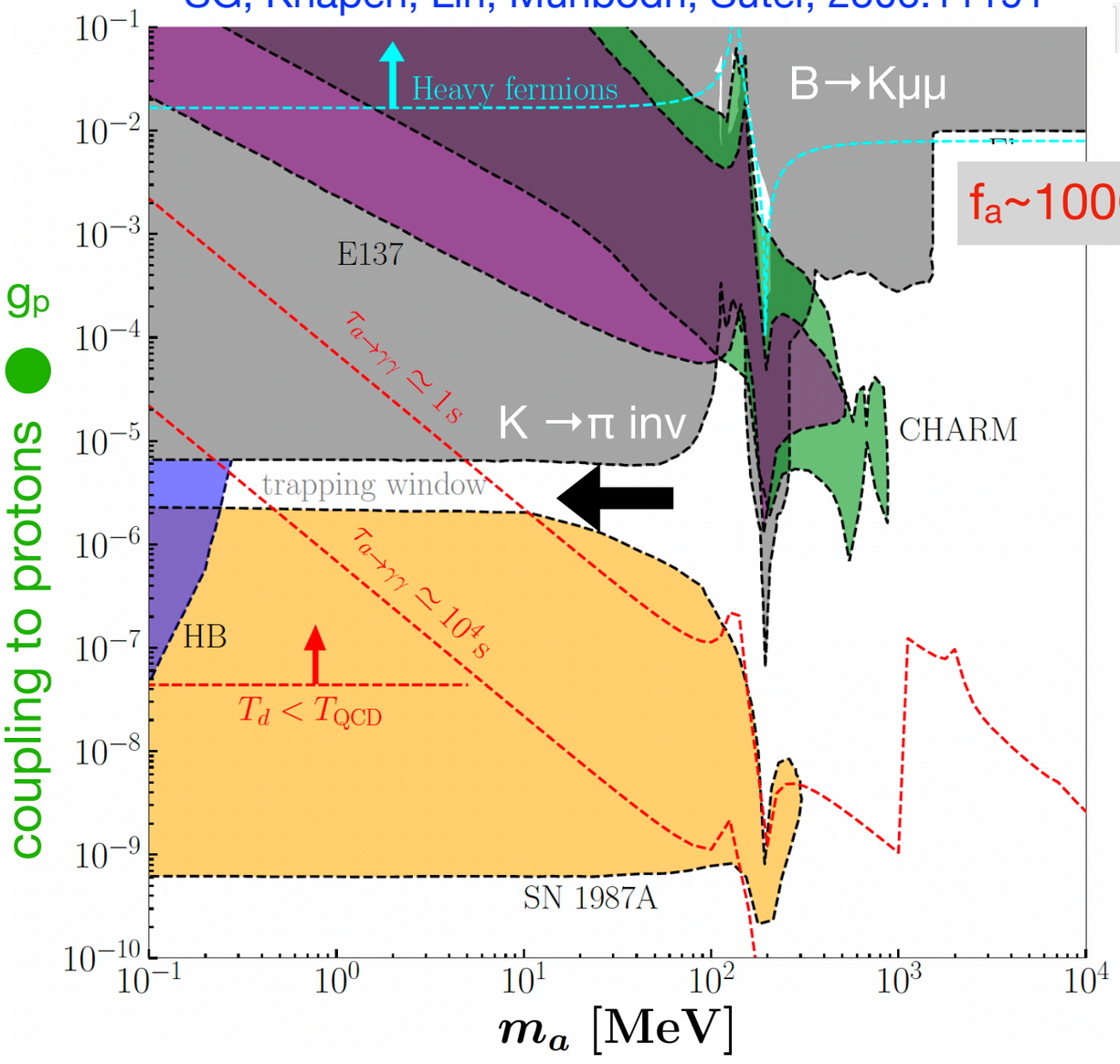


(The ALP decays back to the SM, since it is lighter than DM)

3.

Bounds on the ALP mediator

SG, Knapen, Lin, Munbodh, Suter, 2506.11191



f_a~100GeV

Flavor probes:
K →π inv, B→Kμμ

Fixed target experiments:

E137 (primakoff + strahlung production)
CHARM (axion from meson decays)

Supernova (SN1987a) bounds:
axion emission leads to a modified neutrino spectrum observed in the Kamiokande II detector

Horizontal branch (HB):
the axion reduces the ratio of horizontal branch stars to red giant branch stars in globular clusters

What about present/future fixed targets, LHC auxiliary detectors, and Kaon/B factories?

→ Trapping window: the axion cannot free stream out of the protoneutron star

3.

Direct detection: phonon excitations in crystals

Several strategies to access lighter DM at direct detection experiments have been proposed in the past ~10 years.

General challenge: light DM ⇨ small momentum exchange in DM-nucleus scattering.
Possible ways out: Scattering with electrons, Migdal effect, low threshold detectors, …

3.

Direct detection: phonon excitations in crystals

Several strategies to access lighter DM at direct detection experiments have been proposed in the past ~10 years.

General challenge: light DM ⇨ small momentum exchange in DM-nucleus scattering.
Possible ways out: Scattering with electrons, Migdal effect, low threshold detectors, …

Basic idea

For light DM, the deBroglie wavelength > interatomic spacing.

"Billiard ball" nuclear recoil is not applicable.
The DM sees more than one atom at a time.

⇨ Phonon excitations
(many coupled harmonic oscillators)

3.

Direct detection: phonon excitations in crystals

Several strategies to access lighter DM at direct detection experiments have been proposed in the past ~10 years.

General challenge: light DM ⇨ small momentum exchange in DM-nucleus scattering.
Possible ways out: Scattering with electrons, Migdal effect, low threshold detectors, …

Basic idea

For light DM, the deBroglie wavelength > interatomic spacing.

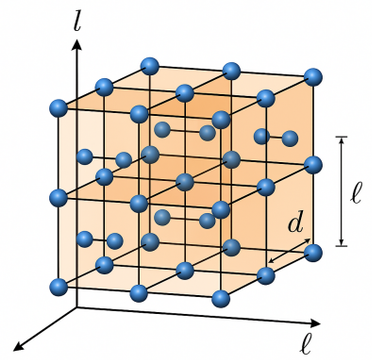
"Billiard ball" nuclear recoil is not applicable.
The DM sees more than one atom at a time.

⇨ Phonon excitations
(many coupled harmonic oscillators)

Expansion in the number of final state phonons, where each phonon comes with a factor of $\frac{q}{\sqrt{2m_d\bar{\omega}_d}}$

(m_d and ω_d are the mass and average oscillation frequency of the atom at position d)

Knapen et al., 1712.06598, Griffin et al., 1807.10291
Campbell-Deem et al., 1911.03482, Kahn et al., 2011.09477, …



Calculations have been developed **only** for spin-independent interactions

After the initial theory studies:

TESSERACT experiment at Berkeley started setting bounds using this technique (threshold energy=1.5eV; 0.233 g × 12 hours), 2503.03683

We extended it to spin-dependent interactions
SG, Knapen, Lin, Munbodh, Suter, 2506.11191

3.

