Semi-Visible Dark Photons

Matheus Hostert mhostert@pitp.ca

University of Minnesota and Perimeter Institute

NA64 Seminar — March 28th, 2023

In collaboration with:

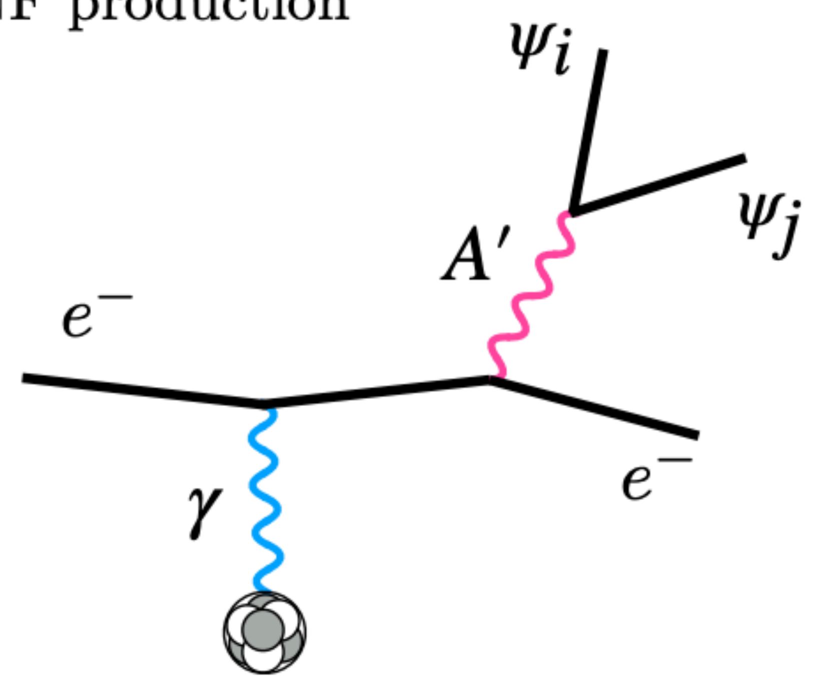
A. Abdullahi, D. Massaro, S.Pascoli

M. Mongillo, P. Crivelli, B. B. Obenhauser, L. Molina Bueno

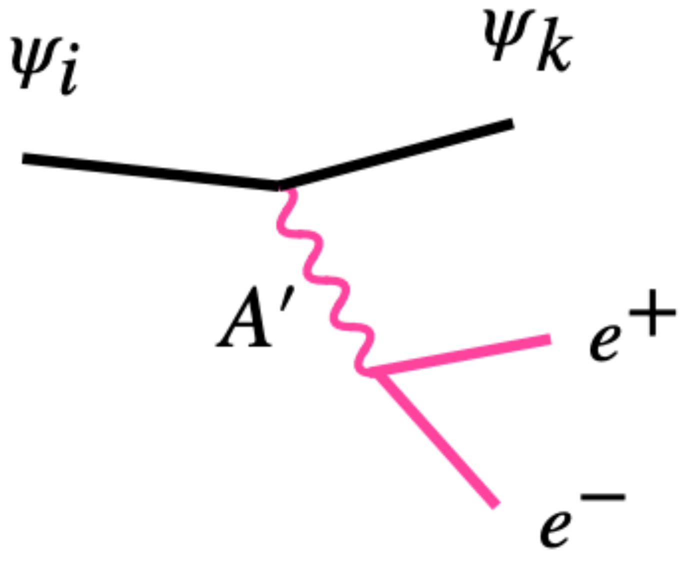
University of Minnesota

PERIMETER INSTITUTE

HNF production



HNF decay



arXiv:2302.05410 and arXiv:2302.05414

Renormalizable Portals:
(SM SINGLET) X (DS SINGLET)
DARK SECTOR (DS)
$\mathscr{L}_{\rm SM}$
$\overline{L}\widetilde{H}N$
Neutrino portal
Heavy neutrinos
$\frac{M_N}{2}\overline{N^c}N$
Neutrino masses.
$B_{\mu\nu}X^{\mu\nu}$
Vector portal
Dark photons
$G_{SM} \times U(1)_X$
New fundamental forces.
$S^\dagger S\,(H^\dagger H)$
Scalar portal
Dark scalars
$V(H,S)$
New Higgses.
Dim-5 axion "portal"
$\frac{a}{\Lambda}G_{\mu\nu}\tilde{G}_{\mu\nu}$

SM

A' couples to EM current

$$\mathscr{L} \supset \varepsilon e A'_\mu \bar{f} \gamma^\mu f$$

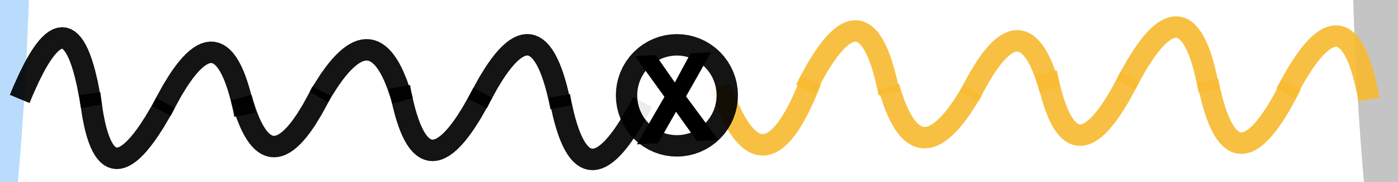
Dark $\mathrm{U}(1)_\mathrm{X}$ symmetry

A' couples to some dark current J^μ_D that can contain DM or HNLs.

