Light Dark Matter: Theory and experiment

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Outline

1. Introduction
2. Theory
3. Experiment
4. Conclusions

The main results and key references are contained in our reviews:

S.N.Gninenko, N.V.K, V.A.Matveev

Int.J.Mod.Phys. A39(2024)34, 2445006;

Usp.Fiz.Nauk 191 (2021)12, 1361;

Phys.Part.Nucl. 51(2020)5, 289

1. Introduction

The main motivation in favor of BSM physics is dark matter.

There are a lot of dark matter models.

For many years SUSY with R-parity was the most popular dark matter model.

However LHC failed to discover SUSY.

Other models became popular now.

We know that dark matter exists and it is cold (nonrelativistic) or warm

But we don’t know:

1. Spin of dark matter particles
2. Mass of dark matter particles
3. SM – DM interactions

In SUSY with R-parity conservation LSP is gaugino with s = ½ and m = O(100 GeV) as a rule

Dark matter constraints

1. Dark matter is nonrelativistic or warm

2. From PLANCK experimental (CMB bounds) data s-wave annihilation is

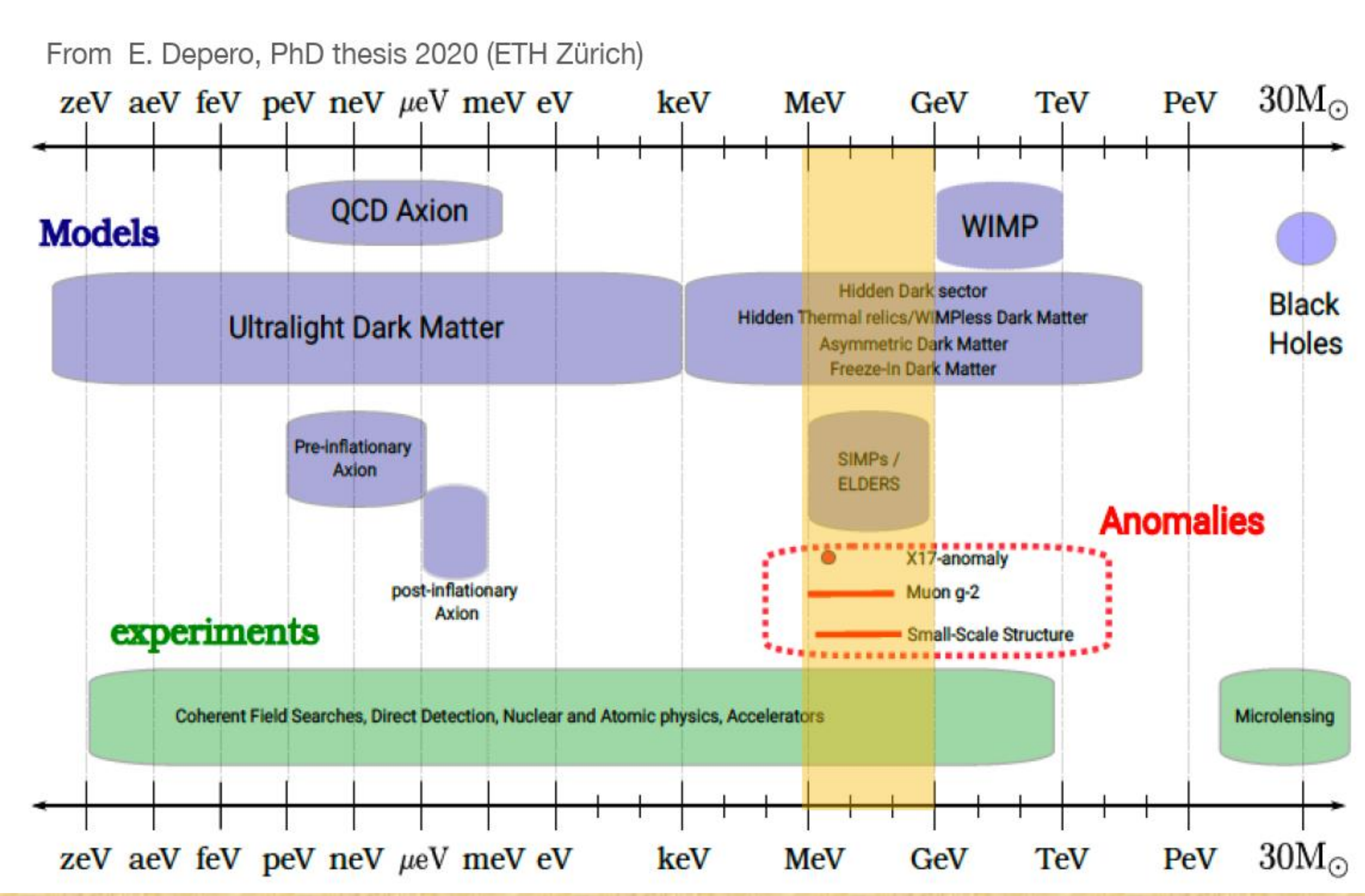
excluded for dark matter masses

$m_\chi \leq$ O(10) GeV

3. LDM constraints from BBN nucleosynthesis

$m_\chi \geq$ (3-10) MeV

Dark matter mass range



WIMP

The most popular mass interval from LHC point of view between O(1) GeV and O(1) TeV -> WIMP = weakly interacting massive particles

Also mass interval between O(1) MeV and O(1) GeV is popular for fixed target experiments like NA64, BELLE, SHIP, …

So called light dark matter

Typical models

At LHC searces depend on particular model. There are a lot of models.

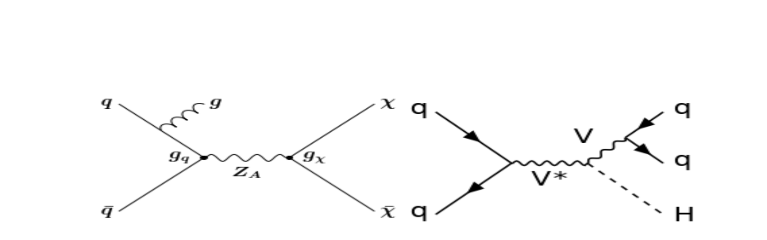
Simplified models:

A. Models with vector mediator

B. Models wth scalar mediator

Dark Matter: scalar, fermion, Majorana, vector Spin 1.

Accelerator searches



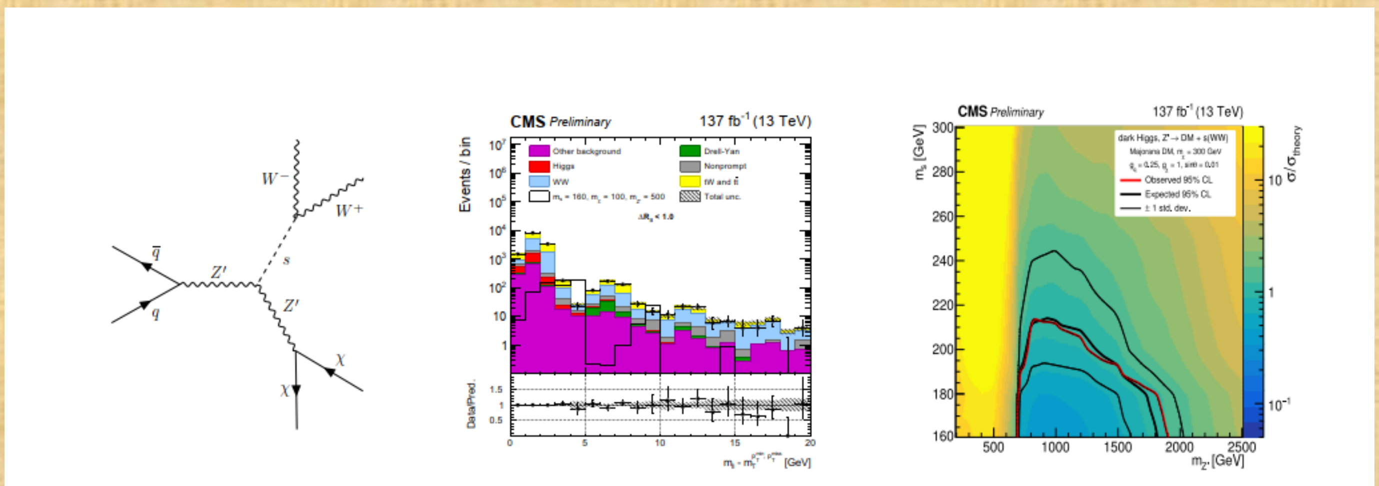
At LHC(CMS and ATLAS)

Use the reaction

proton + proton ->jet(s)+ (DM DM ->missing energy)