A discoverable number of events

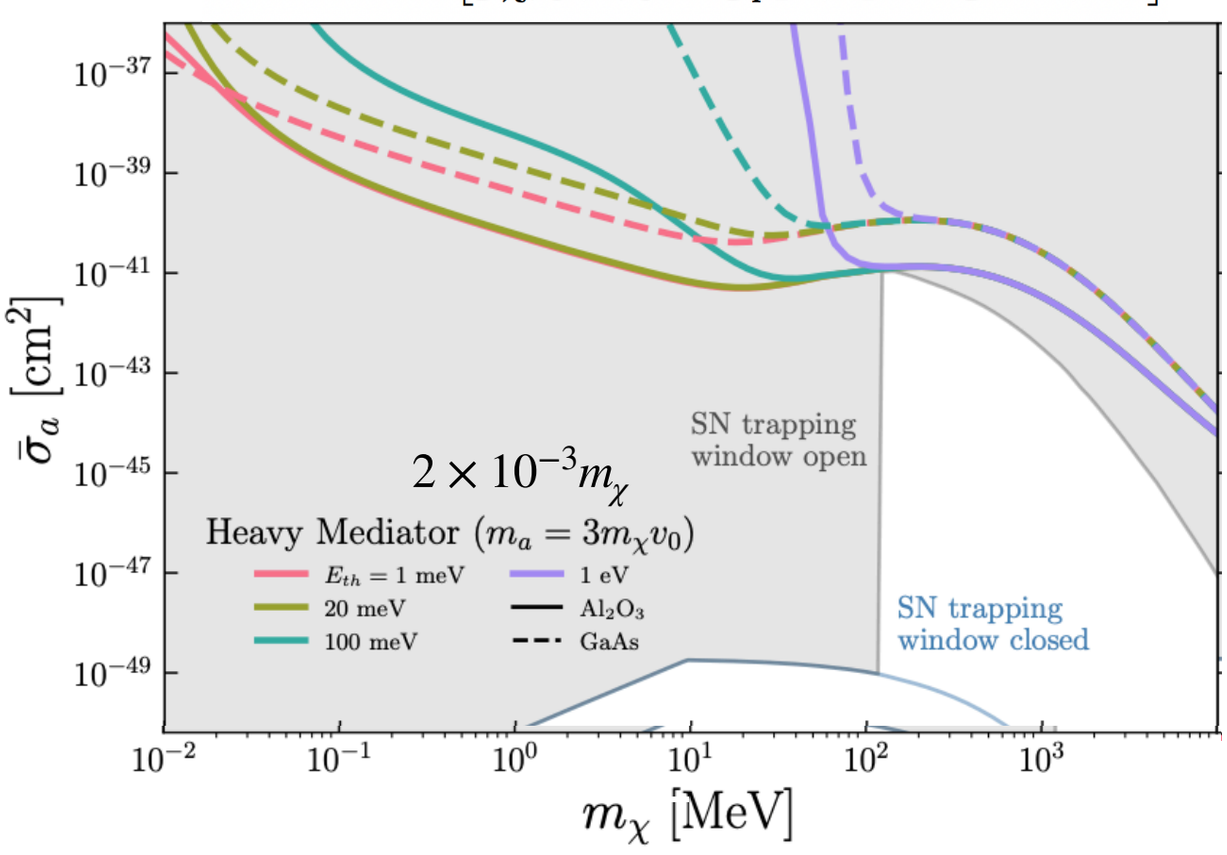


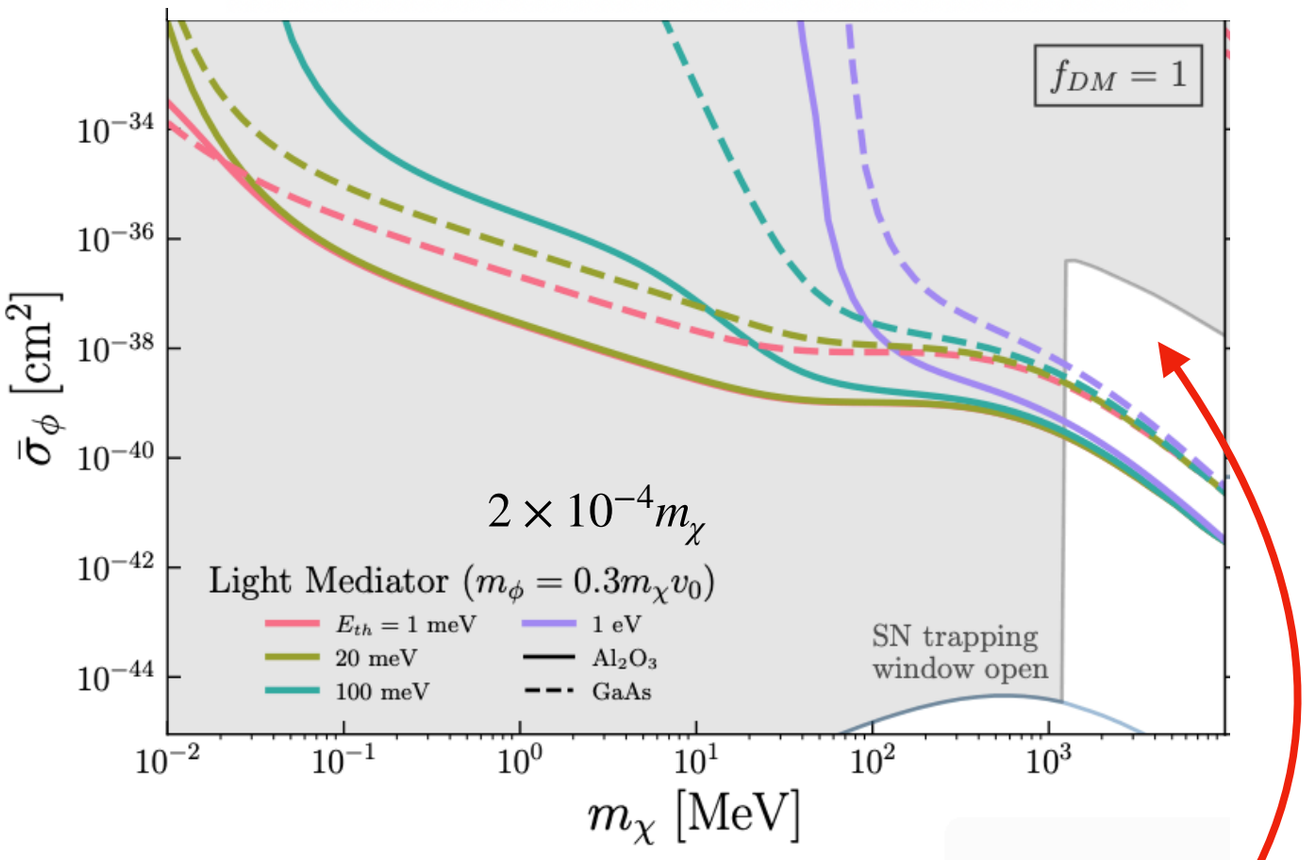
Lines for
3 events/kg year



$$\mathcal{L}_a = a\left[g_\chi \bar{\chi}\gamma_5\chi + g_p\bar{p}\gamma^5 p + g_n\bar{n}\gamma^5 n\right]$$

$$\mathcal{L}_\phi = \phi\left[g_\chi \bar{\chi}\chi + g_p\bar{p}\gamma^5 p + g_n\bar{n}\gamma^5 n\right]$$





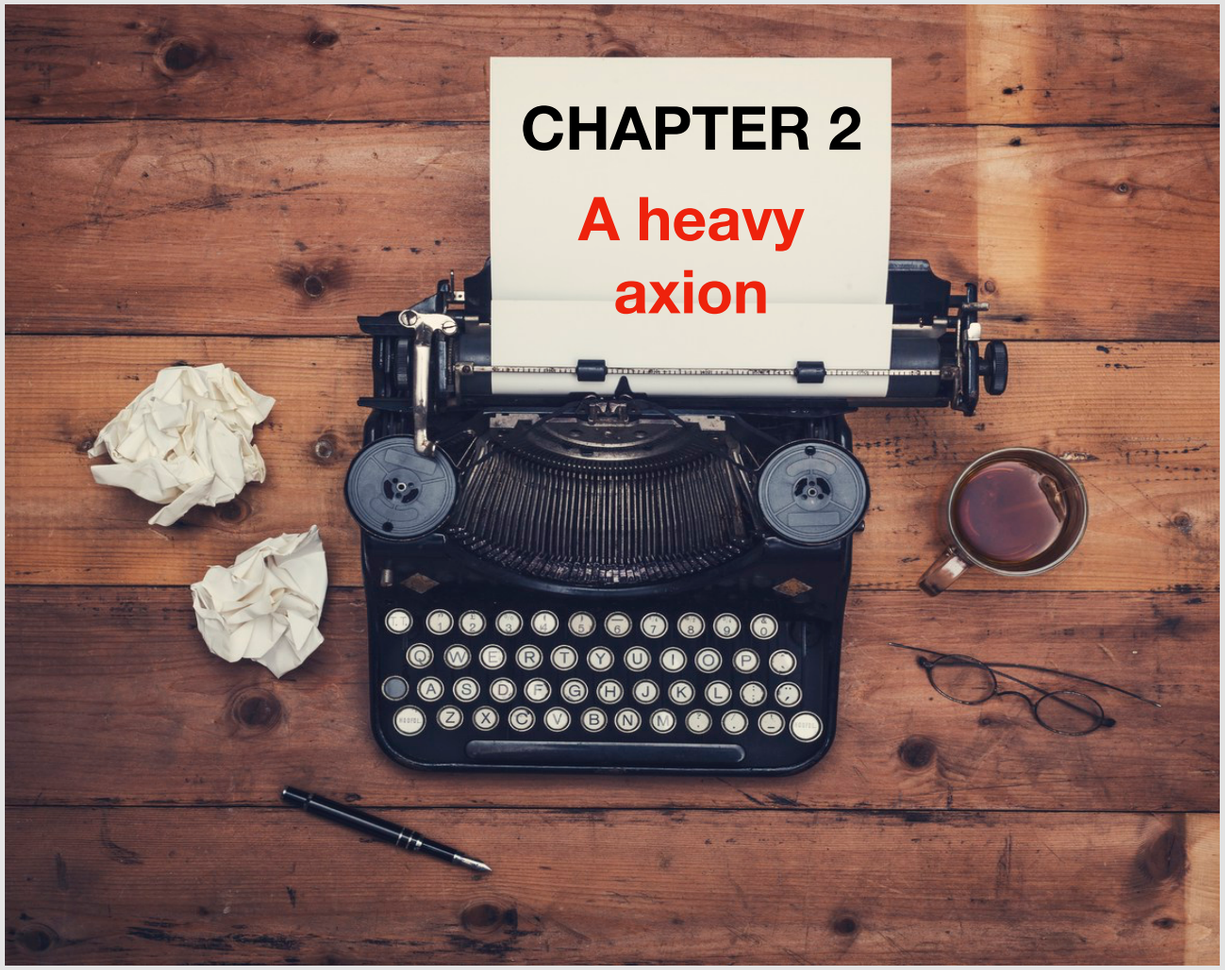
different threshold energies

different materials

Regions probed by accelerator experiments

max number of events
~16000
in the allowed region

SG, Knapen, Lin, Munbodh, Suter, 2506.11191



Dark sectors are not only motivated by the physics of Dark Matter.

Heavy axions at high intensity experiments
(we already discussed signals arising from axions coupling to gluons)

EFTs for (heavy) axions

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

See also talk by R. Szafron yesterday

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

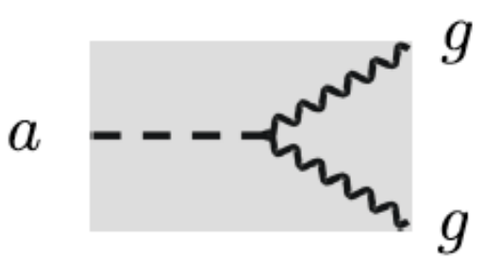
EFTs for (heavy) axions

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

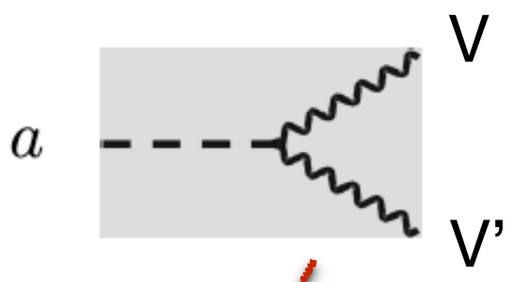
Georgi, Kaplan, Randall 1986

See also talk by R. Szafron yesterday

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



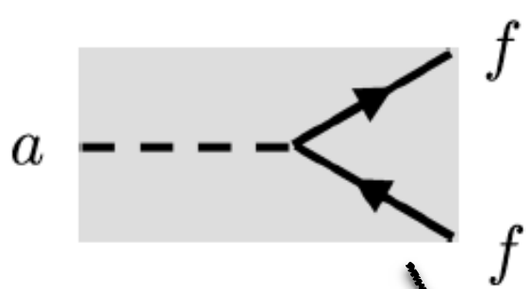
Minimal coupling expected if connection to the strong CP problem.



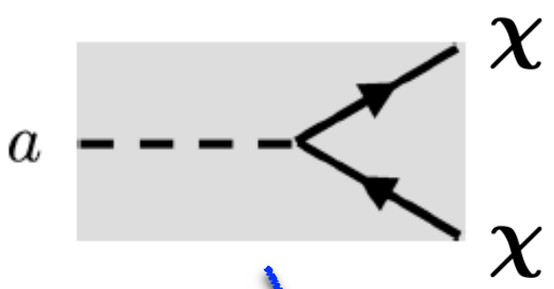
An axion-photon coupling is generated in the broken phase

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

This is the **main coupling** that has been considered for phenomenological studies of axions.



Possible flavor/ CP breaking and/or SU(2) breaking here (see later)



Coupling to DM (already discussed)

Lots of different production mechanisms at meson factories

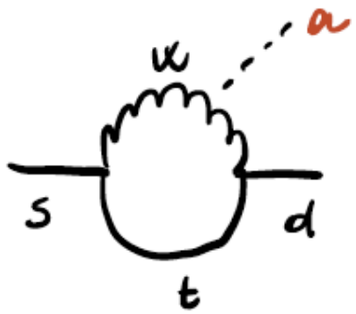
Neutral & charged current meson decays to ALPs

Flavor changing neutral current

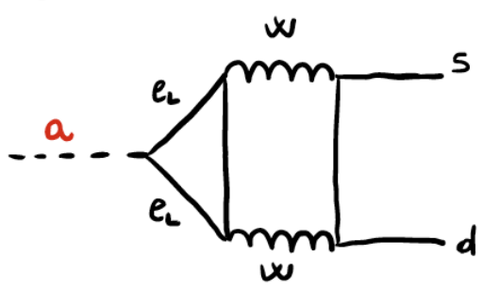
They arise in models with

* ALPs mixed with SM neutral pions
  (e.g. $K^+ \to \pi^+\pi^0 \Rightarrow K^+ \to \pi^+ a$)

* ALPs coupling to W or tops



* ALPs coupling to leptons
  (higher loop)



$$
\begin{aligned}
K_L &\to \pi^0 a \\
K^+ &\to \pi^+ a \\
B &\to K a
\end{aligned}
$$

* Flavor violating ALPs

Most studied (both th. and exp.)