$$\mathscr{L} \supset g_D A'_\mu J^\mu_D$$

$B_{\mu\nu} X^{\mu\nu}$

J^μ_{EM}



J^μ_D

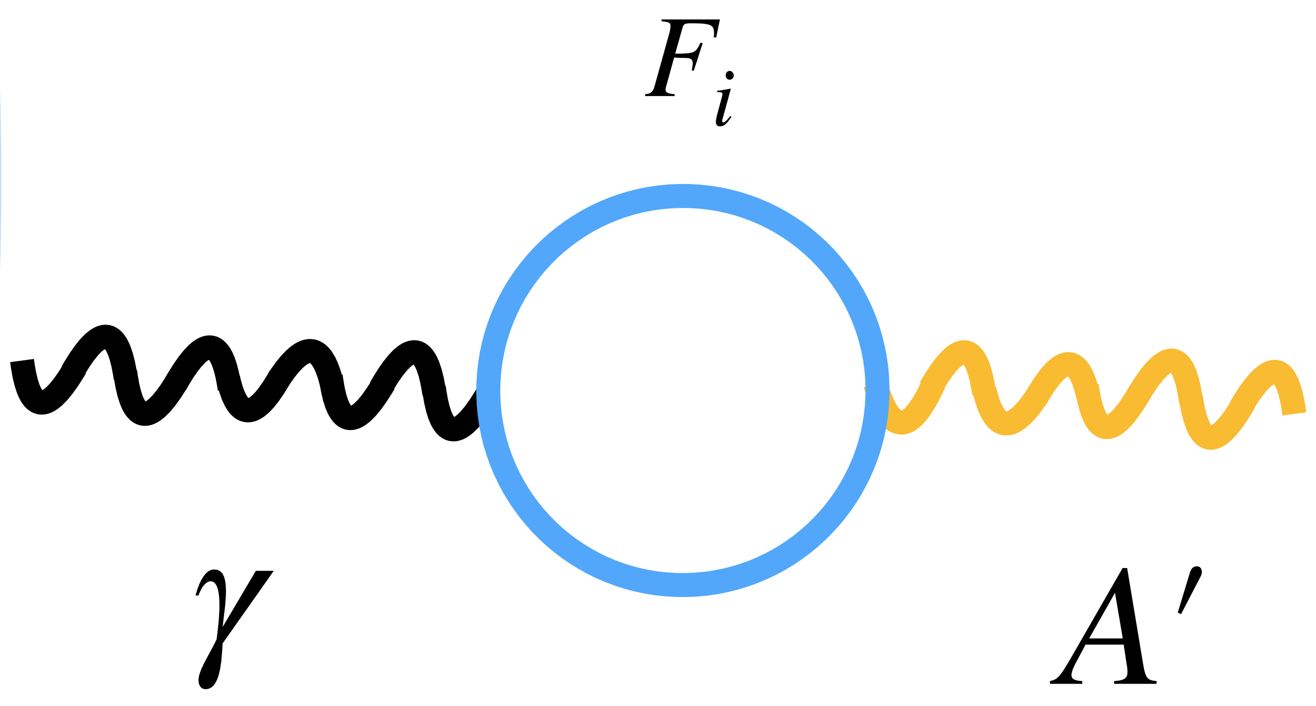
Vector portal

SM

A' couples to EM current

$$\mathscr{L} \supset \varepsilon e A'_\mu \bar{f} \gamma^\mu f$$

J^μ_{EM}



J^μ_D

Dark $\mathrm{U}(1)_\mathrm{X}$ symmetry

A' couples to some dark current J^μ_D that can contain DM or HNLs.

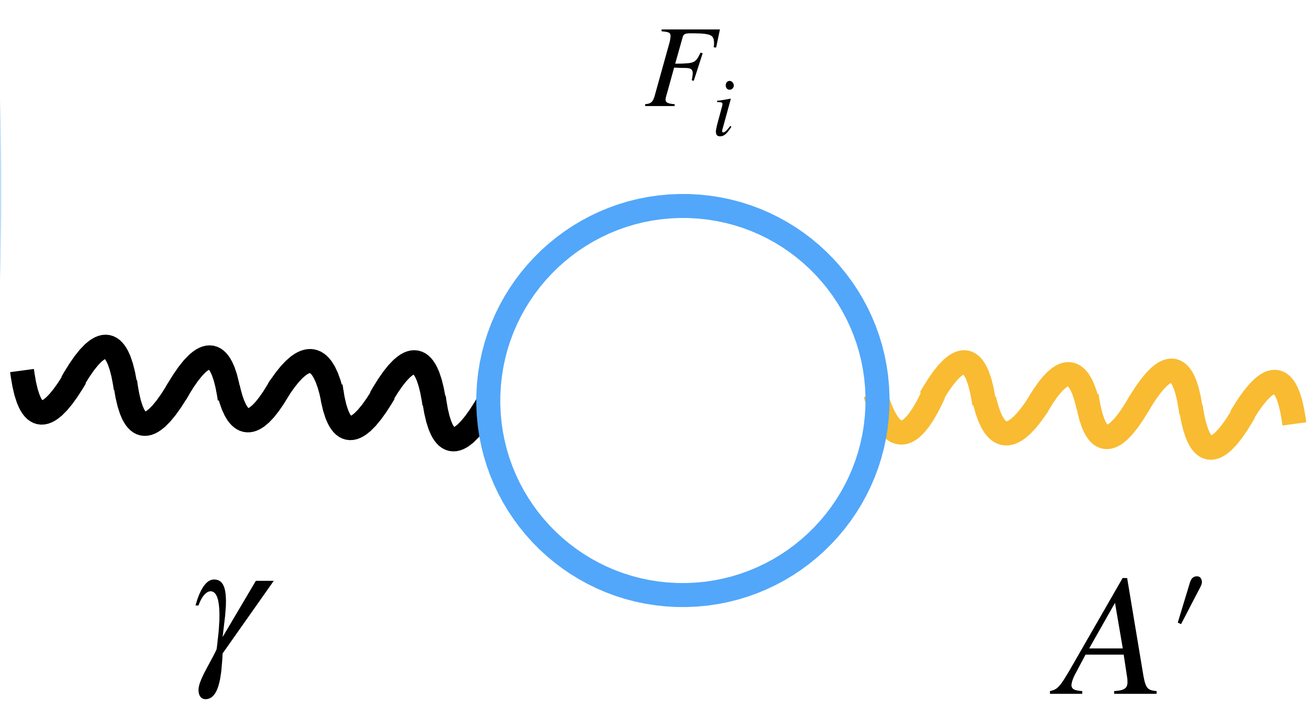
$$\mathscr{L} \supset g_D A'_\mu J^\mu_D$$

SM

A' couples to
EM current

$$\mathscr{L} \supset \varepsilon e\, A'_\mu \bar{f} \gamma^\mu f$$

$J^\mu_{\rm EM}$



Experimental target
kinetic mixing at 1-loop →

J^μ_D

Dark $\mathrm{U}(1)_\mathrm{X}$ symmetry

A' couples to some dark current J^μ_D
that can contain DM or HNLs.