So the signature – hadron jet(s) +

missing energy



Underground experiments

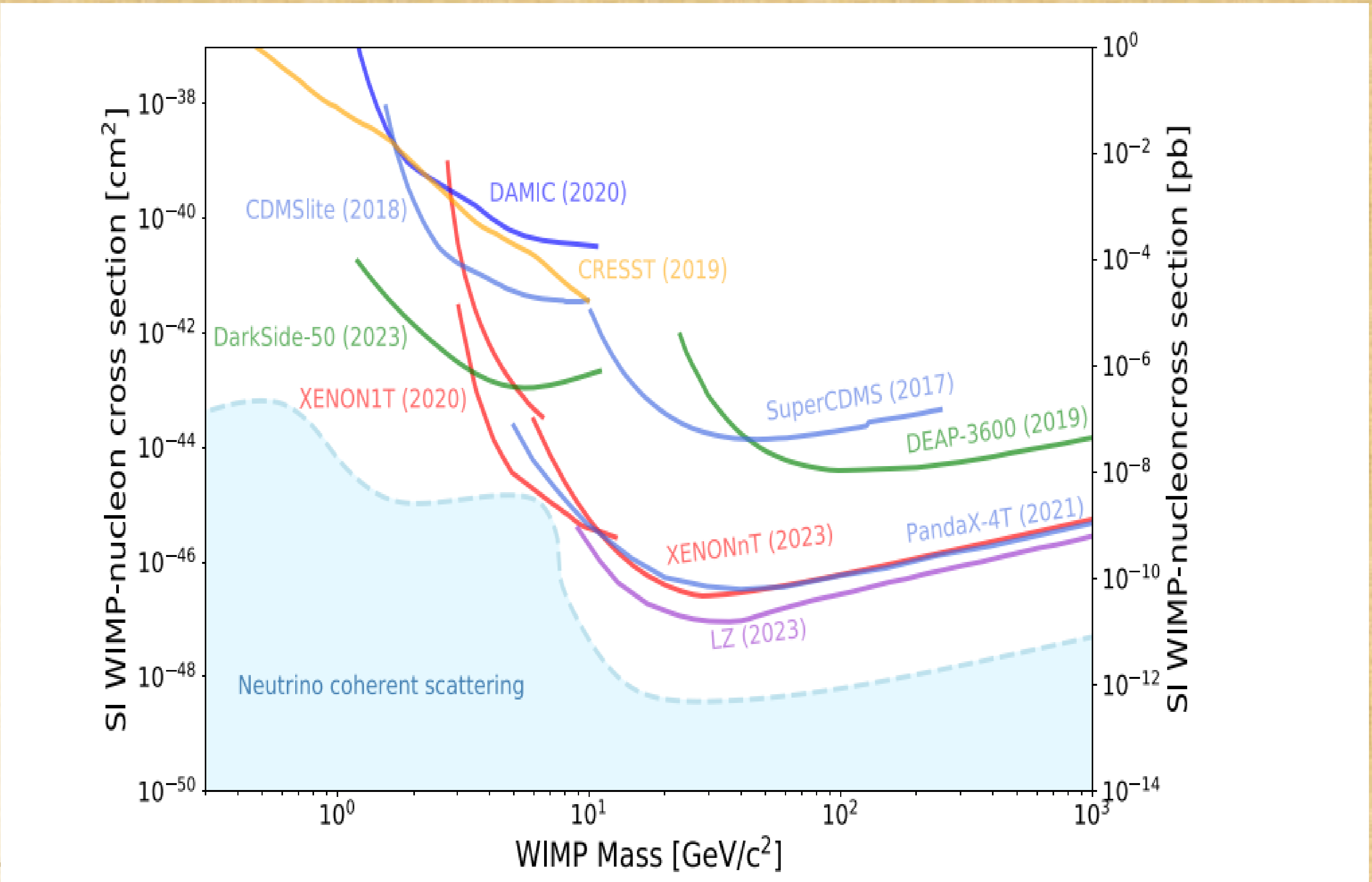
Direct detection of DM using the elastic scattering reaction

DM + (electron)nucleon -> DM + (electron)nucleon

For instance for model with additional vector (B-L) interaction nucleon DM cross section is

$$\sigma(DM + nucleon \to DM + nucleon) = \mu_{\chi N}^2 \frac{g_{B-L}^2 g_\chi^2}{\pi m_{Z'}^4},$$

Elastic DM nucleon cross sections bounds . Bounds from underground experiments. Particle data



1.Introduction

Implications from underground and accelerator experiments for different

DM models are contained in review:

M.Lindner et al., arXiv:2403.15860

A lot of models at the level of exclusion

In many cases there are very strong constraints (for instance B-L model with additional vector bozon)

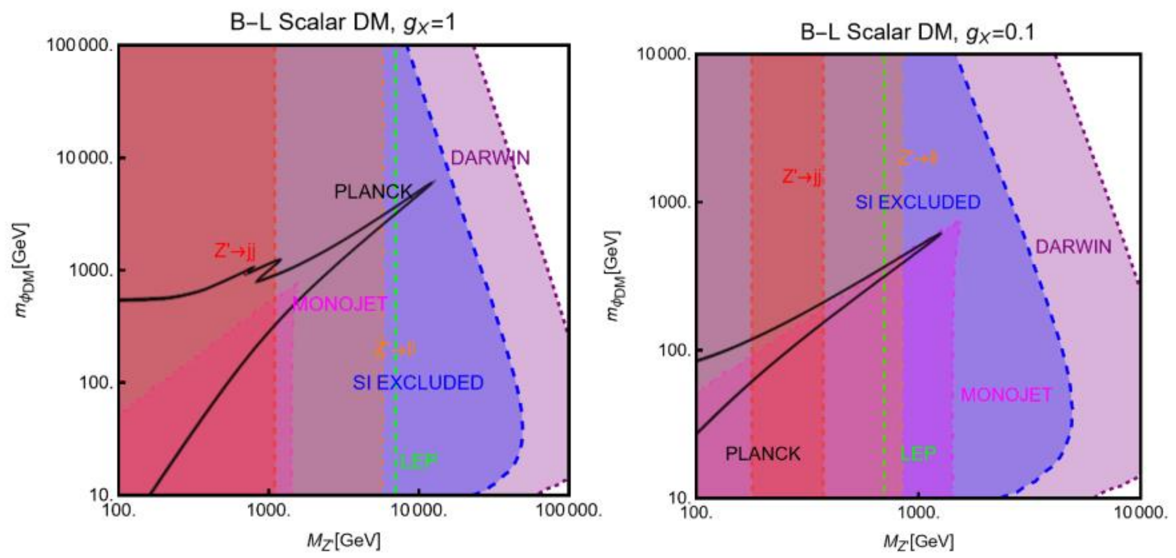
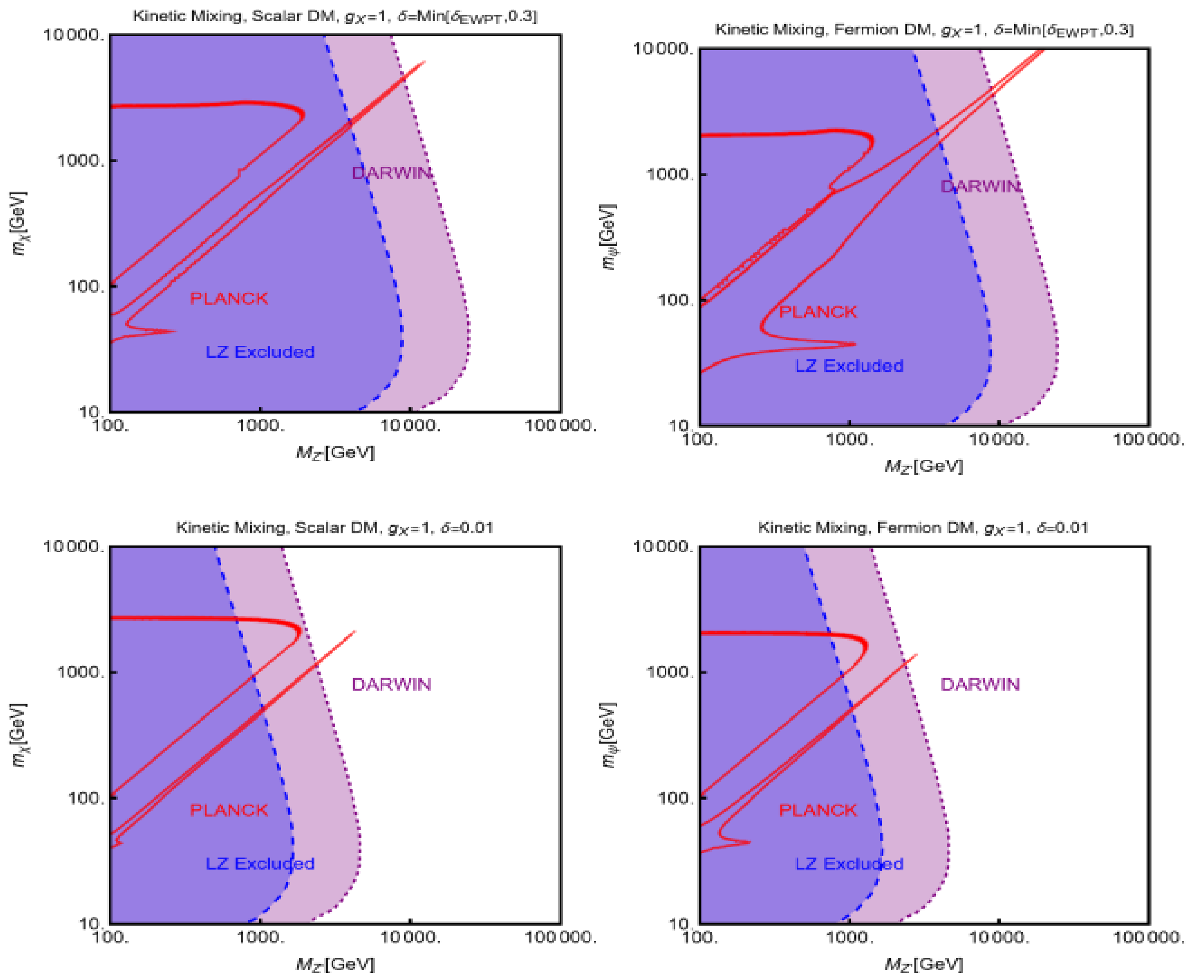


Fig. 36: Combination of constraints for $B-L$ model with a scalar DM ϕ_{DM}. The value of the g_X is 1 (0.1) for the left (right) panel. The red, orange, pink and green coloured regions represent the exclusion limits from the LHC searches of dijets, di-leptons, monojet and the LEP experiment, respectively. The blue (purple) coloured region is based on the sensitivity reach of the current (next generation) DM detection experiments.