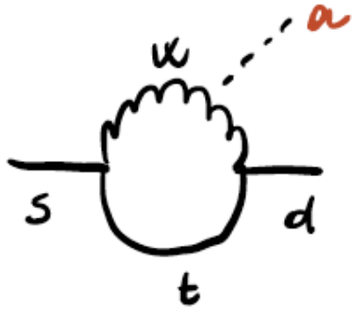
Neutral & charged current meson decays to ALPs

Flavor changing neutral current

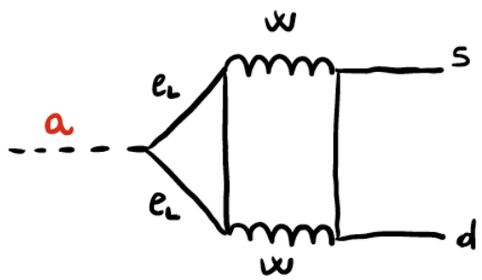
They arise in models with

* ALPs mixed with SM neutral pions
  (e.g. $K^+ \to \pi^+\pi^0 \Rightarrow K^+ \to \pi^+ a$)

* ALPs coupling to W or tops



* ALPs coupling to leptons
  (higher loop)



* Flavor violating ALPs

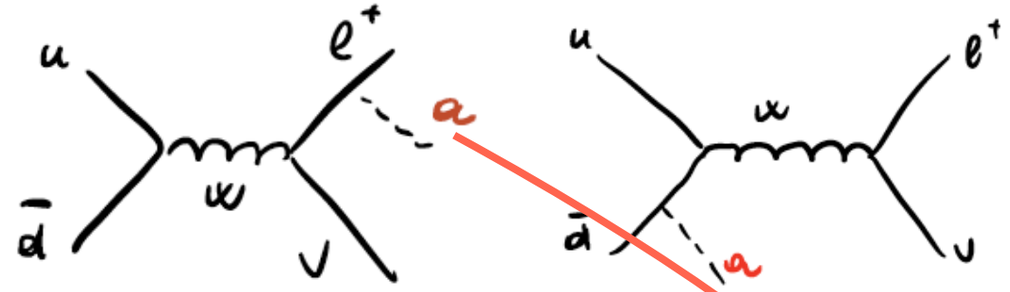
$$K_L \to \pi^0 a$$
$$K^+ \to \pi^+ a$$
$$B \to K a$$

Charged current

They arise in models with

- ALPs mixed with SM neutral pions
  (e.g. $\pi^+ \to \ell^+\nu\pi^0 \Rightarrow \pi^+ \to \ell^+\nu a$)

- ALPs coupling to leptons or quarks



$$\pi^+ \to a\ell^+\nu$$
$$K^+ \to a\ell^+\nu$$
$$B^+ \to a\ell^+\nu$$

These ALPs can also be produced by HPS in electron bremsstrahlung

Most studied (both th. and exp.)

Neutral & charged current meson decays to ALPs

Flavor changing neutral current

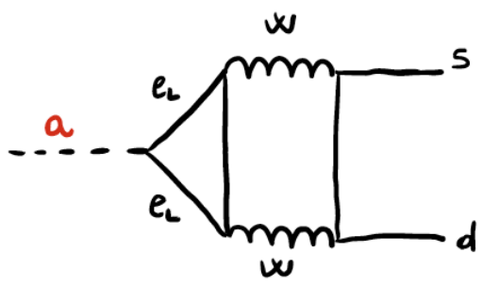
They arise in models with

* ALPs mixed with SM neutral pions
  (e.g. $K^+ \to \pi^+\pi^0 \Rightarrow K^+ \to \pi^+ a$)

* ALPs coupling to W or tops



* ALPs coupling to leptons
  (higher loop)



$$\begin{aligned} K_L &\to \pi^0 a \\ K^+ &\to \pi^+ a \\ B &\to K a \end{aligned}$$

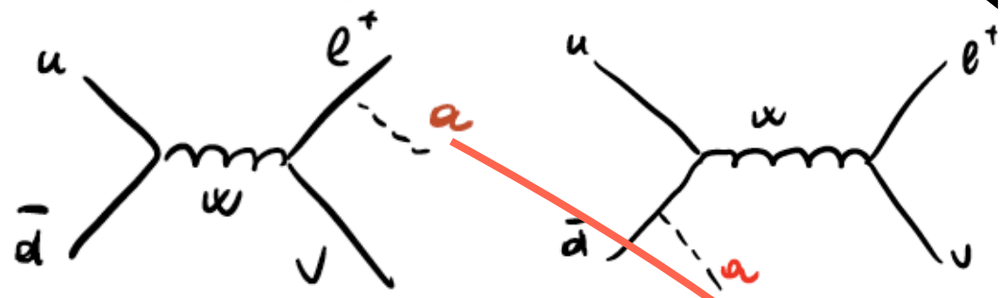
* Flavor violating ALPs

Charged current

They arise in models with

- ALPs mixed with SM neutral pions
  (e.g. $\pi^+ \to \ell^+\nu\pi^0 \Rightarrow \pi^+ \to \ell^+\nu a$)

- ALPs coupling to leptons or quarks



$$\begin{aligned} \pi^+ &\to a\ell^+\nu \\ K^+ &\to a\ell^+\nu \\ B^+ &\to a\ell^+\nu \end{aligned}$$

These ALPs can also be produced by HPS in electron bremsstrahlung

Most studied (both th. and exp.)

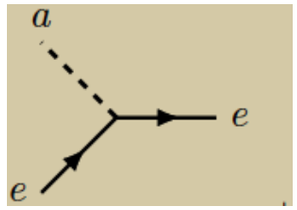
Example scenario: Lepton-coupled ALPs

$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

$$\mathcal{L}=-a\partial_\mu j^\mu_{PQ}$$

$$\partial_\mu j^\mu_{\rm PQ}=g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)$$

"Standard" vertex



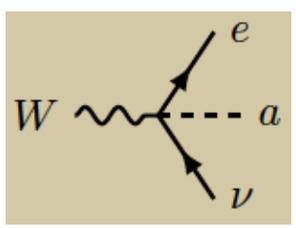
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}+g_{\nu_\ell}}{4s^2_W}W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$

$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}(1-4s^2_W)}{2c_W s_W}F_{\mu\nu}\tilde{Z}^{\mu\nu}-g_{\ell\ell}F_{\mu\nu}\tilde{F}^{\mu\nu}+$$

$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}(1-4s^2_W)-g_{\ell\ell}(1-4s^2_W+8s^4_W)+g_\nu}{8s^2_W c^2_W}Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$+\frac{ig}{2\sqrt{2}m_\ell}(g_{\ell\ell}-\bar{g}_{\ell\ell}+g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L\nu)W^-_\mu$$

Weak vertex



(only present for **SU(2) weak-violating** models)

$$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$$

Example scenario: Lepton-coupled ALPs

$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

$$\mathcal{L}=-a\partial_\mu j^\mu_{PQ}$$

$$\partial_\mu j^\mu_{\rm PQ}=g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)$$

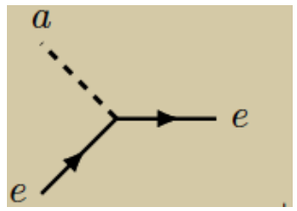
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}+g_{\nu_\ell}}{4s_W^2}W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$

$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}(1-4s_W^2)}{2c_W s_W}F_{\mu\nu}\tilde{Z}^{\mu\nu}-g_{\ell\ell}F_{\mu\nu}\tilde{F}^{\mu\nu}+$$

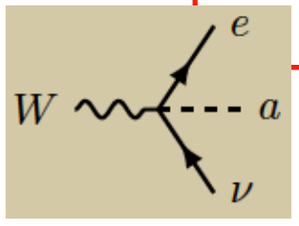
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}(1-4s_W^2)-g_{\ell\ell}(1-4s_W^2+8s_W^4)+g_\nu}{8s_W^2c_W^2}Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$+\frac{ig}{2\sqrt{2}m_\ell}(g_{\ell\ell}-\bar{g}_{\ell\ell}+g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L\nu)W^-_\mu$$

"Standard" vertex



Weak vertex



(only present for **SU(2) weak-violating** models)

$$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$$

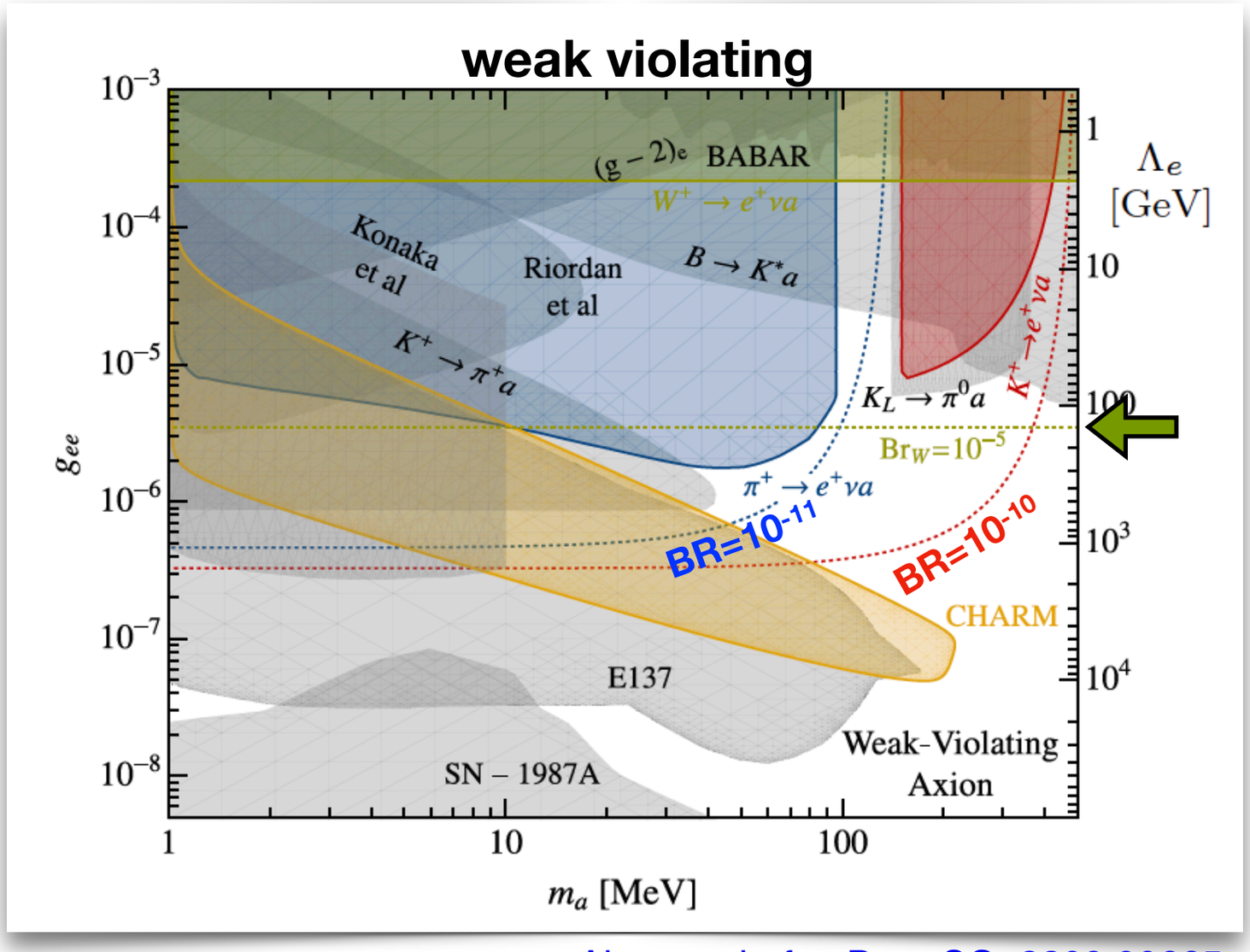
Enhancement of the charged-current decays:

$$\Gamma_{\pi^+\to e^+\nu a}\propto g_{ee}^2\frac{m_\pi^3 f_\pi^2}{m_W^4}$$ "standard" vertex

$$\Gamma_{\pi^+\to e^+\nu a}\propto \frac{m_\pi^2}{m_e^2}g_{ee}^2\frac{m_\pi^3 f_\pi^2}{m_W^4}$$ weak vertex

Altmannshofer, Dror, SG, 2209.00665

Example scenario: Lepton-coupled ALPs



Other probes?