$$\mathscr{L} \supset g_D\, A'_\mu\, J^\mu_D$$

Very naively,

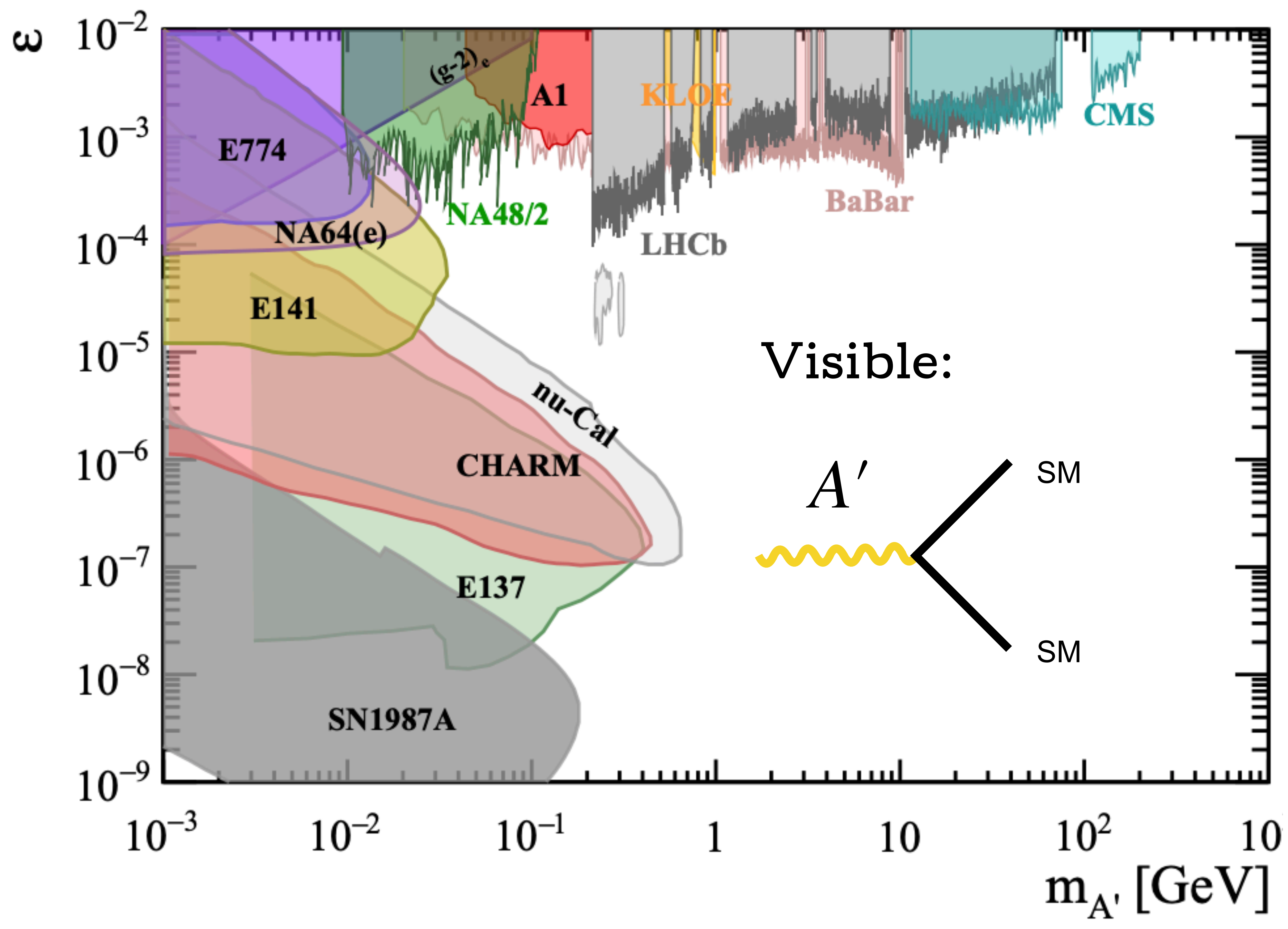
$$\epsilon \sim \frac{g' g_D}{16\pi^2} \sum_i \log\left(\frac{M_i^2}{\mu^2}\right) \sim \mathcal{O}\left(10^{-3} - 10^{-2}\right)$$