Nonzero kinetic mixing



2. Light dark matter. Theory

It is possible that dark matter particles are relatively light with masses O(1 GeV) or less (C.Boehm, P.Fayet)

To avoid Lee-Weinberg-Visotsky-Zeldovich "theorem"

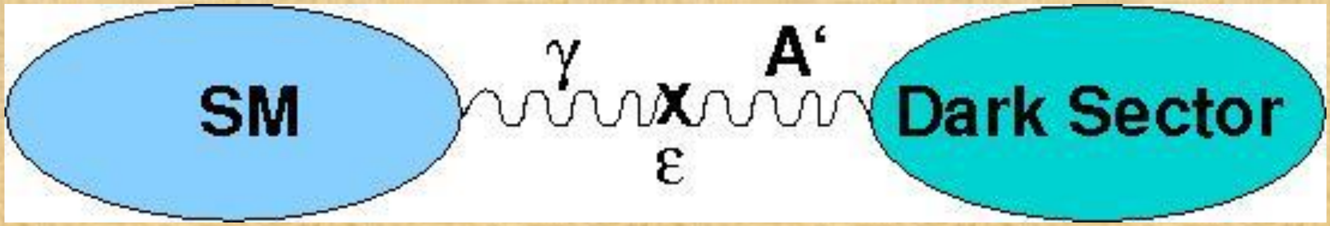
Renormalizable realization – additional interaction connects our world and dark world

The most popular scenario – model with vector messenger dark photon (B.Holdom, L.Okun).

Also models with scalar mediator exist

An example: vector dark mediator A`

Holdom'86, earlier work by Okun, ..



- extra U`(1), new gauge boson A`(dark or hidden photon,…)
- $2\Delta L = \varepsilon F^{\mu\nu} A`_{\mu\nu}$ - kinetic mixing
- γ-A` mixing, ε - strength of coupling to SM
- A` could be light: e.g. $M_{A`} \sim \varepsilon^{1/2} M_Z$
- new phenomena: γ-A`oscillations, LSW effect, A`decays,..
- A`decay modes: e+e-, μ+μ-, hadrons,.. or A`-> DM particles, i.e. A`-> invisible decays

Large literature, >500 papers /few last years, new theoretical and experimental results

Light dark matter models:

1. Scalar dark matter
2. Majorana dark matter
3. Pseudo Dirac dark matter

The main assumption – in the early Universe dark matter is in equilibrium with observable matter. At some temperature dark matter decouples.

Observable dark matter density allows to predict the annihilation cross-section

The most popular light dark matter model – model with additional U(1) gauge field

A’ – dark photon model (Holdom, Okun)

Dark photon connects our world and dark matter world due to nonzero kinetic mixing between dark photon and ordinary photon

The Lagrangian is the sum of 3 terms

2. Light Dark Matter. Theory

$L = L_{SM} + L_{SM,dark} + L_{dark}$

L_{SM} – the SM Lagrangian

L_{dark} - dark particles Lagrangian

$L_{SM,dark} = -(\varepsilon/2\cos(\theta_W))F'_{\mu\nu}B^{\mu\nu}$

$F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'$

$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

B_μ - U(1) gauge field of SM

SU(2)·U(1) – gauge fields

Scalar dark matter χ

$L_{dark,s} = (\partial_\mu\chi - ie_D A'_\mu\chi)^* \cdot (\partial_\mu\chi - ie_D A'_\mu\chi) - m^2_\chi \chi^*\chi - \lambda(\chi^*\chi)^2$

$-(1/4)F'_{\mu\nu}F'^{\mu\nu} + (m^2_{A'}/2)A_\mu' A'^\mu$

It is possible to use Higgs mechanism to

create dark photon mass in a gauge invariant way

Also models with Majorana fermion

($\chi = C\chi^*$) are often used

$L_M = (e_D/2)\chi^*\gamma_\mu\gamma_5\chi A'^\mu$

THERMAL ORIGIN

We assume that in the early Universe dark matter is in equilibrium with the SM matter

Today DM density tells us about annihilation cross-section. Correct DM density corresponds to $\langle \sigma_{an} v \rangle \sim O(1)$ pb*c

Dark matter dark photon model depends on four unknown parameters

1. Mixing ε
2. Fine coupling constant for dark sector $\alpha_D = e^2_D/4\pi$
3. Dark photon mass $m_{A'}$
4. Dark matter mass m_χ

Thermal origin condition → $<\sigma_{an}v> \sim O(1)$ pb*c

As a consequence: 3 independent parameters

$$\sigma(\chi\bar{\chi} \to e^- e^+)v_{rel} = \frac{16\pi\epsilon^2\alpha_D m_\chi^2}{(m_{A'}^2 - 4m_\chi^2)^2}$$

$$\varepsilon^2\alpha_D = F(m_{A'}, m_\chi)$$

Important Comment

At the mass of dark photon close to two masses of light dark matter particles

Due to denominator in the previous formula the value of the mixing parameter ε

could be very small that allows to escape experimental bounds

Dark photon model generalization with a additional vector massive field (N.V.K., Phys.Lett. B854(2024)138747)

Direct underground experiments lead to very strong bounds on DM models. In particular, strong bounds arise for dark photon model on mixing parameter ε. The main idea is that ε parameter depends on the square of momentum transfer q^2, i.e. $\varepsilon(q^2)$ and for $\varepsilon(q^2) = cq^2$ at small q^2 direct elastic cross section is suppressed. Two possible realizations of this idea

1. Nonlocal field theory – SM and dark sector are described by renormalizable field theory but the interaction between them

Is described by nonlocal field theory

2. The introduction of additional vector field allows realize this idea.

Suppose we have additional Z’ boson interacting only with the SM fields, for instance Z’ interacting with (B-L) current of the SM

We assume that dark sector interacts with massive vector boson A'. In considered model the interaction between our world and dark world is performed due to nonzero kinetic mixing of Z' and A' bosons. As a consequence tree level nucleon DM matrix element has suppression factor q^2 and elastic cross section is suppressed by factor $O(v^4) = O(10^{-12})$

Dark matter annihilation mechanism

Direct annihilation

$\chi\chi^{*}$--> $e^{+}e^{-}$, … ($m_{\chi} < m_{A'}$)

Secluded annihilation

$\chi\chi^{*}$--> A'A' ($m_{\chi} > m_{A}$)

For dark photon model secluded annihilation is s-wave and for light

dark matter it is excluded . For scalar mediator secluded annihilation is

possible. Here we shall consider direct annihilation

To estimate DM density we have to solve Boltzmann equation

$$\frac{dn_d}{dt} + 3H(T)n_d = - < \sigma v_{rel} > (n_d^2 - n_{d,eq}^2) \,.$$

$$n_d(T) = \int \frac{d^3p}{2\pi^3} f_d(p,T)$$

The dark matter relic density can be numerically estimated as

$$\Omega_d h^2 = 8.76 \times 10^{-11} GeV^{-2} [\int_{T_0}^{T_d} (g_*^{1/2} < \sigma v >) \frac{dT}{m_d}]^{-1}$$

In nonrelativistic approximation with $< \sigma v_{rel} >= \sigma_o x_f^{-n}$ one can find that

$$\Omega_{DM} h^2 = 0.1 \Big(\frac{(n+1) x_f^{n+1}}{(g_{*s}/g_*^{1/2})} \Big) \frac{0.876 \cdot 10^{-9} GeV^{-2}}{\sigma_0}$$

$$x_f = c - (n + \frac{1}{2}) \ln(c) \,,$$

$$c = \ln(0.038(n+1) \frac{g}{\sqrt{g_*}} M_{Pl} m_\chi \sigma_0)$$

Here g_*, g_{*s} are the effective relarivistic energy and entropy degrees of freedom and g is an internal number of freedom degree. If DM particles differ from DM antiparticles $\sigma_o = \frac{\sigma_{an}}{2}$.

For s-wave annihilation cross-section with $n = 0$

$$< \sigma v_{rel} >= 7.3 \cdot 10^{-10} GeV^{-2} \cdot \frac{1}{g_{*,av}^{1/2}} (\frac{m_d}{T_d})$$

$$\sigma(\chi\bar{\chi} \to e^- e^+) v_{rel} = \frac{16\pi\epsilon^2 \alpha_D m_\chi^2}{(m_{A'}^2 - 4m_\chi^2)^2}$$

$$\epsilon^2 \alpha_D = 2 \cdot 10^{-8} GeV^{-2} \frac{(m_{A'}^2 - 4m_\chi^2)^2}{m_\chi^2} \cdot \frac{2c_s}{g_{*,av}^{1/2}}$$

For $m_{A'}=3m_\chi$ we find that dark matter is : (T_D/m_χ) = (0.1 -0.05) for nonrelativistic

$1\ \mathrm{MeV} < m_\chi < 1\ \mathrm{GeV}$

Scalar dark matter (p-wave)

$$\epsilon^2 \alpha_D \sim 10^{-11} \cdot (\frac{m_\chi}{MeV})^2$$

for Majorana dark matter additional factor 1/2

For fermion dark matter(s-wave)

$$\epsilon^2 \alpha_D \sim 0.4 \cdot 10^{-12} \cdot (\frac{m_\chi}{MeV})^2$$

So the main features of light dark matter

1. p-wave annihilation(or annihilation shuts off before CMB) (Planck data)
2. The annihilation cross-section

$\langle\sigma_{an}\cdot v\rangle$ = O(1) pb*c → The main assumption: at the early Universe dark matter is in equilibrium with our matter.