Altmannshofer, Dror, SG, 2209.00665

Gray: neutral current decays K→π **a**, B→K **a**

Blue: π→ev**a**→ev(ee), interpretation from SINDRUM search, ‘80s

Red: K → ev**a**→ev(ee), interpretation from E865, ’00s

Green: W→ ev**a**→ev(ee) **exotic W boson decay**

No targeted searches yet!

Future

PIONEER

NA62

LHC

Take home messages

Dark sectors - i.e. new particles not charged under the SM gauge symmetries - very often arise in well-motivated beyond the SM theories.

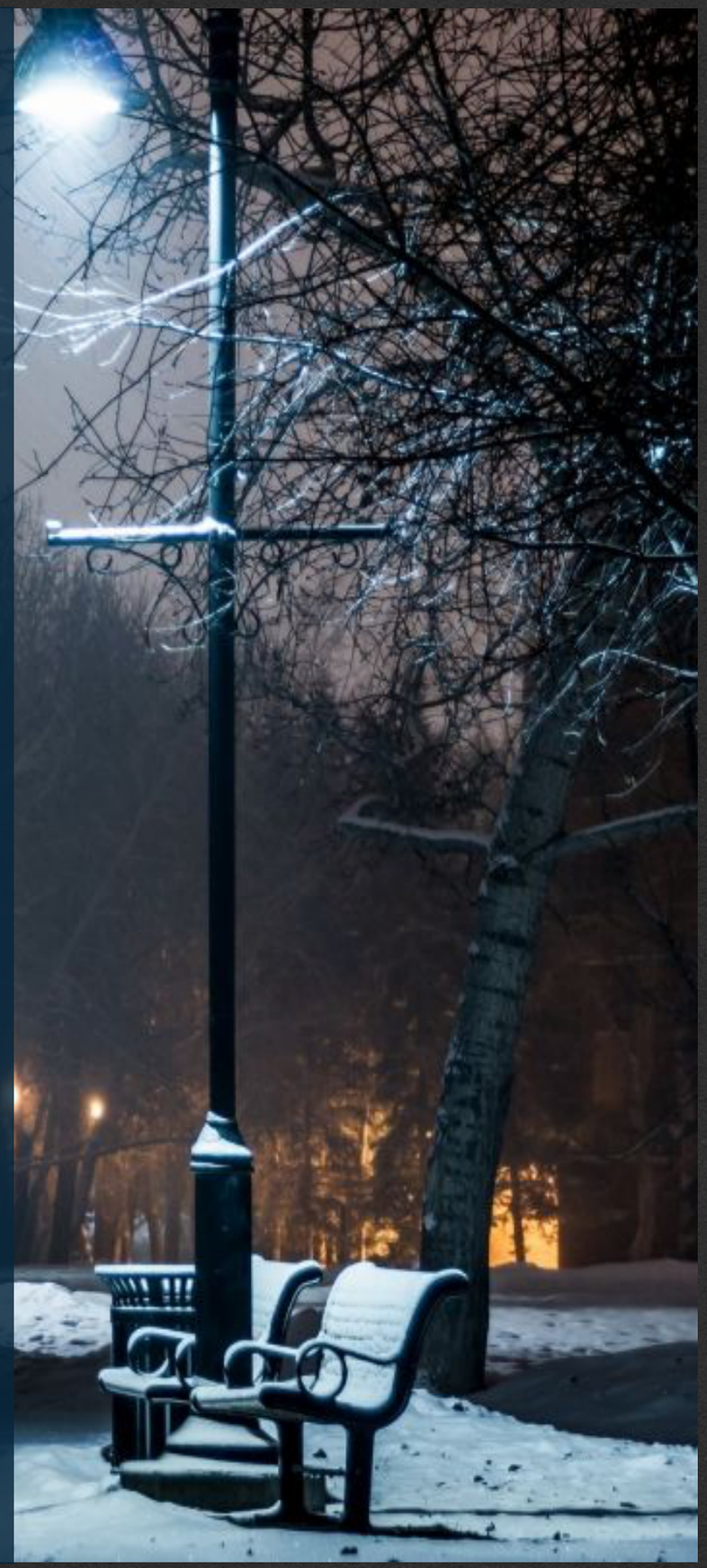
They can address open problems in particle physics (origin of Dark matter (DM), hierarchy problem, strong CP problem, origin of neutrino masses, …)

Secluded and non-secluded DM models

- interplay between searches for the mediator (dark photons, axions) and DM direct and indirect detection
- Novel way to look for spin-dependent DM-nucleus interactions: phonon excitations

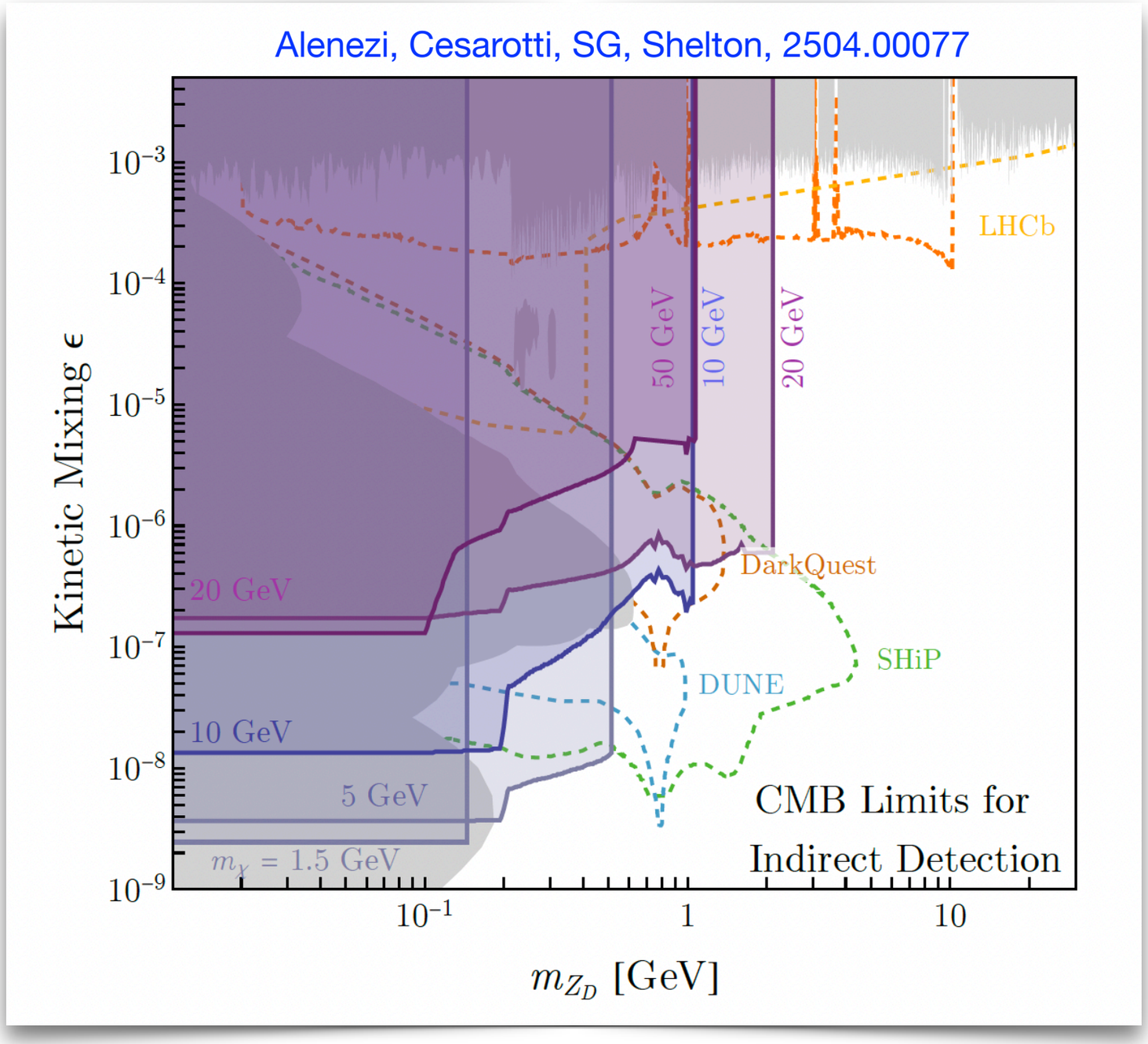
Heavy axion (or ALP) effective field theory

- Many different production channels at meson factories
- New signatures to look for

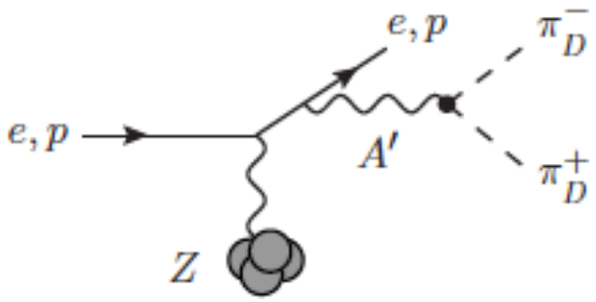


CMB constraints on secluded DM

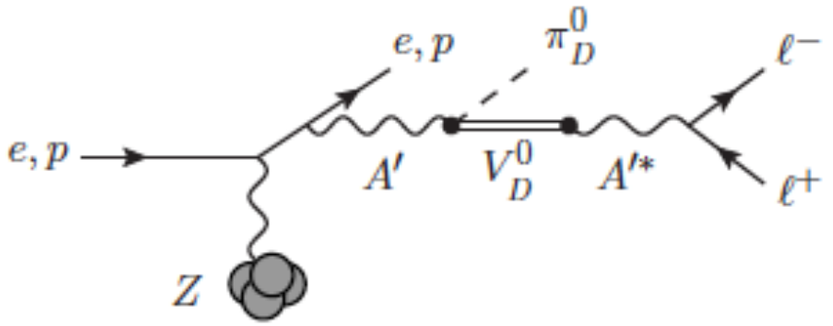
Alenezi, Cesarotti, SG, Shelton, 2504.00077