$$M_{A'} \sim \varepsilon\, v_{\rm EW} \sim \mathcal{O}(0.1 - 1)\,\mathrm{GeV}$$

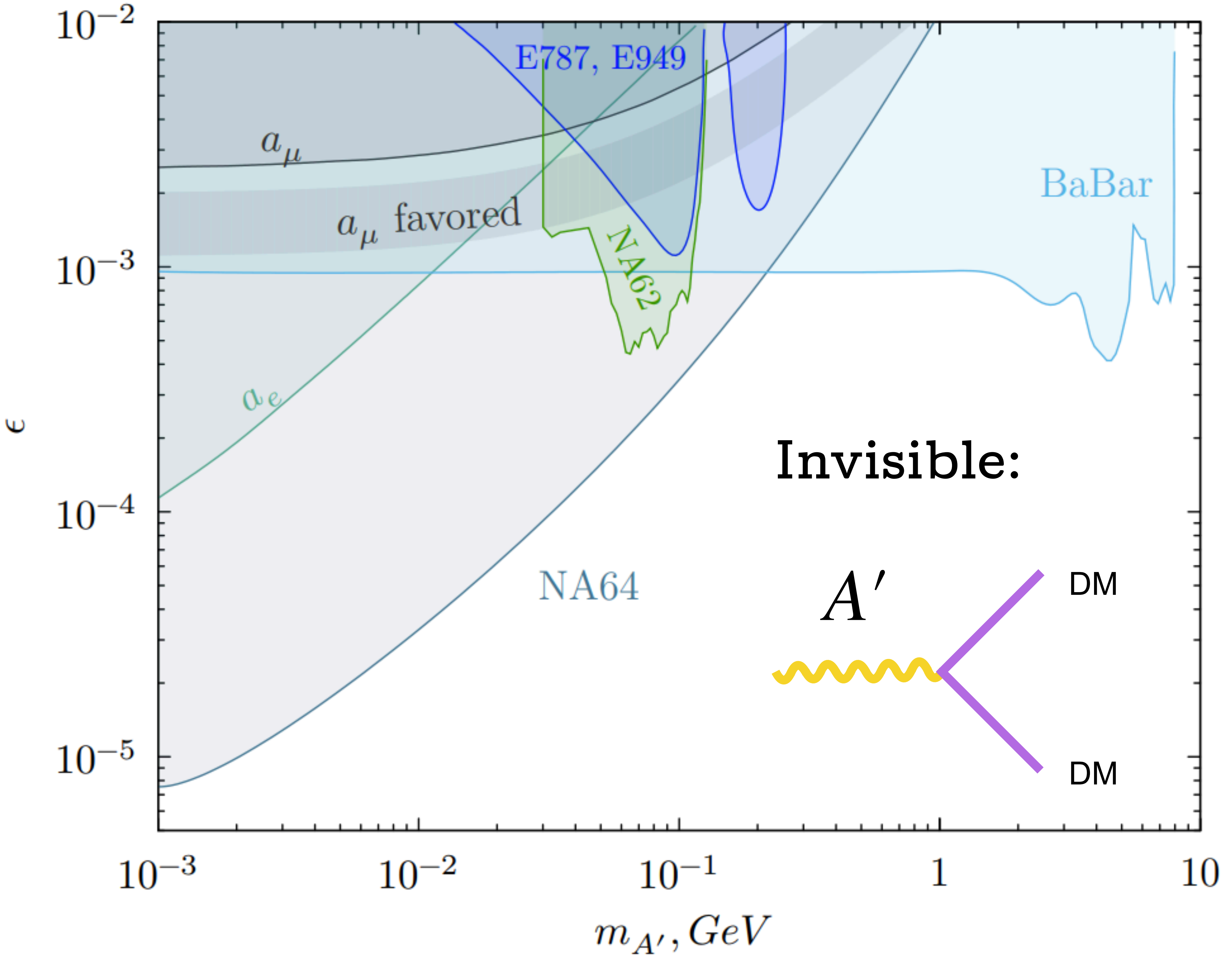
Dark Photons

Visible and Invisible dark photons

M. Fabbrichesi et al, SpringerBriefs in Physics, 2005.01515



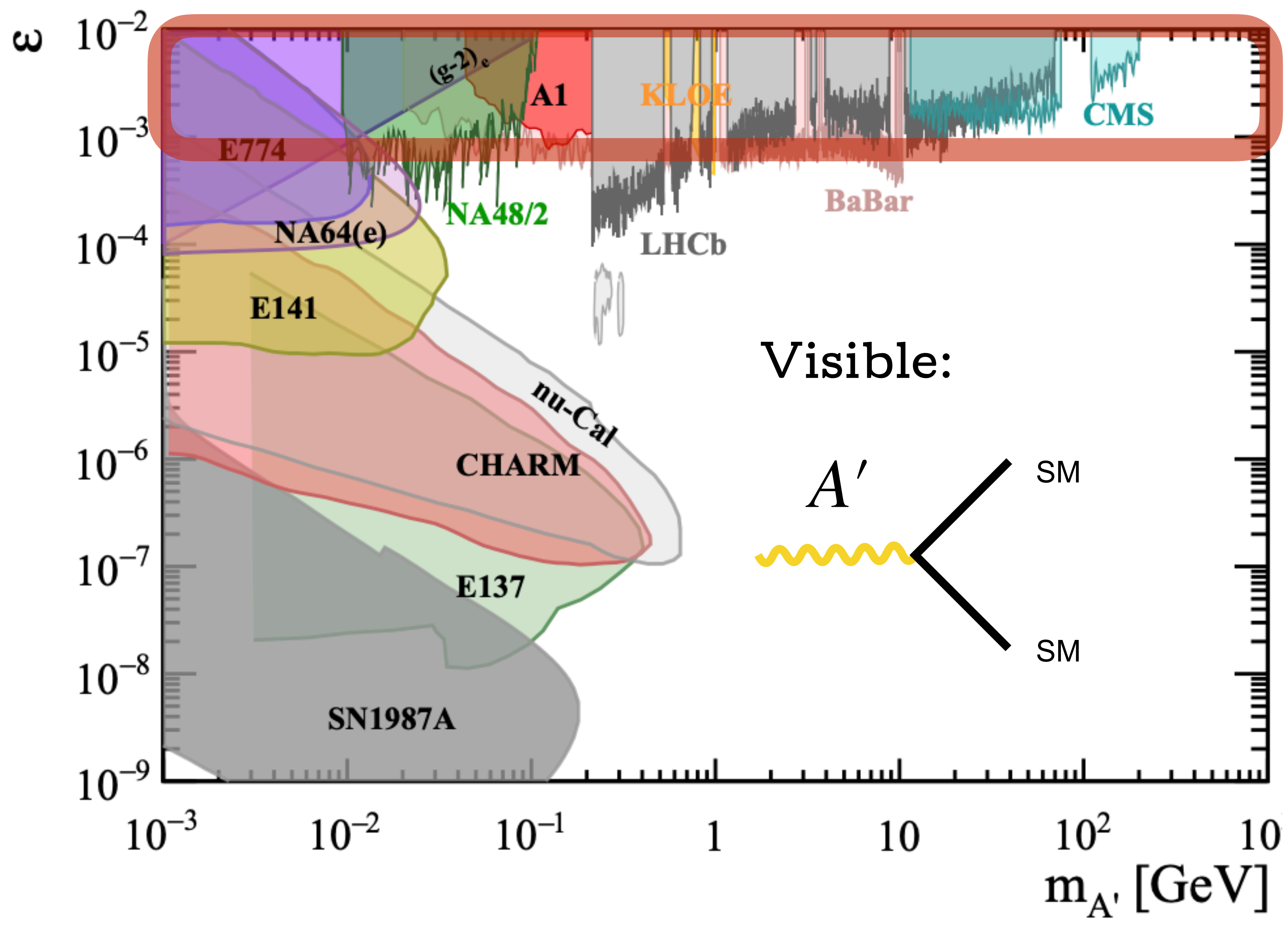
D. Banerjee et al, PRL 123, 121801 (2019)