However other scenario are possible

Freeze-in scenario

S.Dimopoulos and H.Georgi, 1981

L.J.Hall et al., 2010

R.Essig et al., 2012

Dark sector was never in thermal equilibrium with

the SM, out-of-equilibrium scattering populates

the dark matter. Couplings are very small.

$\alpha_D \varepsilon^2 = O(3 \cdot 10^{-24})$ for $m_{A'}$=100 MeV

Not very exciting from accelerator point of view

From the requirement of the absence of Landau pole singularity(H.Davoudiasl and W.J.Marciano, Phys.Rev. D92 035008 (2015)) upper bound on α_D See also N.V.K, arXiv:2504.01514

The bound depends on the Landau pole scale Λ and the model. For instance,

for $\Lambda = 1$ TeV

$\alpha_D \leq$ 0.8(0.2) for scalar(Majorana or pseudo Dirac)

For $\Lambda = M_{PL} = 1.2 \cdot 10^{19}$ GeV

$\alpha_D \leq$ 0.2(0.05) for scalar(Majorana or pseudo Dirac)

3. Light dark matter. Experiment

Visible A’ decays A’ → e^+e^- ,$\mu^+\mu^-$

1. Prompt decays – resonant behavior in invariant mass distribution
2. Displaced decays –long lived A’ (NA64 exp.)

Invisible decays

3. Missing momentum(energy) from A’ → χχ decays into DM particles

Light dark Matter: Experiment. Invisible mode detection

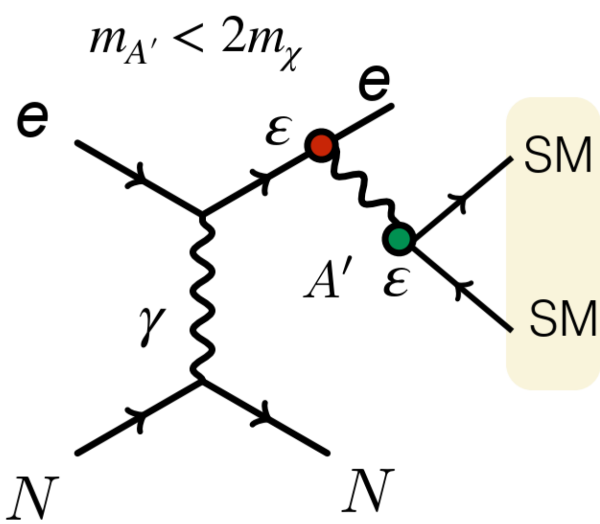
1. Beam dump (SHiP-future , …)
2. Missing mass measurement – resonant distribution (PADME, …)
3. Missing energy measurement (NA64)
4. Missing momentum measurement (LDMX-future)

Two main reactions

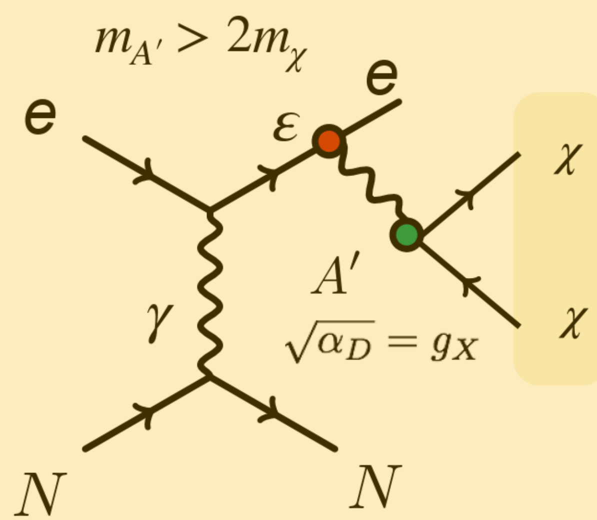
A’

S. Andreas et al., arXiv:1312.3309 (2013)
S. N. Gninenko, Phys. Rev. D 89, 075008 (2014)

Setup: Visible mode



Invisible mode



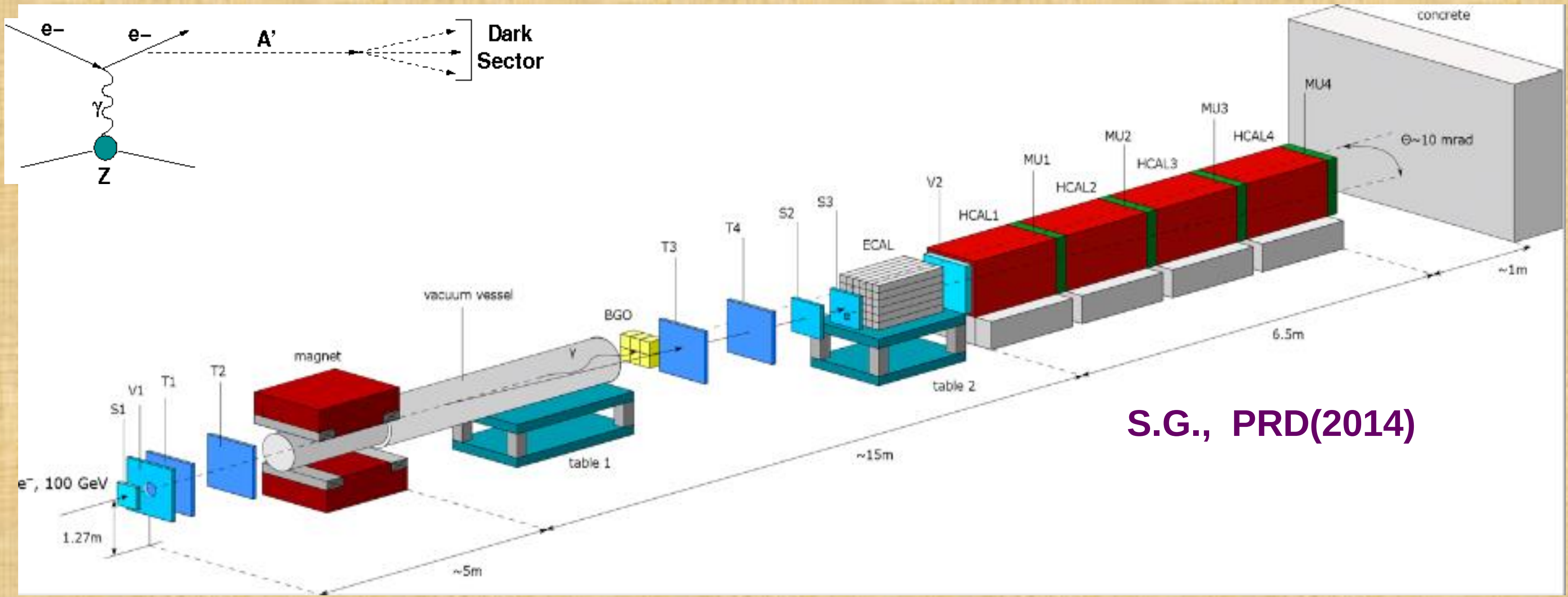
Signature: SM particles pair production

Missing energy

Focus of this talk

search for *A´->invisible* at CERN SPS

Invisible decay of Invisible State!



S.G., PRD(2014)

3 main components :

- clean, mono-energ. 100 GeV e- beam
- e- tagging system: MM tracker + SR
- 4π fully hermetic ECAL+ HCAL

Signature:

- in: 100 GeV e- track
- out: < 50 GeV e-m shower in ECAL
- no energy in the Veto and HCAL
- Sensitivity ~ ε^2