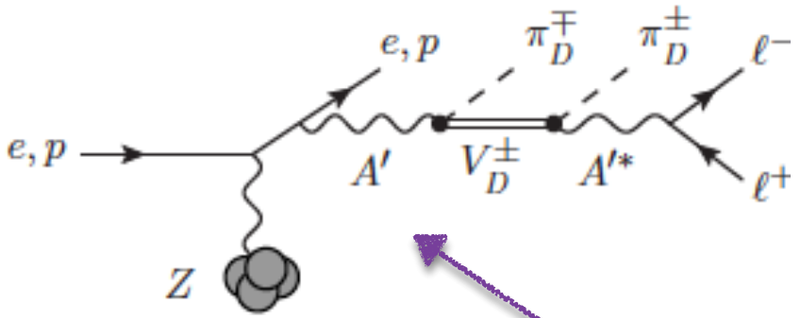


SIMP experimental signals



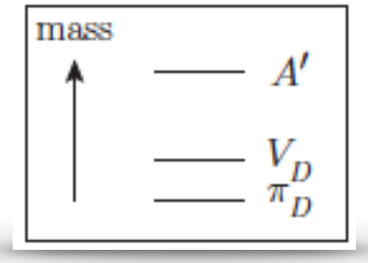
Invisible
A' decay



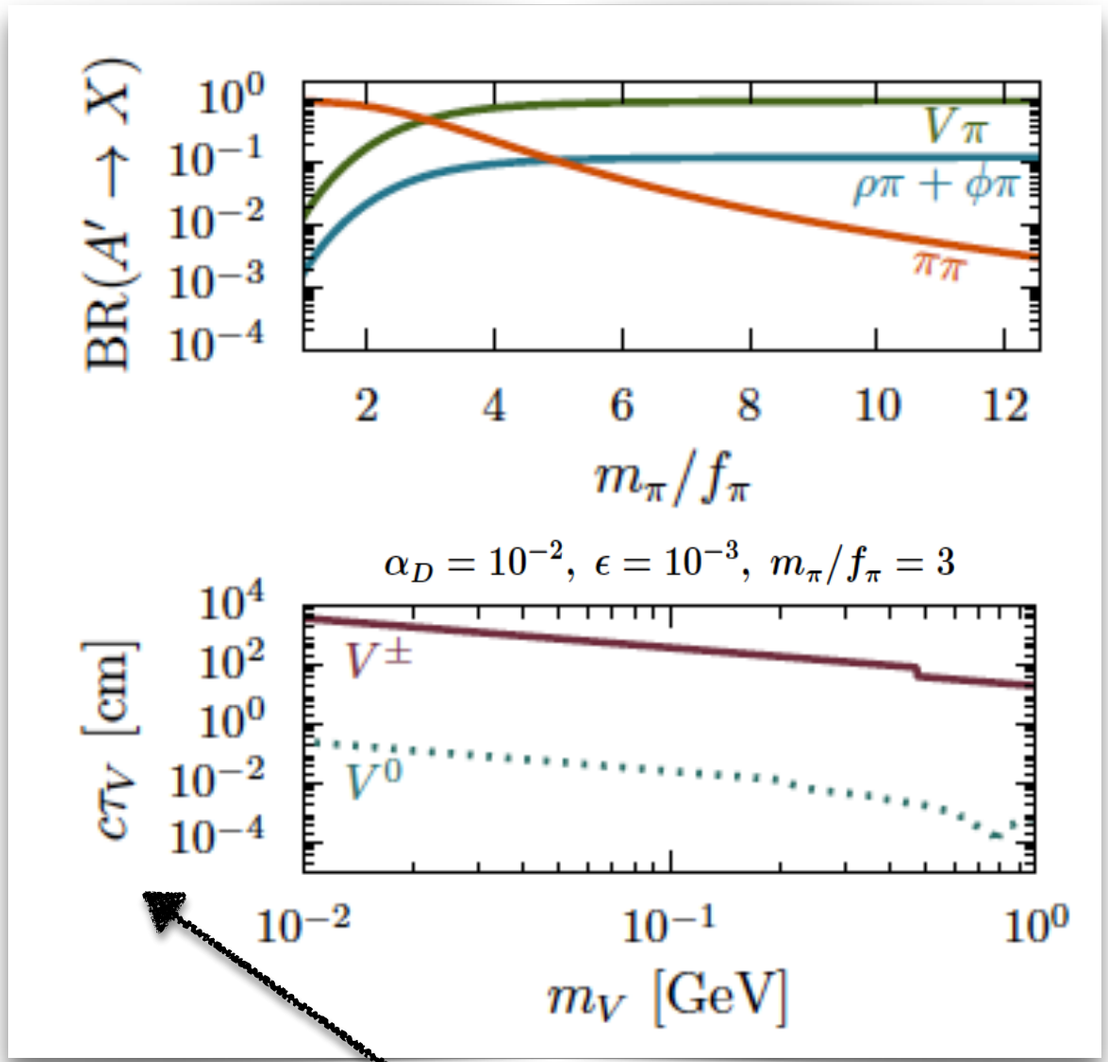


Visible
A' decay

Similar to the
IDM signature



Berlin, Blinov, SG, Schuster, Toro



The vectors are
generically long-lived

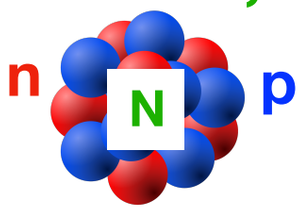
Our extension to spin-dependent interactions

SG, Knapen, Lin, Munbodh, Suter, 2506.11191

Nuclei, N

$$\mathcal{H}^N = -\frac{g_\chi g_N}{q_0^2 + m_{\rm med}^2} F_{\rm med}(\mathrm{q})\, \mathcal{O}\left(\mathbf{J}_\chi, \mathrm{q}\right) \cdot \mathbf{J}\, e^{i\mathrm{q}\cdot\mathrm{r}} \qquad g_N \equiv g_p f_p + g_n f_n$$

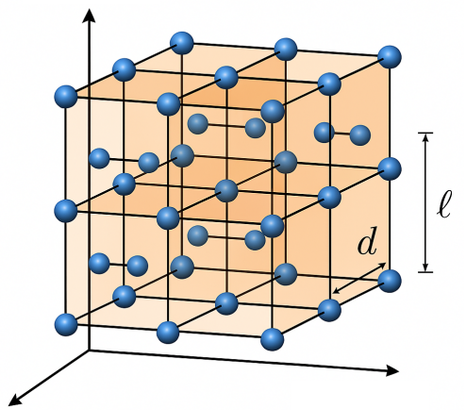
Using the Wigner-Eckart theorem: $f_{p/n} = \dfrac{\langle JJ|S^{\rm tot,z}_{p/n}|JJ\rangle}{J}$ nuclear form factors



matching

Crystal

$$\mathcal{H}^c(q) = -\frac{g_\chi g_p}{q_0^2 + m_{\rm med}^2} F_{\rm med}(\mathrm{q}) \sum_{\ell,d} \lambda_{\ell,d} \mathcal{O}\left(\mathbf{J}_\chi, \mathrm{q}\right) \cdot \mathbf{J}_{\ell,d}\, e^{i\mathrm{q}\cdot\mathrm{r}_{\ell,d}} \qquad \lambda_{\ell,d} = \frac{g_{N_{\ell,d}}}{g_p}$$



we consider an unpolarized crystal

random spin states

$$\Gamma = \frac{2\pi}{V} \sum_{i,f} \sum_{i_\chi, f_\chi} w_i w_{i_\chi} \int \frac{d^3q}{(2\pi)^3} |\langle f, f_\chi|\mathcal{H}^c(q)|i, i_\chi\rangle|^2 \delta(E_f - \omega - E_i)$$

ω = energy deposited by DM
i (f) = initial (final) state of the crystal
i_χ, f_χ = initial (final) state of DM

$$|i\rangle = |i_s\rangle \otimes |0\rangle$$

$$\begin{cases} \Gamma = \dfrac{g_\chi^2 g_p^2}{(q_0^2 + m_{\rm med}^2)^2} \dfrac{N}{V} \displaystyle\int \frac{d^3\mathrm{q}}{(2\pi)^3} |F_{\rm med}(\mathrm{q})|^2 G(\mathrm{q}) S(\mathrm{q}, \omega) \\ G(\mathrm{q}) \equiv \dfrac{1}{3} \displaystyle\sum_{i_\chi} w_{i_\chi} \langle i_\chi|\mathcal{O}\left(\mathbf{J}_\chi, \mathrm{q}\right) \cdot \mathcal{O}\left(\mathbf{J}_\chi, \mathrm{q}\right)|i_\chi\rangle \quad \text{DM part of the rate} \\ S(\mathrm{q}, \omega) = \displaystyle\sum_d \overline{\lambda_d^2 J_d (J_d + 1)} C_{\ell,d}(\mathrm{q}, \omega), \quad C_{\ell,d}(\mathrm{q}, \omega) \equiv \int_{-\infty}^{+\infty} dt\, e^{i\omega t} \langle 0|e^{-i\mathrm{q}\cdot r_{\ell,d}(0)} e^{i\mathrm{q}\cdot r_{\ell,d}(t)}|0\rangle \end{cases}$$

Crystal part of the rate

different than in the spin-independent case

computed for spin-independent interactions (expansion in the number of phonons)

DM-crystal interaction rate (more details)

$$\Gamma = \frac{2\pi}{V}\sum_{i,f}\sum_{i_\chi,f_\chi} w_i w_{i_\chi}\int\frac{d^3q}{(2\pi)^3}|\langle f,f_\chi|\mathcal{H}^c(q)|i,i_\chi\rangle|^2\delta(E_f-\omega-E_i)$$

energy deposited by DM into the crystal

Fourier transform:

$$\Gamma = \frac{1}{V}\int_{-\infty}^{+\infty}dt\int\frac{d^3q}{(2\pi)^3}\sum_{i,f}\sum_{i_\chi,f_\chi} w_i w_{i_\chi}\langle i,i_\chi|\mathcal{H}^{c\dagger}|f,f_\chi\rangle\langle f,f_\chi|e^{-iE_f t}\mathcal{H}^c e^{iE_i t}|i,i_\chi\rangle e^{i\omega t}$$

eigenvalues of the crystal Hamiltonian

$$= \frac{1}{V}\int_{-\infty}^{+\infty}dt\, e^{i\omega t}\int\frac{d^3q}{(2\pi)^3}\sum_{i,i_\chi} w_i w_{i_\chi}\langle i,i_\chi|\mathcal{H}^c(0)^\dagger\mathcal{H}^c(t)|i,i_\chi\rangle$$

$$\Gamma = \frac{1}{V}\frac{g_\chi^2 g_p^2}{(q_0^2+m_{\rm med}^2)^2}\int_{-\infty}^{+\infty}dt\, e^{i\omega t}\int\frac{d^3q}{(2\pi)^3}|F_{\rm med}(\mathrm{q})|^2\times \sum_{\alpha,\beta=x,y,z}\left[\sum_{i_\chi} w_{i_\chi}\langle i_\chi|\mathcal{O}\left(\mathrm{J}_\chi,\mathrm{q}\right)^\alpha\mathcal{O}\left(\mathrm{J}_\chi,\mathrm{q}\right)^\beta|i_\chi\rangle\right]\times \left[\sum_i w_i\sum_{\ell,d;\ell',d'}\lambda_{\ell,d}\lambda_{\ell',d'}\langle i|J^\alpha_{\ell,d}e^{-iq\cdot r_{\ell,d}(0)}J^\beta_{\ell',d'}e^{iq\cdot r_{\ell',d'}(t)}|i\rangle\right]$$