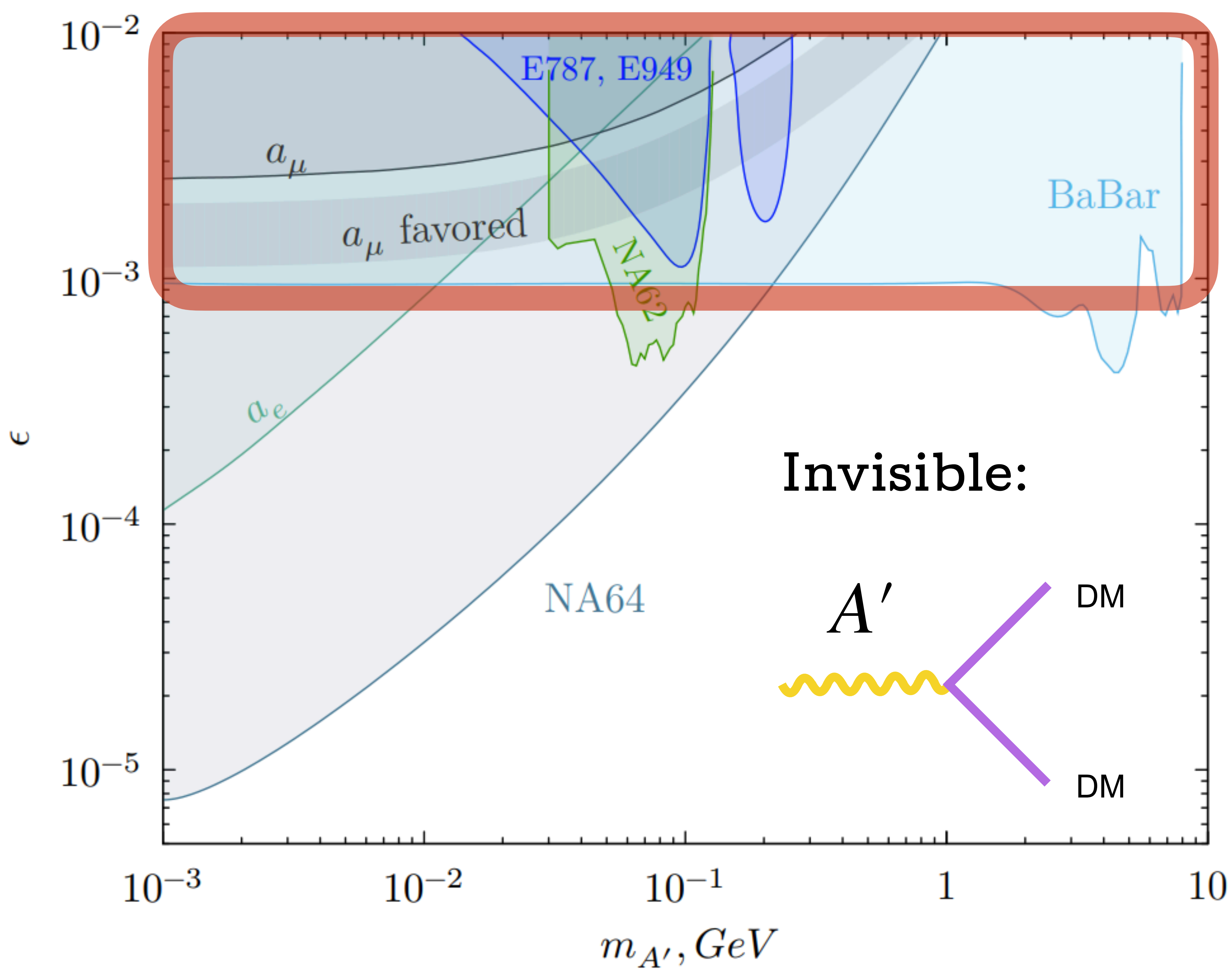
Dark Photons

Visible and Invisible dark photons

M. Fabbrichesi et al, SpringerBriefs in Physics, 2005.01515

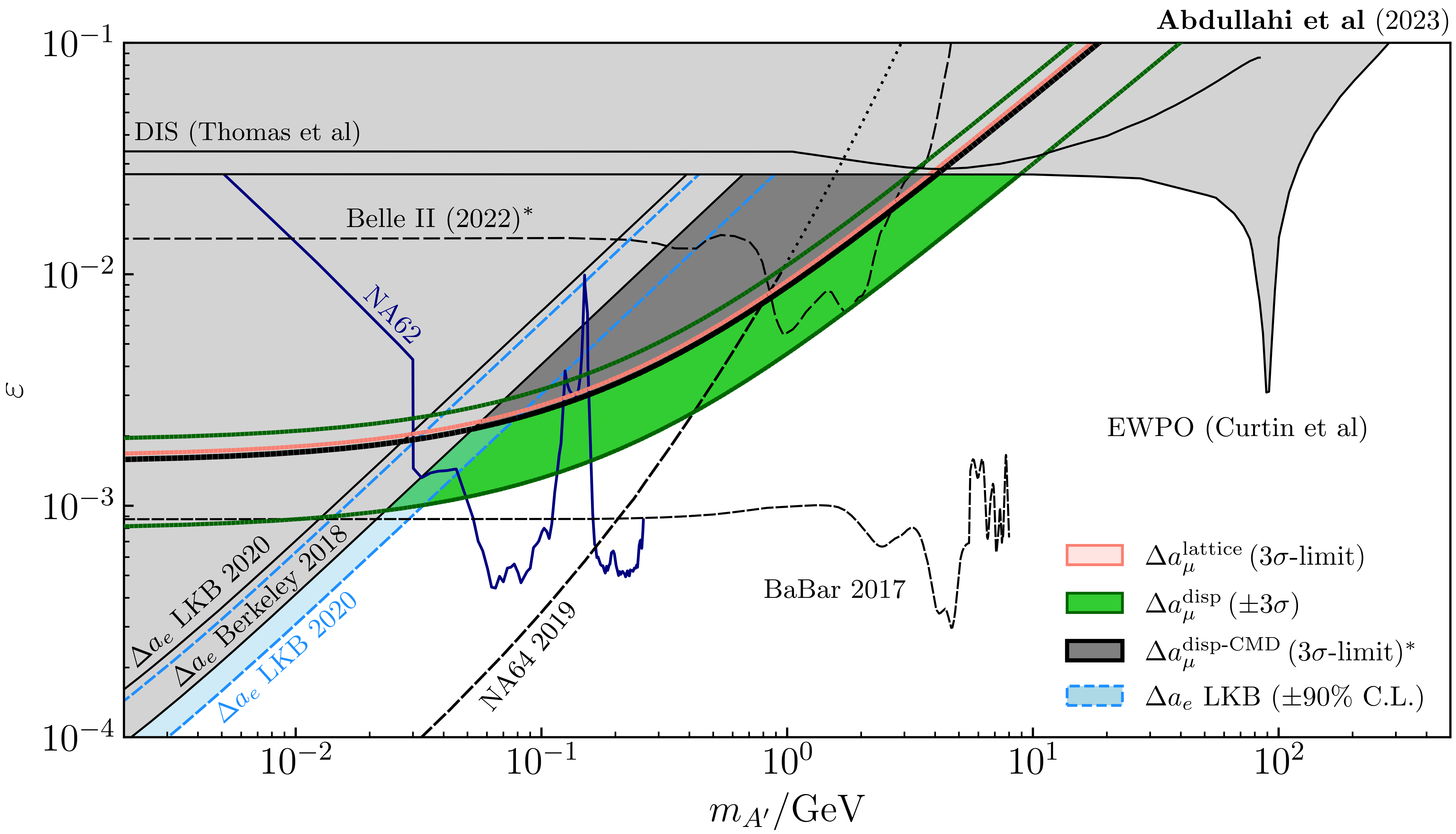


D. Banerjee et al, PRL 123, 121801 (2019)