NA64 dark photon detection

A' – production in ECAL, invisible decay

The A' production in electron nucleus interactions

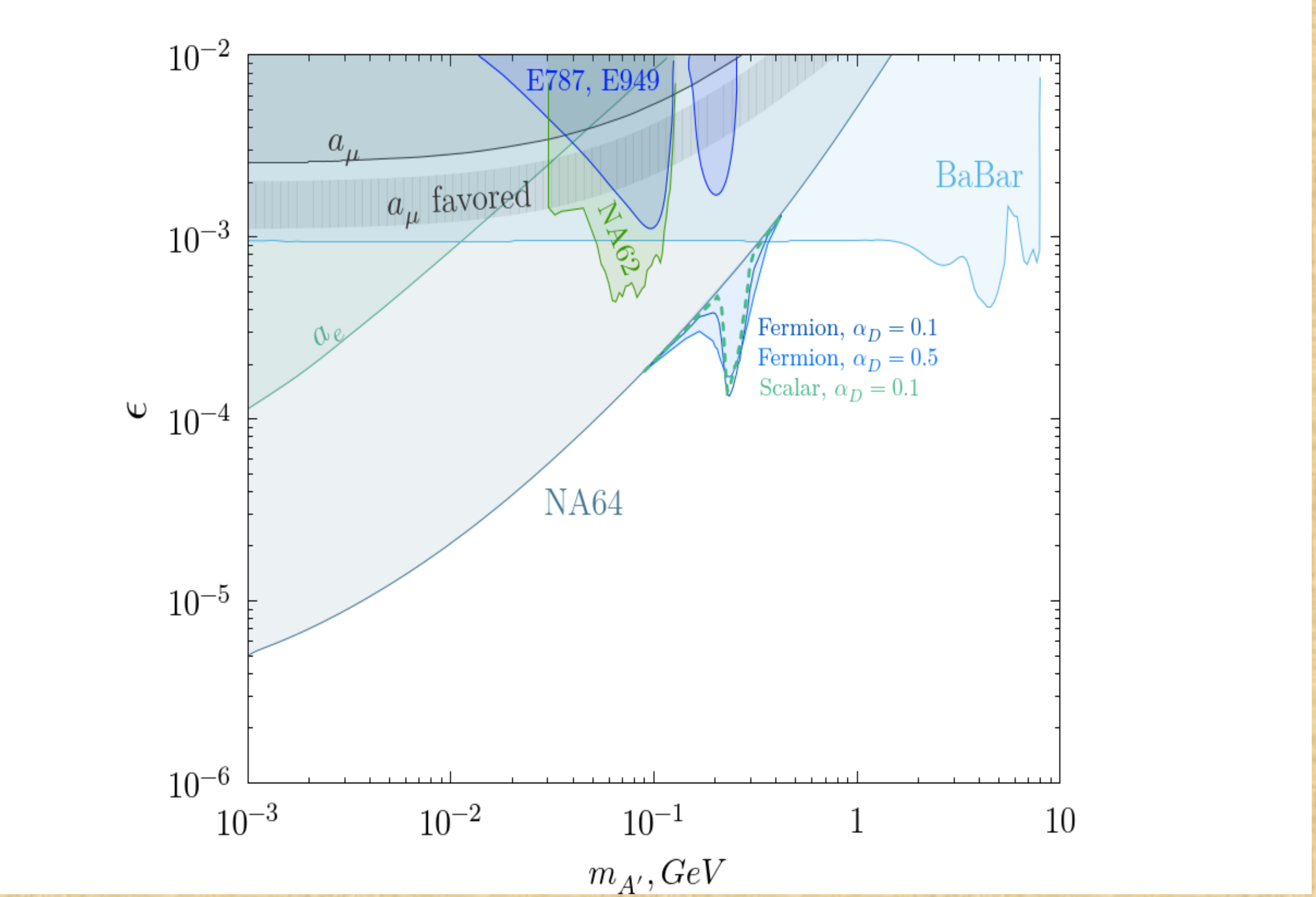
eZ → eZA',   A' → invisible

Signature: missing energy in ECAL + HCAL

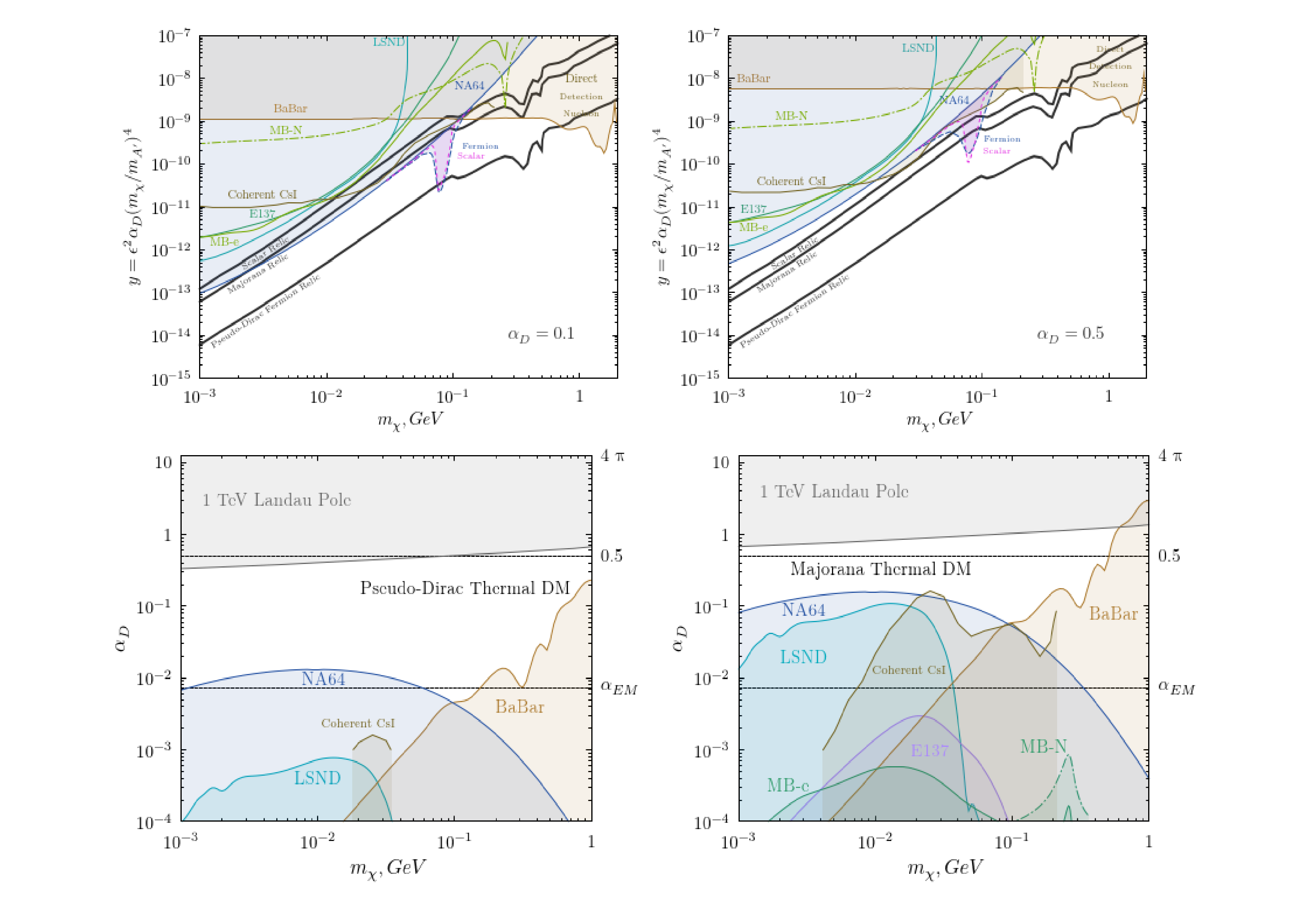
In comparison with initial 100 GeV electron

plus no essential activity in HCAL(E_{HCAL}<2 GeV)

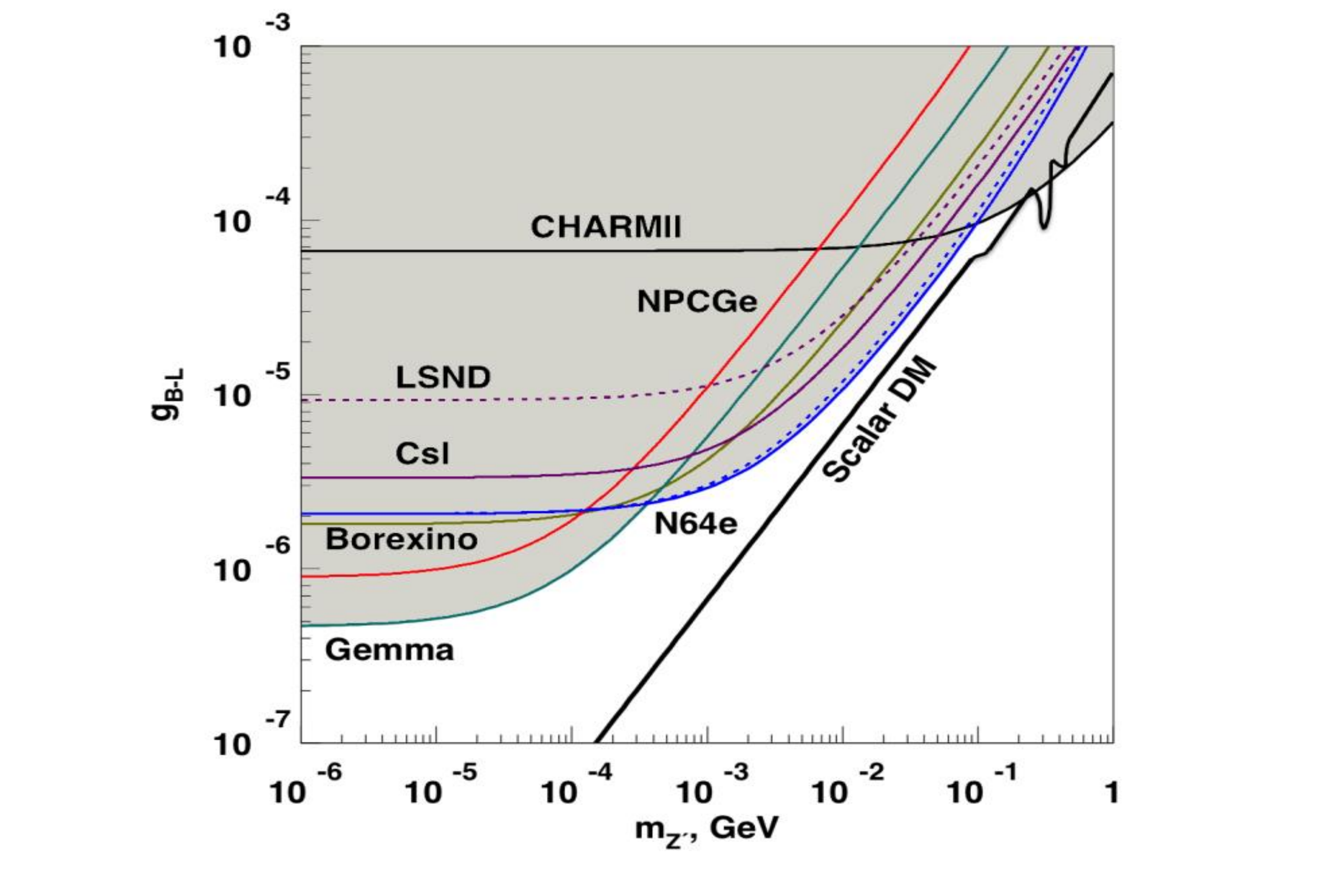
Last NA64 result on ε parameter invisible dark photon decay: $N_{eot} = 0.937*10^{12}$ arXiV:2307.024404, Phys.Rev.Lett.(2023)