→

* nuclear spin orientations are isotropically distributed;
* $\ell\neq\ell'$, $d\neq d'$ average to zero when summed over all initial nuclear spin configurations

$$J^\alpha_{\ell,d}J^\beta_{\ell',d'}\rightarrow\frac{1}{3}\delta^{\alpha\beta}\delta_{\ell\ell'}\delta_{dd'}J^2_{\ell,d}$$

$$\Gamma = \frac{g_\chi^2 g_p^2}{(q_0^2+m_{\rm med}^2)^2}\frac{N}{V}\int\frac{d^3\mathrm{q}}{(2\pi)^3}|F_{\rm med}(\mathrm{q})|^2 G(\mathrm{q})S(\mathrm{q},\omega)$$

$$S(q,\omega) = \frac{1}{N}\sum_{\ell,d}\lambda^2_{\ell,d}C_{\ell,d}(q,\omega)\sum_{i_s}w_{i_s}\langle i_s|J^2_{\ell,d}|i_s\rangle = \sum_d\overline{\lambda^2_d J_d(J_d+1)}C_{\ell,d}(\mathrm{q},\omega)$$

$$C_{\ell,d}(q,\omega) \equiv \int_{-\infty}^{+\infty}dt\, e^{i\omega t}\langle 0|e^{-iq\cdot r_{\ell,d}(0)}e^{iq\cdot r_{\ell,d}(t)}|0\rangle$$

DM-crystal interaction rate (more details)

$$\Gamma = \frac{2\pi}{V}\sum_{i,f}\sum_{i_\chi,f_\chi} w_i w_{i_\chi}\int\frac{d^3q}{(2\pi)^3}|\langle f,f_\chi|\mathcal{H}^c(q)|i,i_\chi\rangle|^2\delta(E_f-\omega-E_i)$$

energy deposited by DM into the crystal

Fourier transform:

$$\Gamma = \frac{1}{V}\int_{-\infty}^{+\infty}dt\int\frac{d^3q}{(2\pi)^3}\sum_{i,f}\sum_{i_\chi,f_\chi} w_i w_{i_\chi}\langle i,i_\chi|\mathcal{H}^{c\dagger}|f,f_\chi\rangle\langle f,f_\chi|e^{-iE_f t}\mathcal{H}^c e^{iE_i t}|i,i_\chi\rangle e^{i\omega t}$$

eigenvalues of the crystal Hamiltonian

$$= \frac{1}{V}\int_{-\infty}^{+\infty}\dots$$

$$\Gamma = \dots \to \frac{1}{3}\delta^{\alpha\beta}\delta_{\ell\ell'}\delta_{dd'}J^2_{\ell,d}$$

Correlation function computed in Campbell-Deem et al., 2205.02250
(in the context of spin-independent transitions)

$$C_{\ell,d}(q,\omega) = 2\pi e^{-2W_d(q)}\sum_{n=1}^{\infty}\frac{1}{n!}\left(\frac{q^2}{2m_d}\right)^n\prod_{i=1}^{n}\int d\omega_i\frac{D_d(\omega_i)}{\omega_i}\delta\left(\sum_{i=1}^{n}\omega_i-\omega\right)$$

Debye-Waller factor: $W_d(q)\equiv\frac{q^2}{4m_d}\int d\omega'\frac{D_d(\omega')}{\omega'}$

$$\Gamma = \frac{g_\chi^2 g_p^2}{(q_0^2+m_{\rm med}^2)^2}\frac{N}{V}\int\frac{d^3q}{(2\pi)^3}|F_{\rm med}(q)|^2 G(q) S(q,\omega)$$

$$S(q,\omega) = \frac{1}{N}\sum_{\ell,d}\lambda^2_{\ell,d}C_{\ell,d}(q,\omega)\sum_{i_s}w_{i_s}\langle i_s|J^2_{\ell,d}|i_s\rangle = \sum_d\overline{\lambda_d^2 J_d(J_d+1)}C_{\ell,d}(q,\omega)$$

$$C_{\ell,d}(q,\omega) \equiv \int_{-\infty}^{+\infty}dt\, e^{i\omega t}\langle 0|e^{-iq\cdot r_{\ell,d}(0)}e^{iq\cdot r_{\ell,d}(t)}|0\rangle$$

More details on matrix element calculations

From nucleon to nucleus matrix element:

$$\langle Jm_f|S^{\mathrm{tot},z}_{p/n}|Jm_i\rangle = f_{p/n}\langle Jm_f|J|Jm_i\rangle \Rightarrow f_{p/n} = \frac{\langle JJ|S^{\mathrm{tot},z}_{p/n}|JJ\rangle}{J}$$

Wigner-Eckart theorem

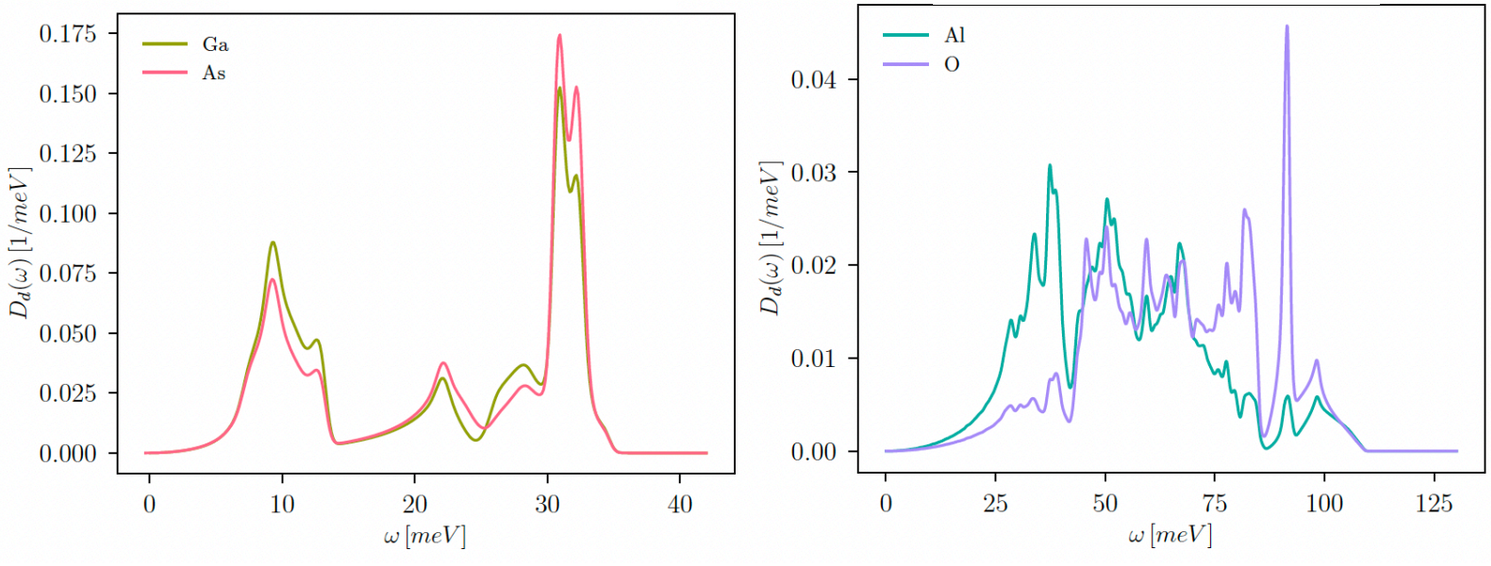
Computed using Shell-model or Odd-Group Model

Phonon part of the matrix element. Summing over phonon excitations, n:

$$C_{\ell,d}(q,\omega) = 2\pi e^{-2W_d(q)} \sum_{n=1}^{\infty} \frac{1}{n!}\left(\frac{q^2}{2m_d}\right)^n \prod_{i=1}^{n} \int d\omega_i \frac{D_d(\omega_i)}{\omega_i} \delta\left(\sum_{i=1}^{n}\omega_i - \omega\right)$$

Sum converges to a Gaussian in the regime where q^2/m_d is much larger than the typical phonon frequency

phonon partial density of states, D_d:



Access to lower energy DM states

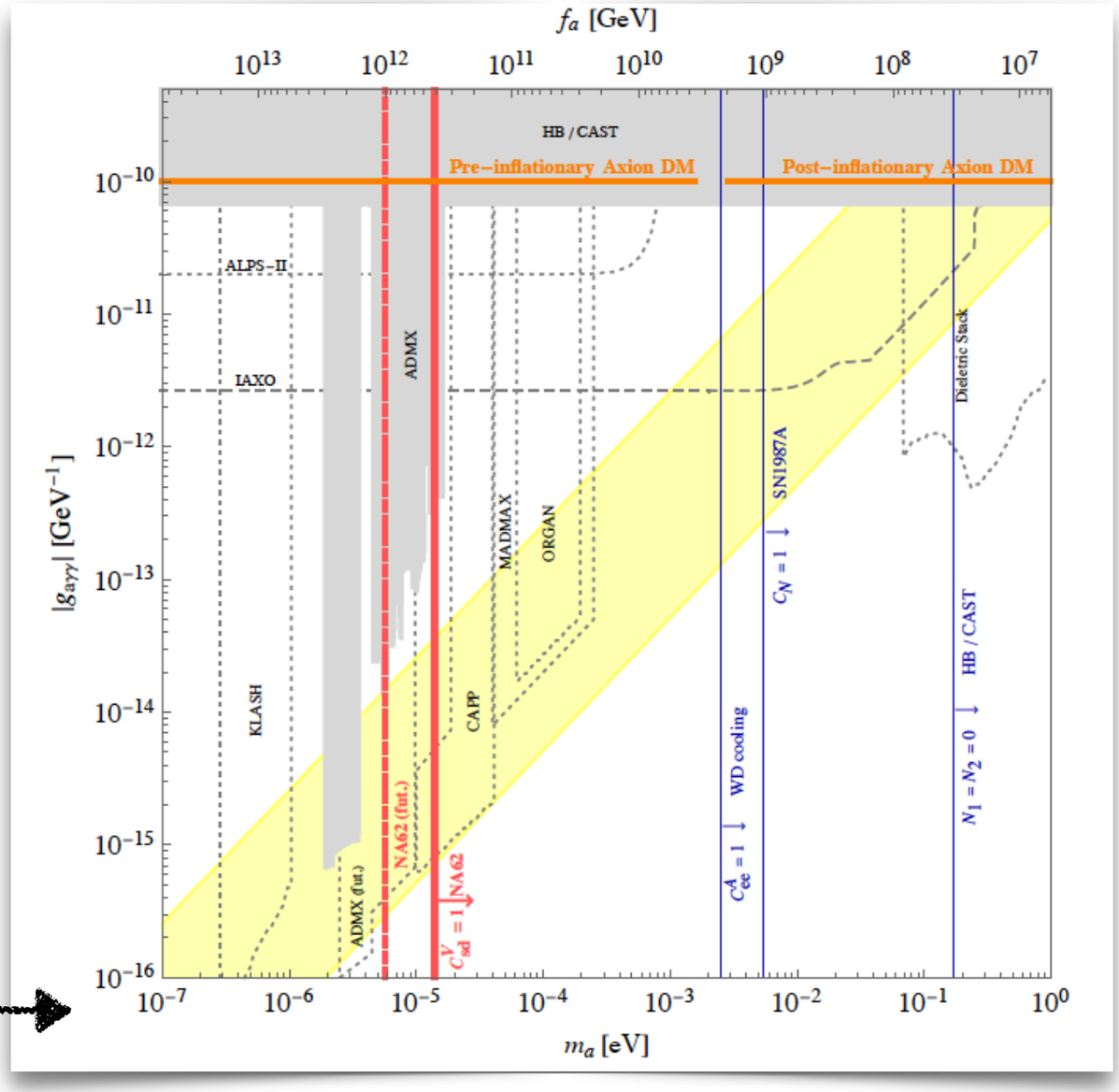
Flavor violating QCD axion

Kaon factories **can probe the QCD axion**, in the case of additional flavor violating couplings:

$$\mathcal{L} \supset \frac{\partial_\mu a}{2f_a} C_{sd}^V (\bar{s}\gamma^\mu d)$$

access to **very low masses** (sub-eV):