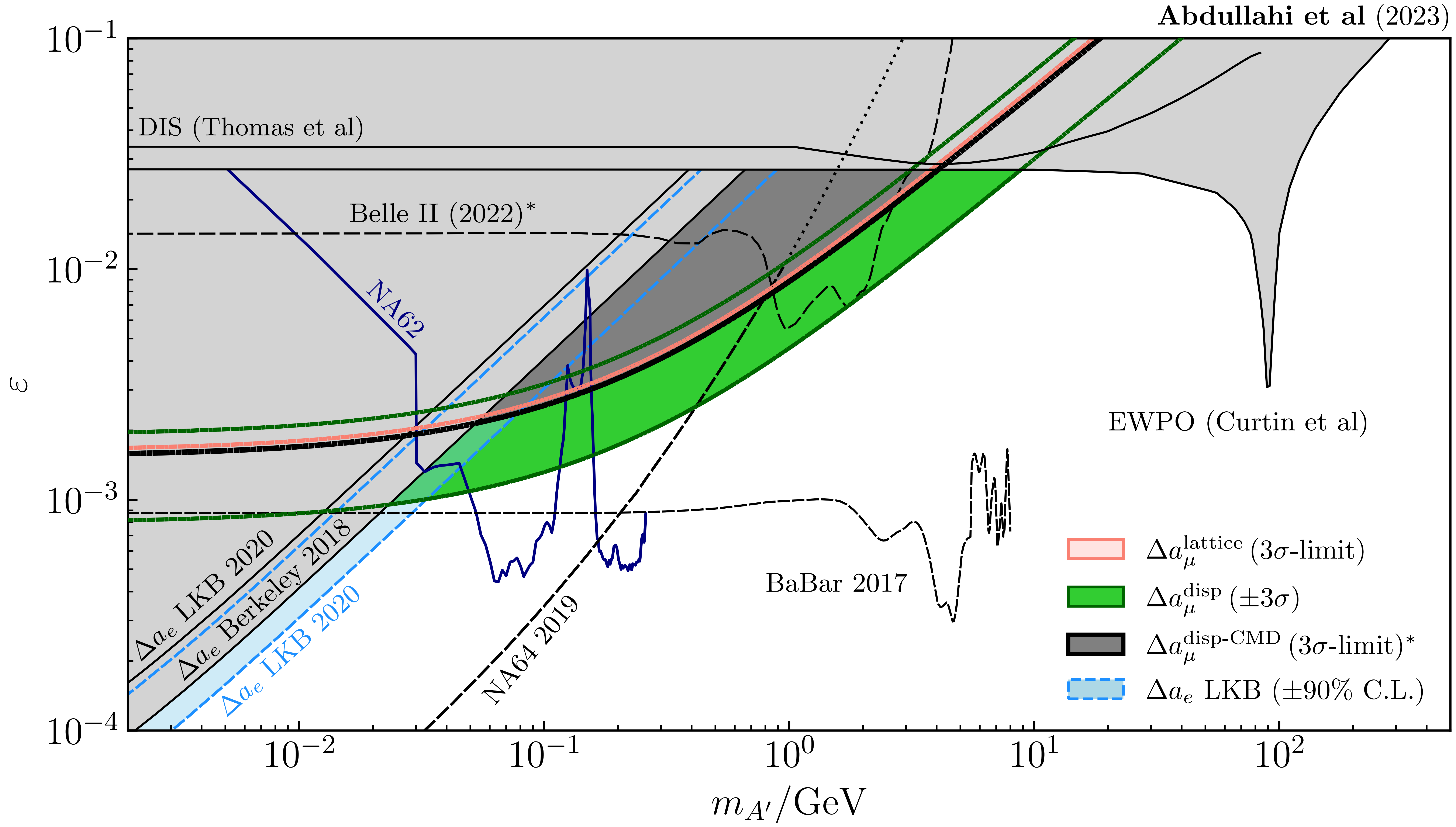
Dark Photons

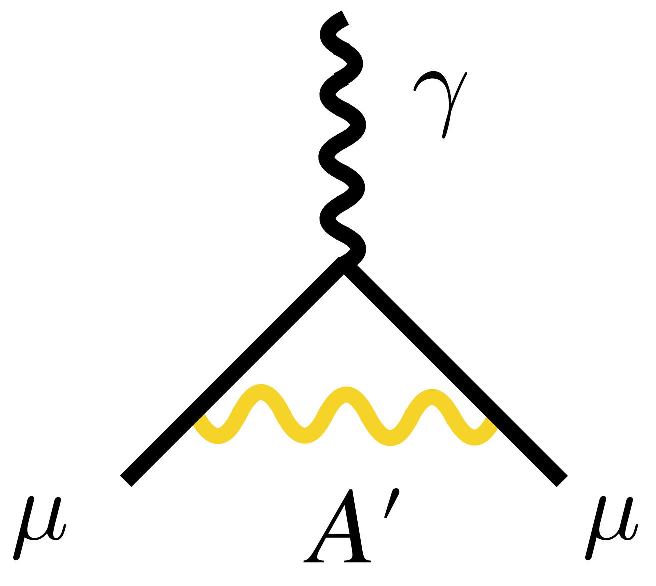
“Model-independent” limits



Dark Photons

Leptonic $g-2$ contribution





$$\Delta a_\mu^{A'} \sim \frac{\varepsilon^2 \alpha}{3\pi} \frac{m_\mu^2}{m_{A'}}$$