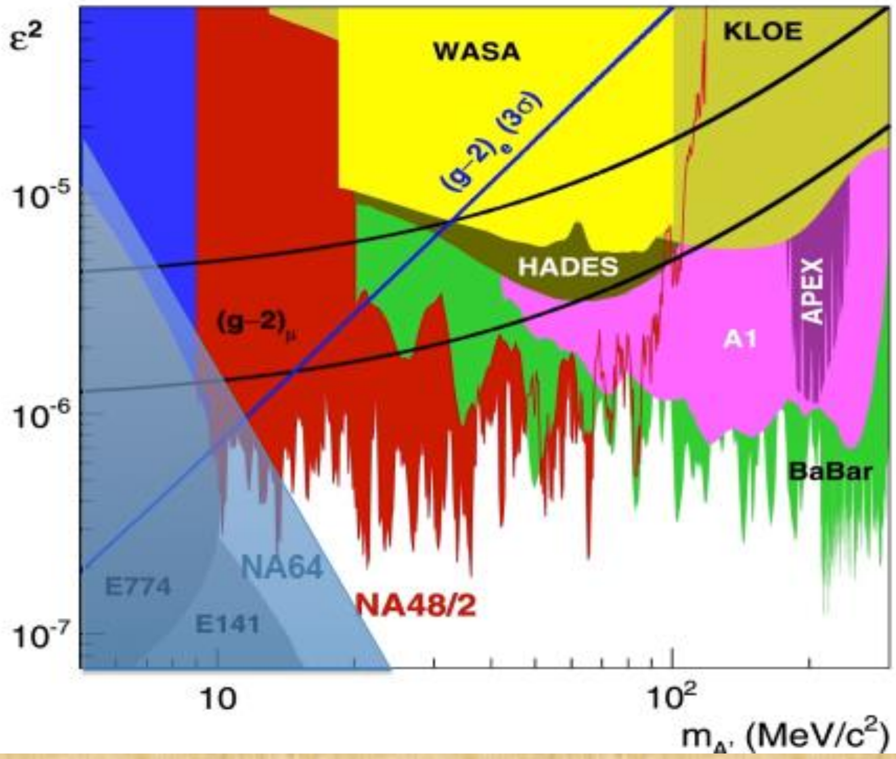
The comparison with different models



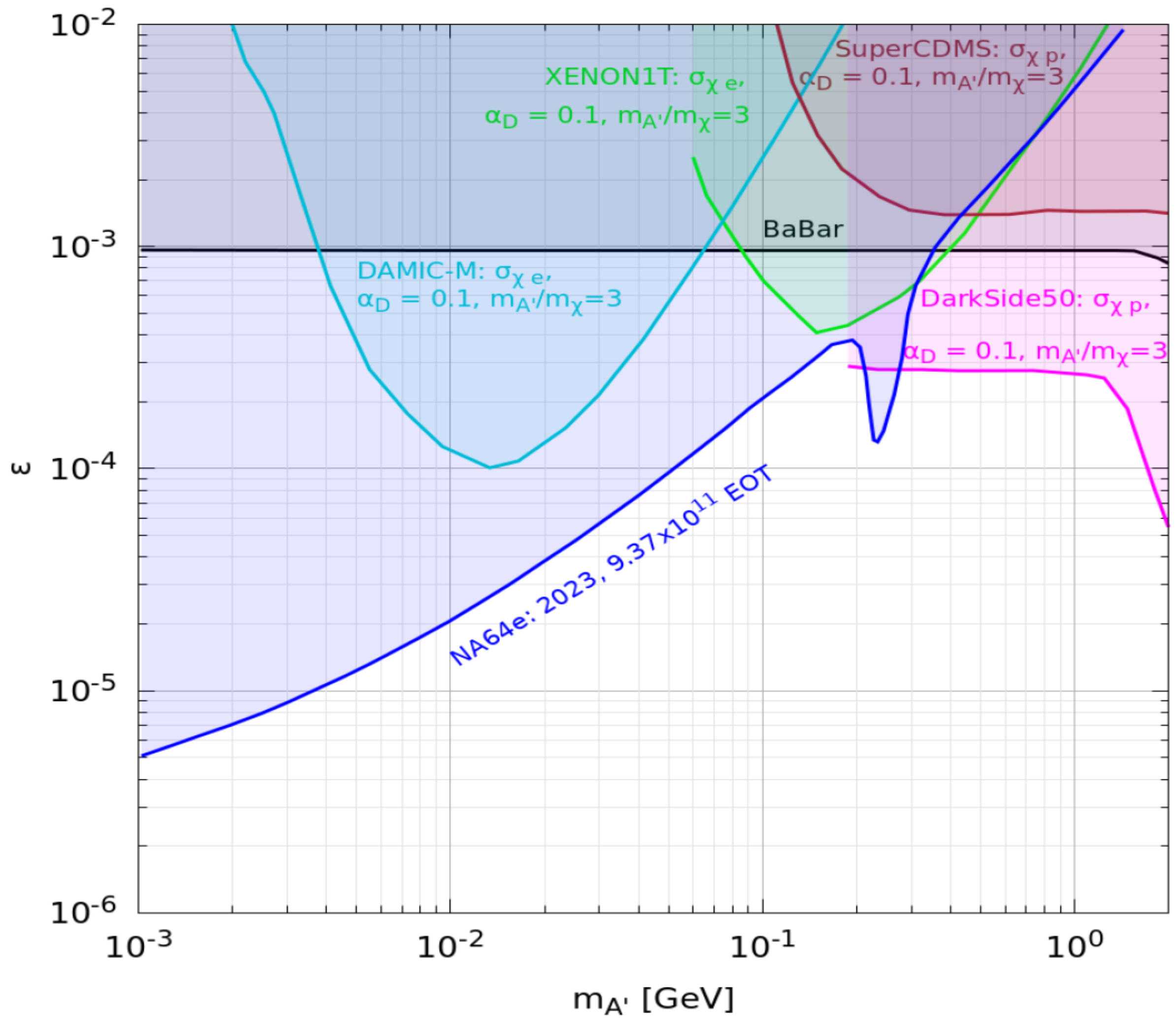
Bound for (B-L) model
Phys.Rev.Lett. 129,1618011(2022)