Goudzovski, et al., 2201.07805



now

future

$K^+ \to \pi^+ + \text{inv.}$ at NA62

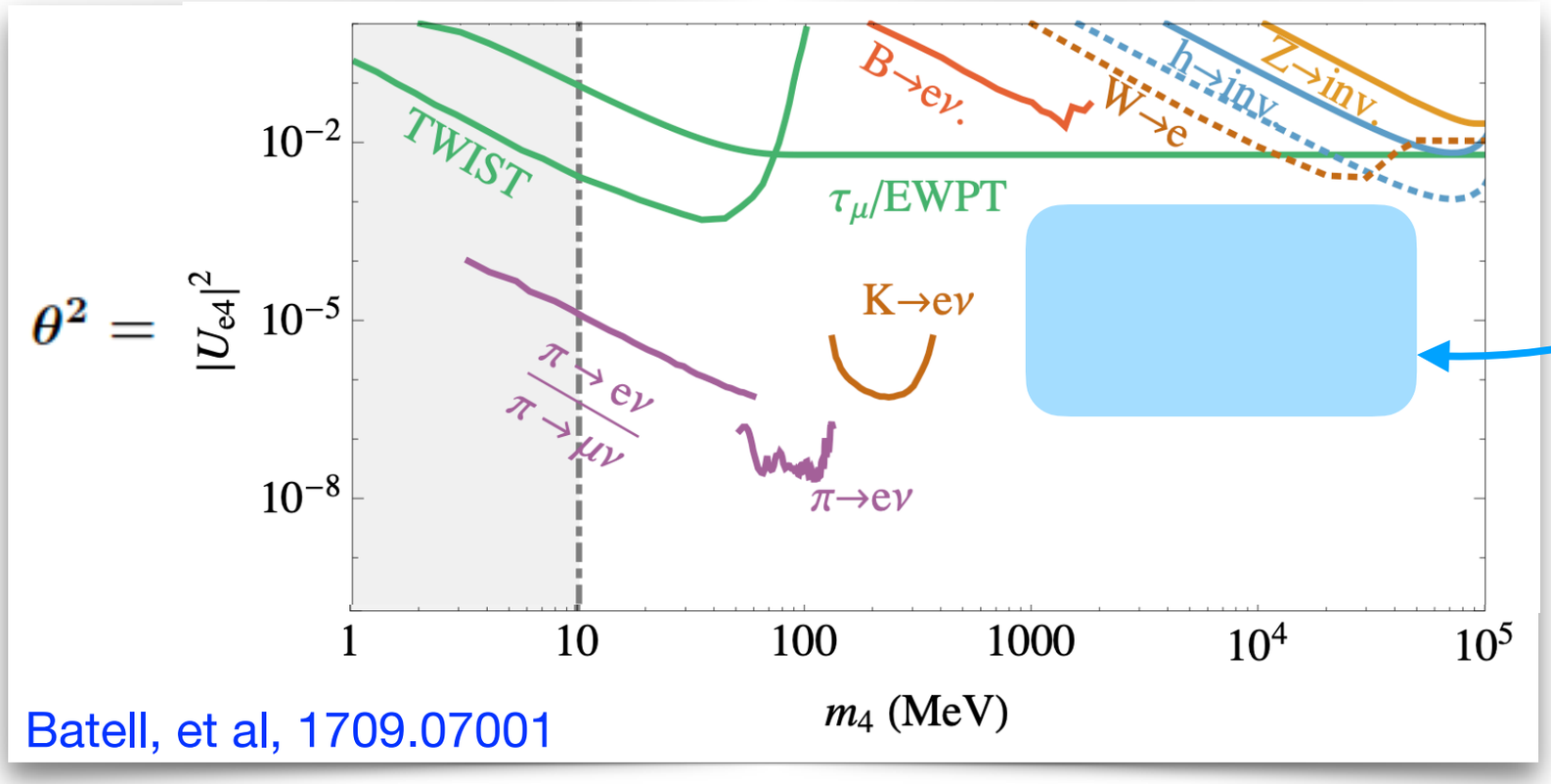
Example of weak violating axions

$$\mathcal{L} \supset -yHLN^c - Me^{ia/f_a}NN^c + \text{h.c.}$$

N (with Dirac partner N^c) charged under PQ

After EWSB, sterile neutrinos and SM neutrinos mix and

$$\mathcal{L} \supset \frac{\theta^2}{f_a}\partial_\mu a(\bar{\nu}_e\gamma^\mu P_L\nu_e) \Rightarrow \begin{cases} g_\nu = \frac{2\theta^2 m_e}{f_a} = 1.0\times10^{-5}\left(\frac{\theta}{0.1}\right)^2\left(\frac{\text{GeV}}{f_a}\right) \\ g_{ee} = \bar{g}_{ee} = 0 \end{cases}$$



Batell, et al, 1709.07001

additional constraints from visibly decaying HNL (less robust)

Similar construction for vector-like leptons charged under PQ:

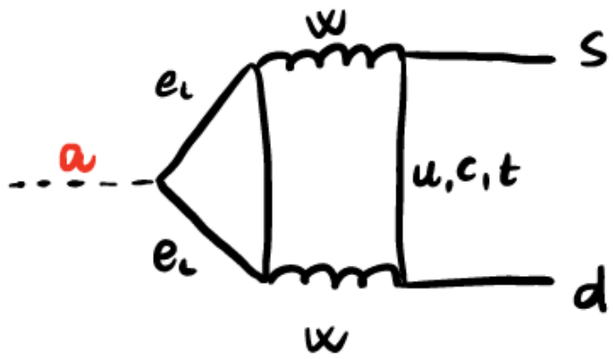
$$\bar{g}_{ee} - g_{ee} \neq 0, \quad g_{\nu_e} = 0$$

Complementarity with neutral current decays

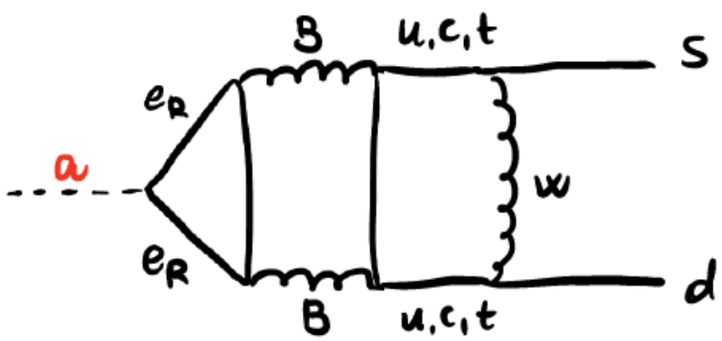
Neutral current meson decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

$K \to \pi a$

1. ALP with LH coupling



2. ALP with RH coupling



Similar diagrams for $B \to K^{(*)} a$

Main bounds: reinterpreting past data

NA62, 2103.15389: $K^+ \to \pi^+ + (a \to \text{invisible})$

KTeV, 0309072: $K_L \to \pi^0 (a \to e^+ e^-)$

m_{ee} in (140, 363) MeV

777 @ BNL, Phys. Rev. Lett. 59 (1987) 2832–2835:

$K^+ \to \pi^+ (a \to e^+ e^-)$ $m_a < 100$ MeV

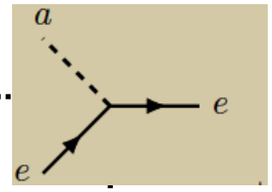
see also Alves, Weiner, 1710.03764

LHCb, 1501.03038: $B^0 \to K^{(*)0} (a \to e^+ e^-)$

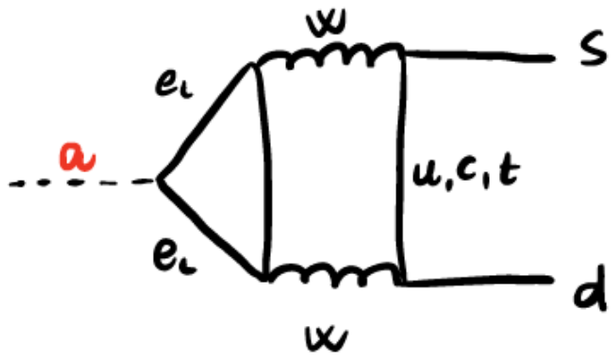
Complementarity with neutral current decays