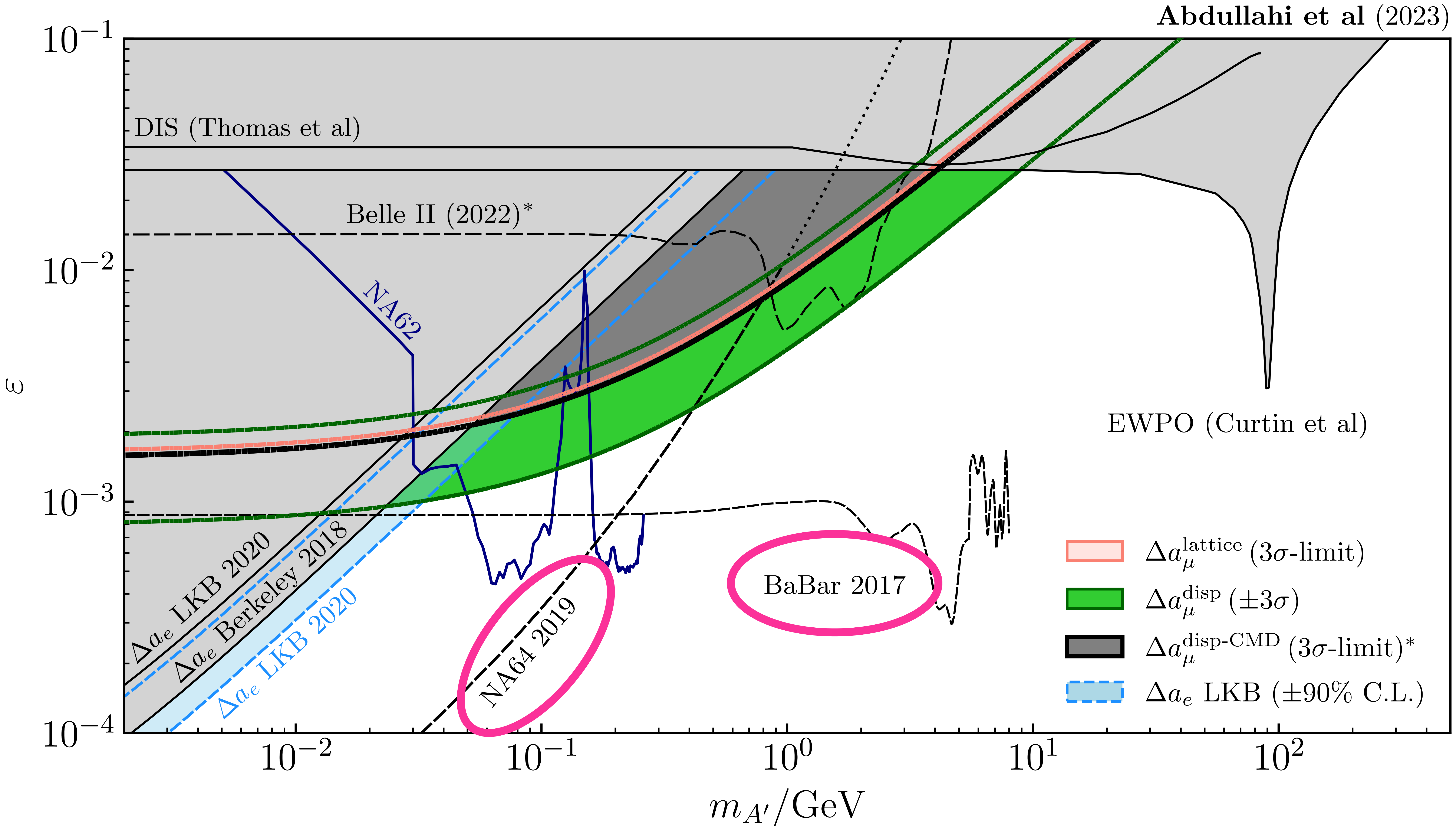
for

$$m_\mu \ll m_{A'}$$

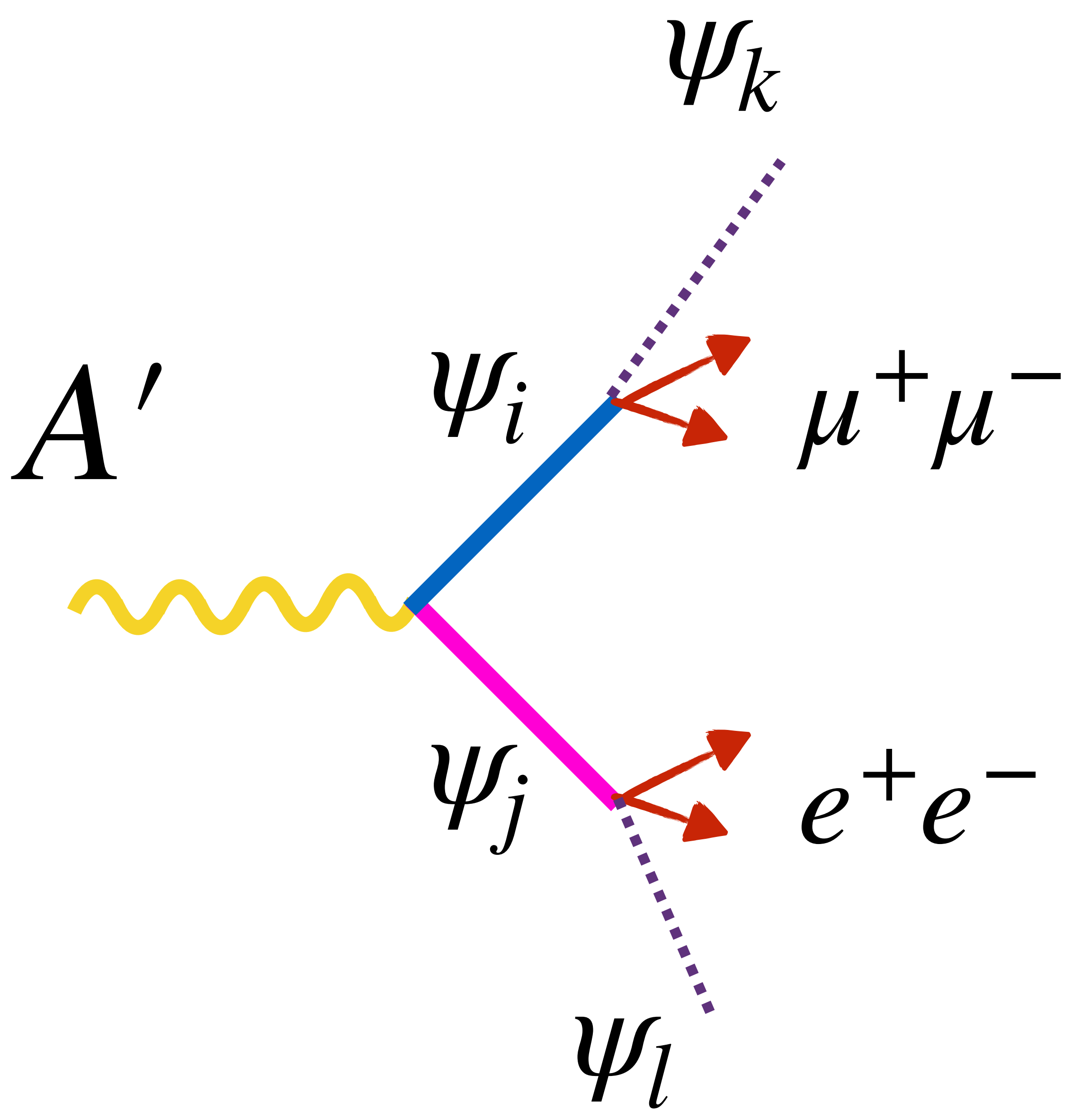
Gninenko and Krasnikov, PLB 513 (2001) 119
Pospelov, PRD 80 (2009) 095002

Dark Photons

Semi-visible decays



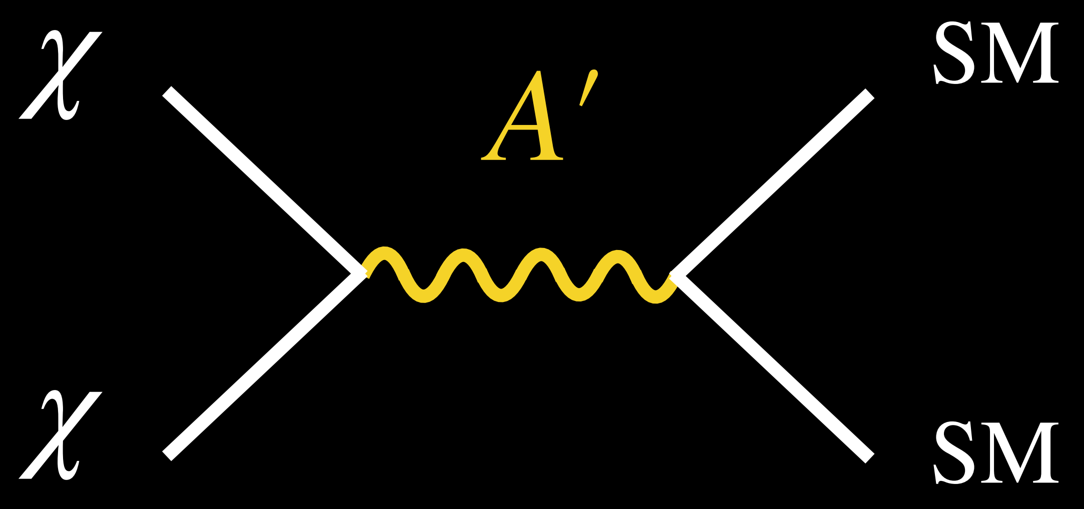
Semi-visible decays chains, e.g.,

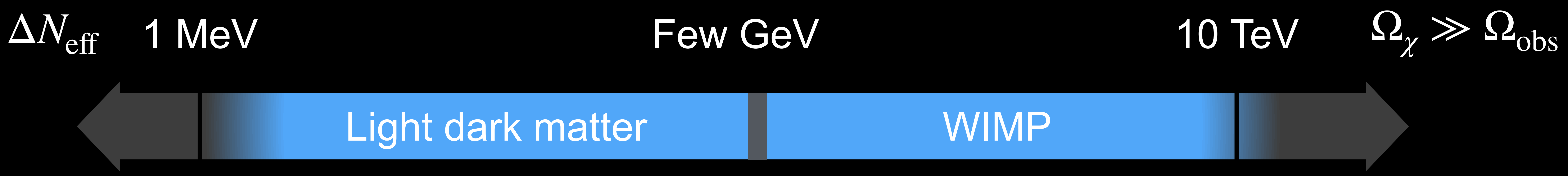


Light Dark Matter

Thermal freeze-out dark matter with direct annihilation to SM particles

Predictive and testable.