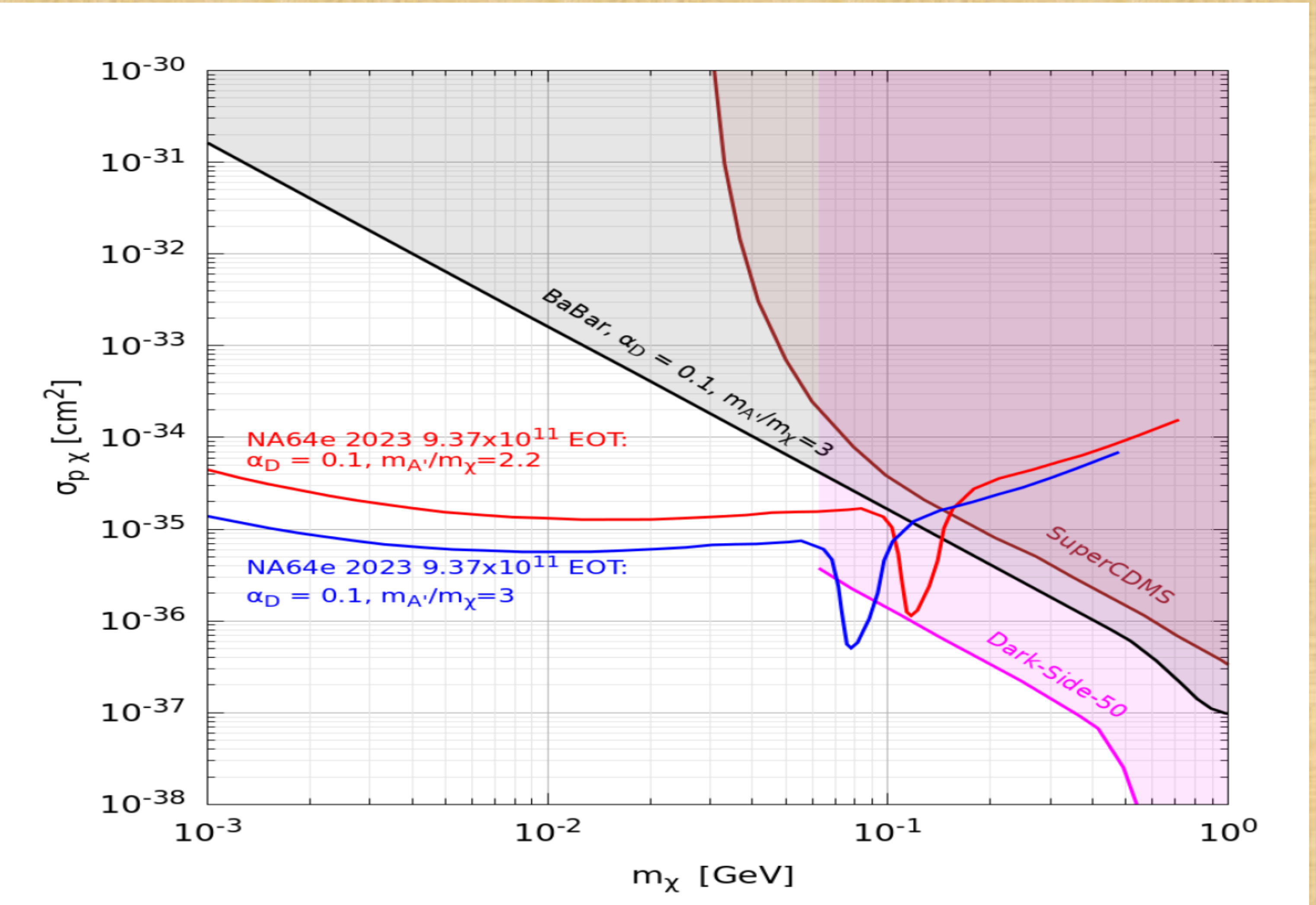
Summary plot for visible A’ decays



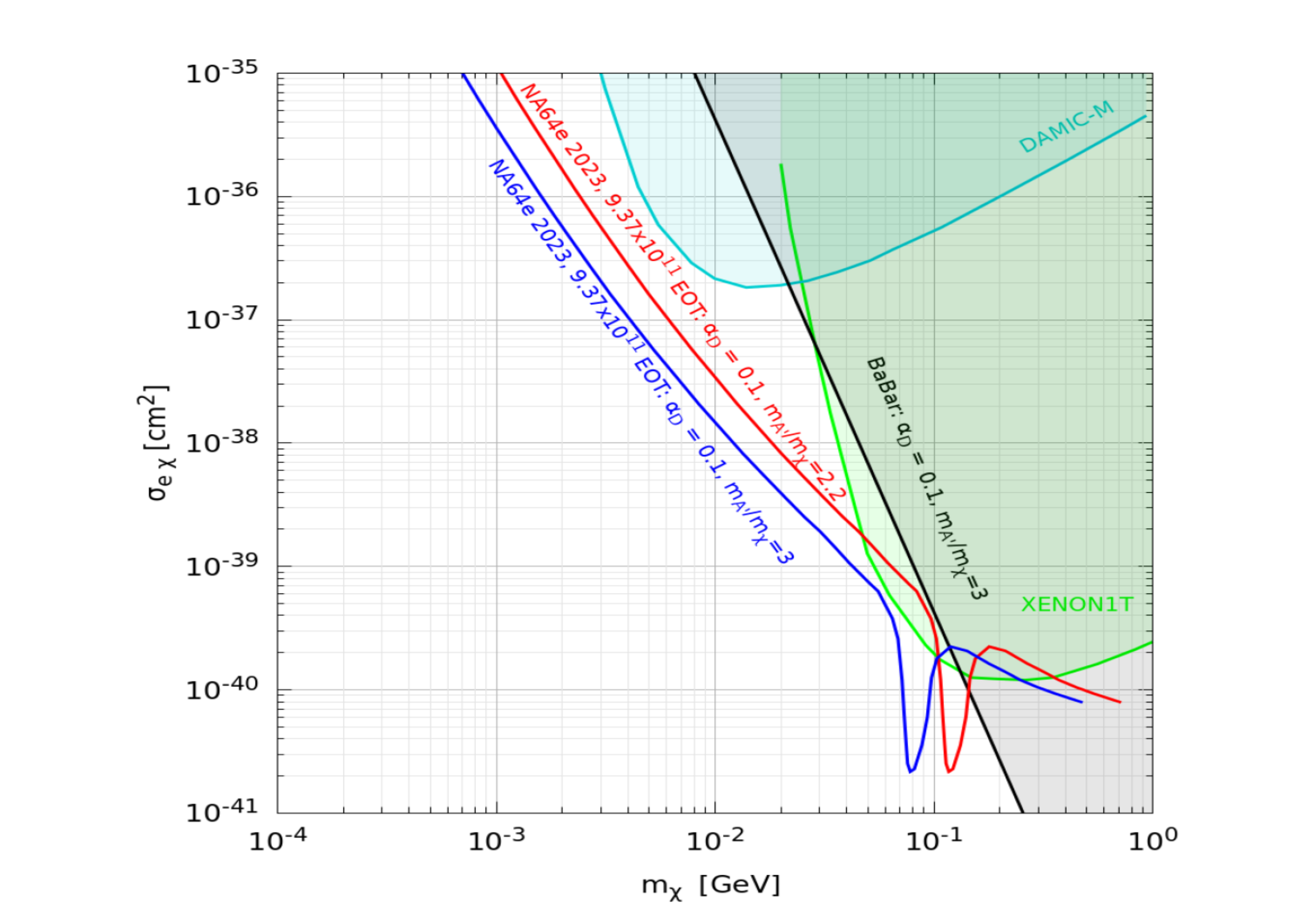
The comparison of NA64 and underground experiments(arXiv:2307.14865) for dark photon model for different ε



The comparison for proton DM cross sections



The comparison for cross sections – electron DM scattering



The NA64 experiment with muon beam

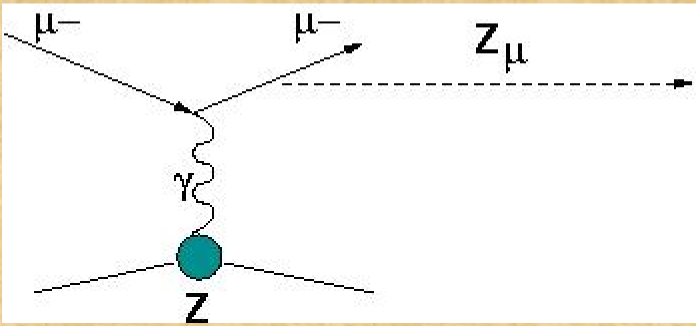
S.Gninenko, N.Krasnikov and V.Matveev,

Phys.Rev. D91(2015)095015

Proposal to look for dark photon and LDM in collisions of CERN SPS muon beams

$$\mu(p) + Z(P) \to Z(P^{'}) + \mu(p^{'}) + Z_{\mu}(k)$$

The NA64 experiment at CERN with muon beam



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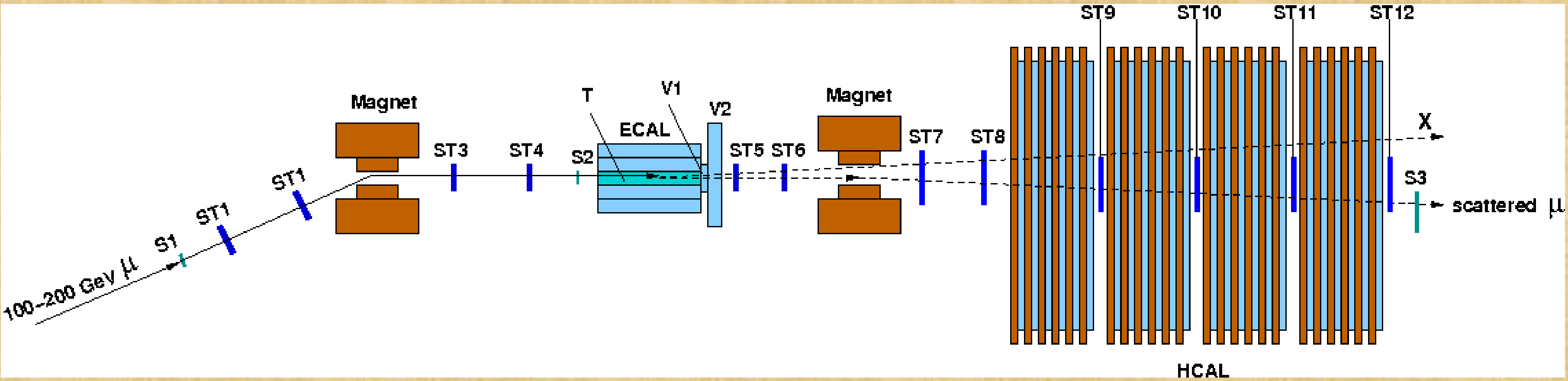
Schematic illustration of the setup to search for dark boson



NA64 at CERN SPS with muon beam

Coming muon produces dark boson at the target. Dark boson decays into neutrino or light dark matter and escapes the detection. So the signature is imbalance in energy for incoming and outcoming muons without big activity in HCAL and ECAL