Neutral current meson decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

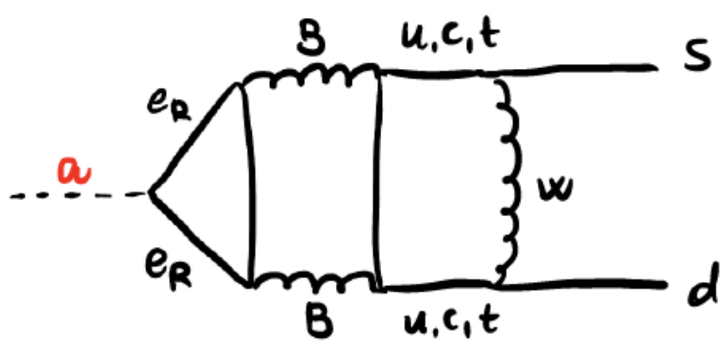
$K \to \pi a$



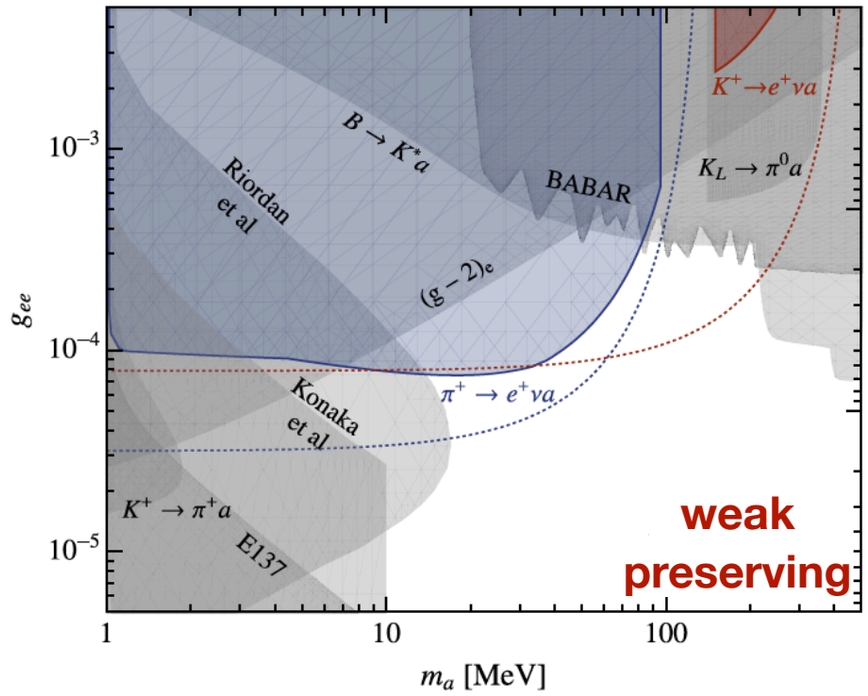
1. ALP with LH coupling

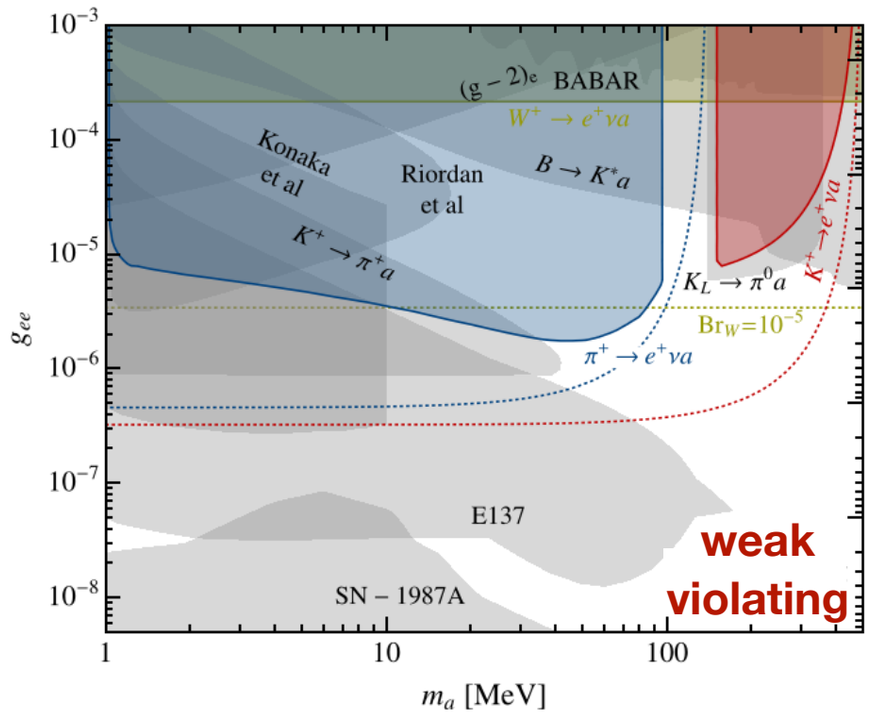


2. ALP with RH coupling



Similar diagrams for $B \to K^{(*)} a$

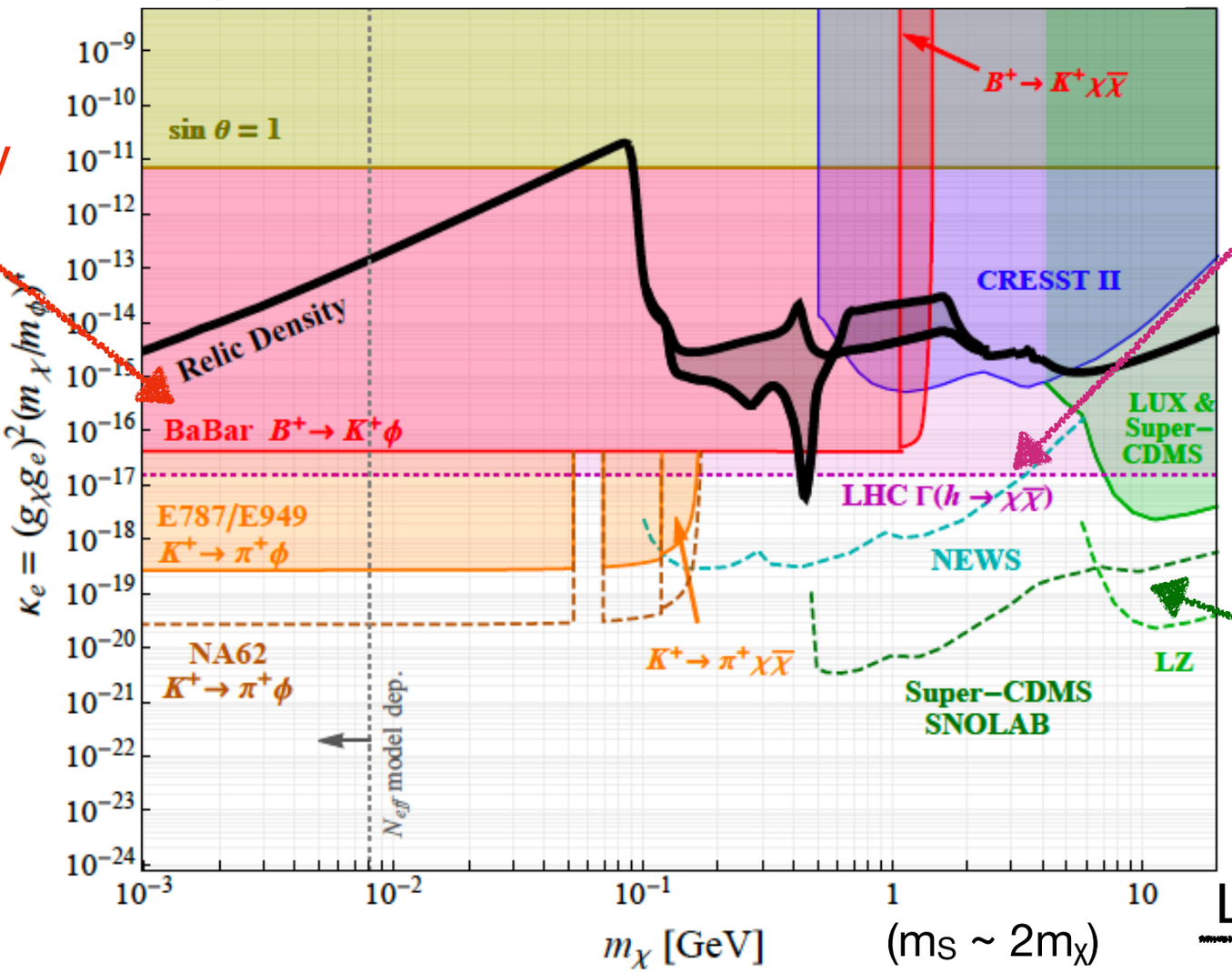




Invisible dark sectors at B-factories

The dark Higgs, S, can decay (invisibly) to dark matter particles, χ, and then…

Krnjaic, 1512.04119



(Past) B-factory BaBar

LHC search for Higgs **exotic decay** (to invisible)

Direct detection experiments

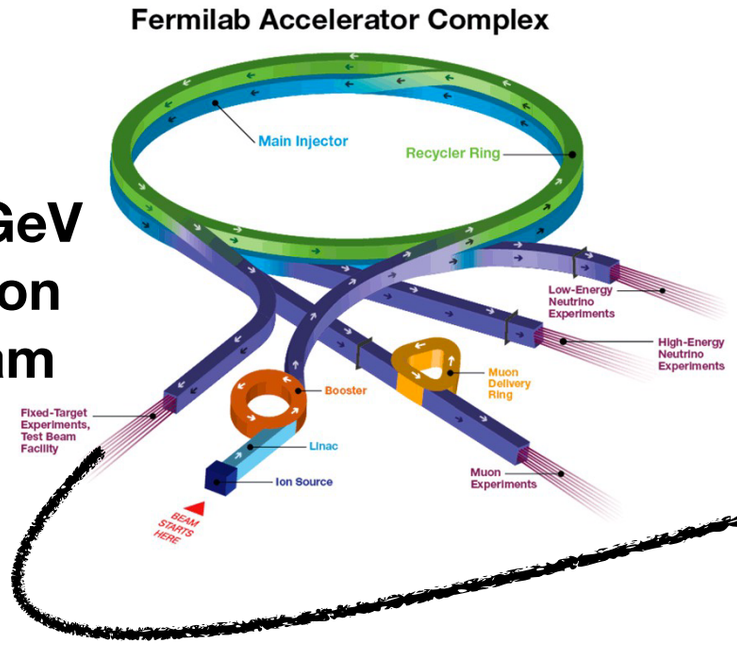
Belle II will record ~ O(100) more data than Babar

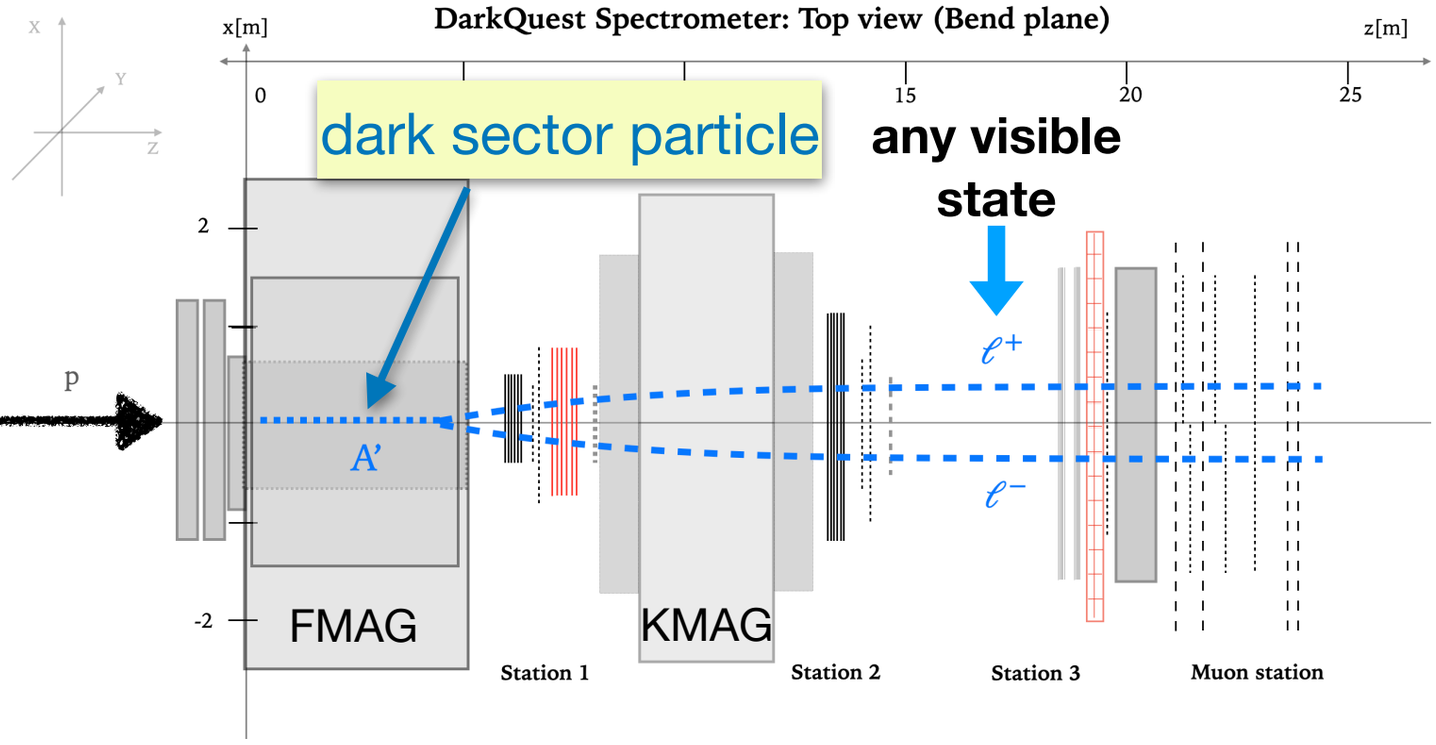
What regions will Belle-II be able to probe?

What about the other dark particles? axions, dark photons, dark neutrinos, …

The DarkQuest experiment

120 GeV proton beam





SpinQuest → DarkQuest

proposed upgrade
(calorimeter +
more tracking layers +
hodoscope for triggering)

Nuclear physics: Measuring the Drell-Yan muon process for studies of the proton structure

Particle Physics: Visible dark sector searches (any visible)

Initial proposal:
Berlin, SG, Schuster, Toro, 1804.00661