Motivation for the muon beam use

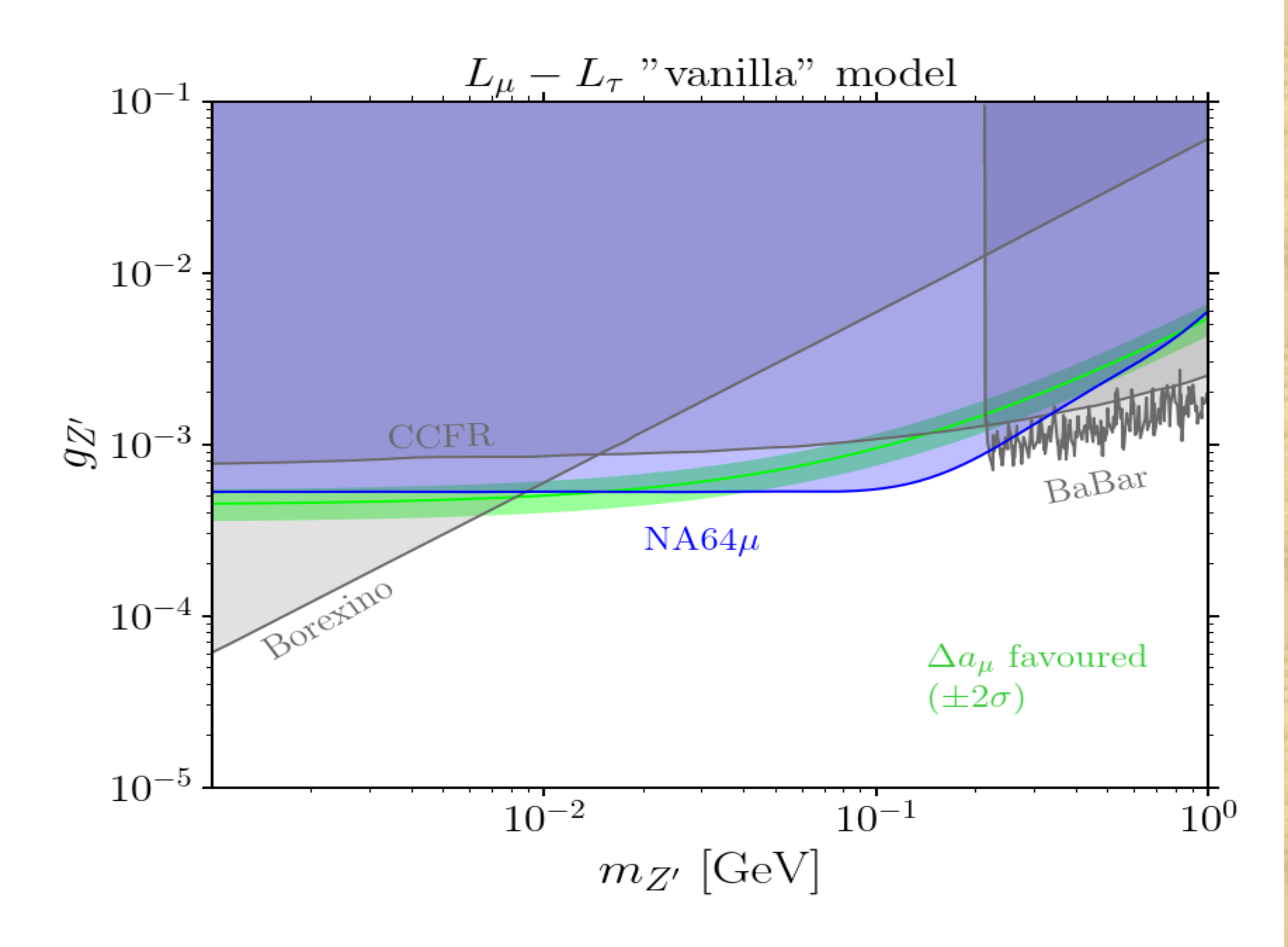
There is possibility that new boson Z_μ interacts only with $L_\mu - L_\tau$ current

$$L_{Z_\mu} = e_\mu [\bar{\mu}\gamma_\nu \mu + \bar{\nu}_{\mu L}\gamma_\nu \nu_{\mu L} - \bar{\tau}\gamma_\nu \tau - \bar{\nu}_{\tau L}\gamma_\nu \nu_{\tau L}] Z^\nu_\mu$$

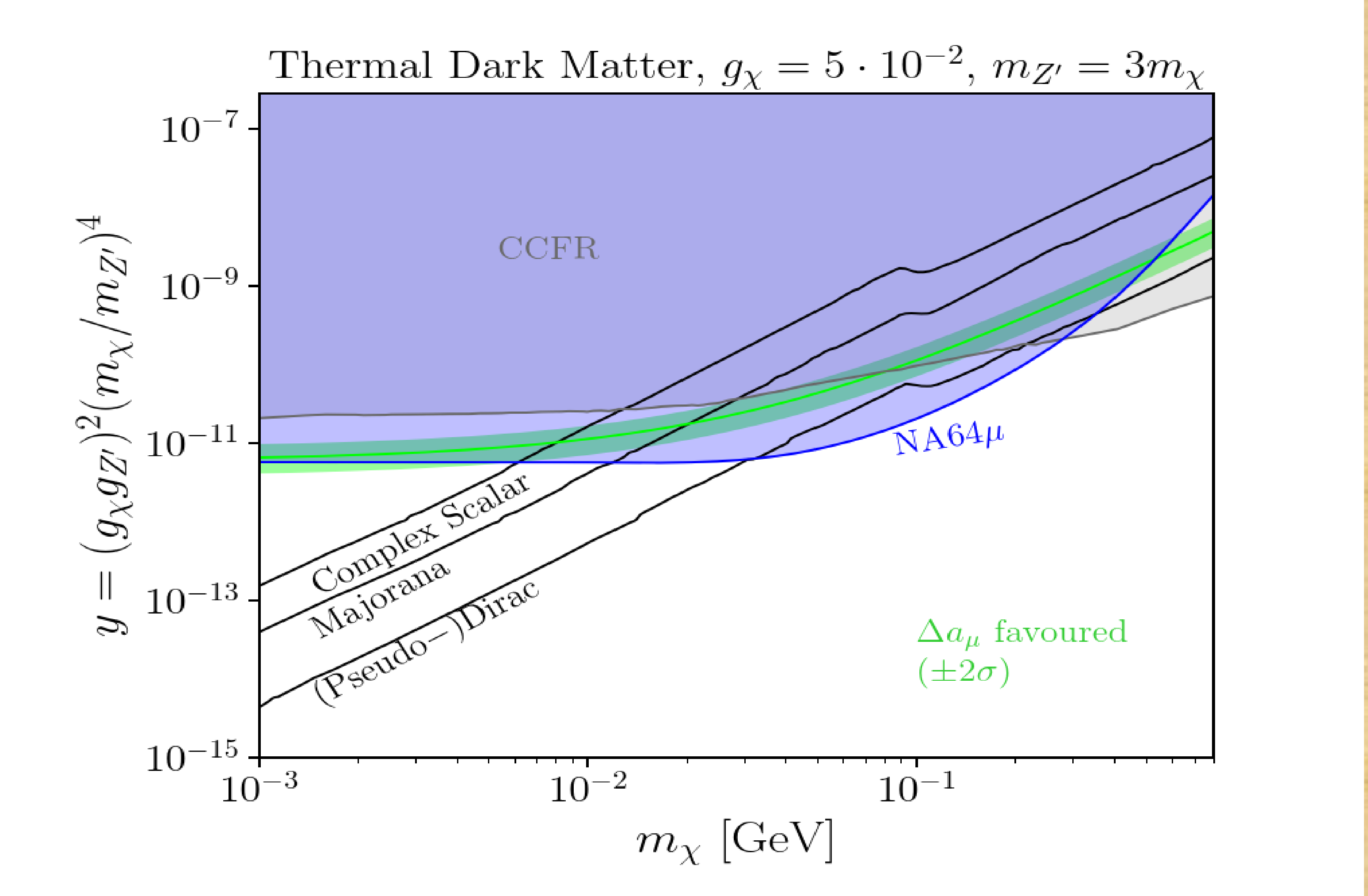
For this model the most nontrivial bound (W.Almannsofer et. al) comes from CCFR data on neutrino trident $\nu_\mu N \to \nu_\mu N + \mu^+\mu^-$ production. Masses $m_{Z_\mu} \geq 400\ MeV$ are excluded

New BaBaR bound excludes m > 214 MeV

Last NA64 result
Phys.Rev.Lett132(.2024)211803



Last NA64 results

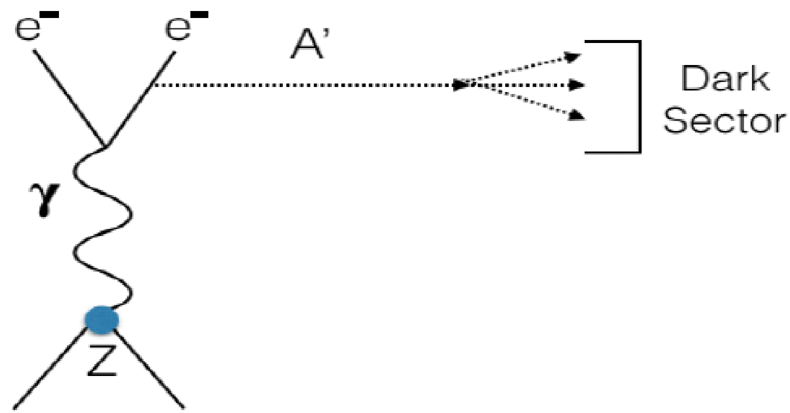


4.Conclusions

1. At present there are rather strong underground and accelerator bounds on dark matter models. However from theoretical point of view it is difficult to choose the most natural and promising model.
2. Dark photon model is the simplest realization of light dark matter scenario
3. Dark photon model predicts mixing interesting for experimental search
4. NA64 with future statistics $5 \cdot 10^{12}$ EOT will be able to test a lo of interesting models

Thank You for your attention

NA64 Experiment



NA64 is a fixed target experiment combining the active beam dump technique with missing energy measurement searching for invisible decays of massive A' produced in the reaction eZ—> eZA' of electrons scattering off a nuclei (A,Z), with a mixing strength $10^{-5} < \epsilon < 10^{-3}$ and masses $M_{A'} < 100$ MeV.