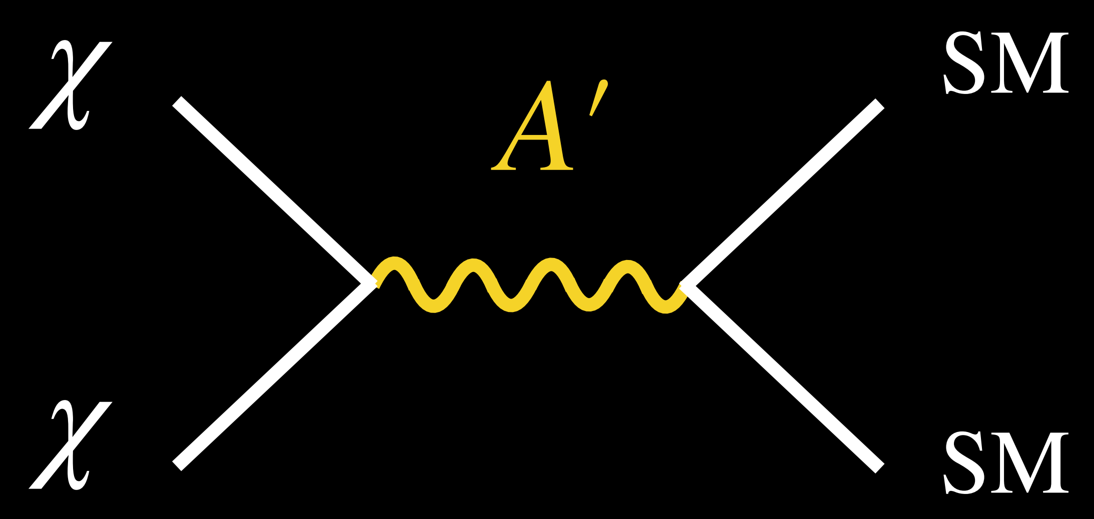


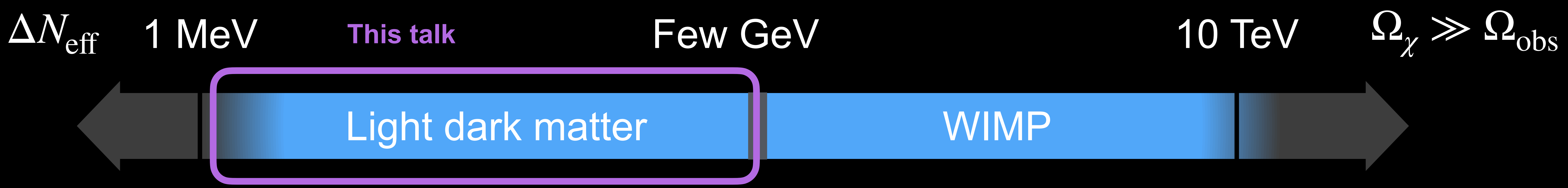


Light Dark Matter

Thermal freeze-out dark matter with direct annihilation to SM particles

Predictive and testable.



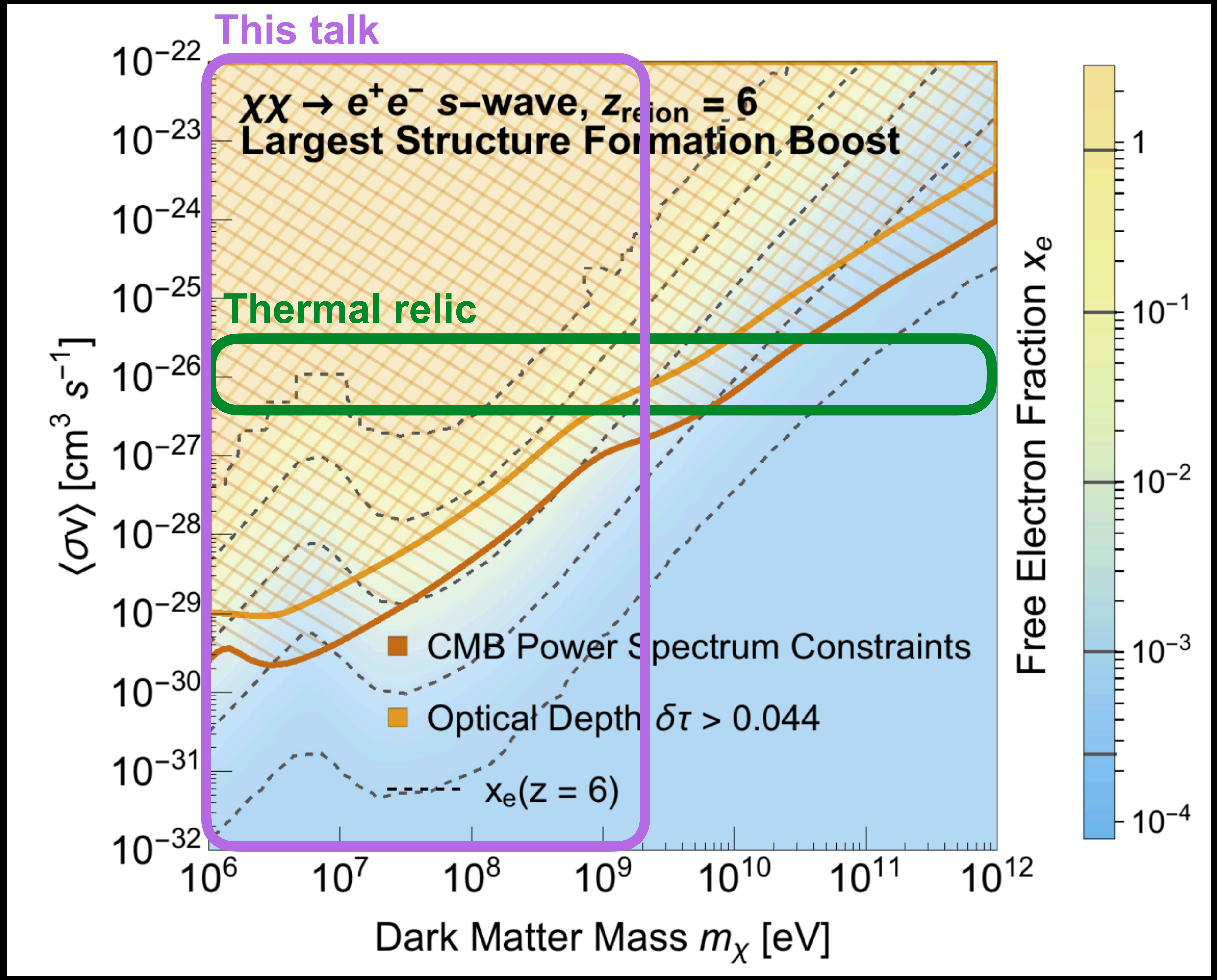


Light Dark Matter

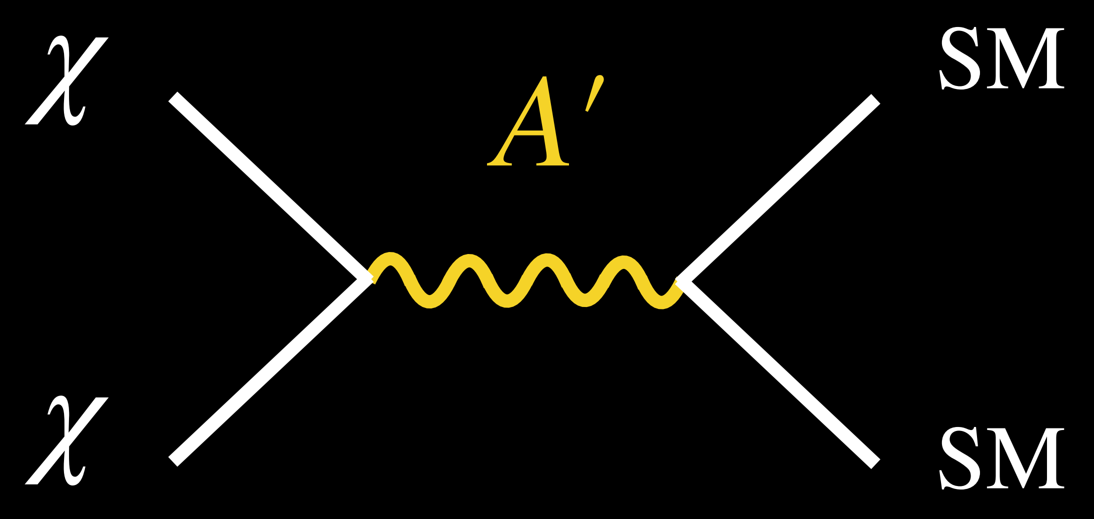
Freeze-out and CMB limits

Self-annihilations inject energy into CMB at late times (H/He ionization)

H. Liu, T. Slatyer, J. Zavala, 1604.02457



S-wave annihilation (i.e. velocity-independent annihilation xsec $\langle\sigma v\rangle \sim a$) is excluded by CMB at low masses.

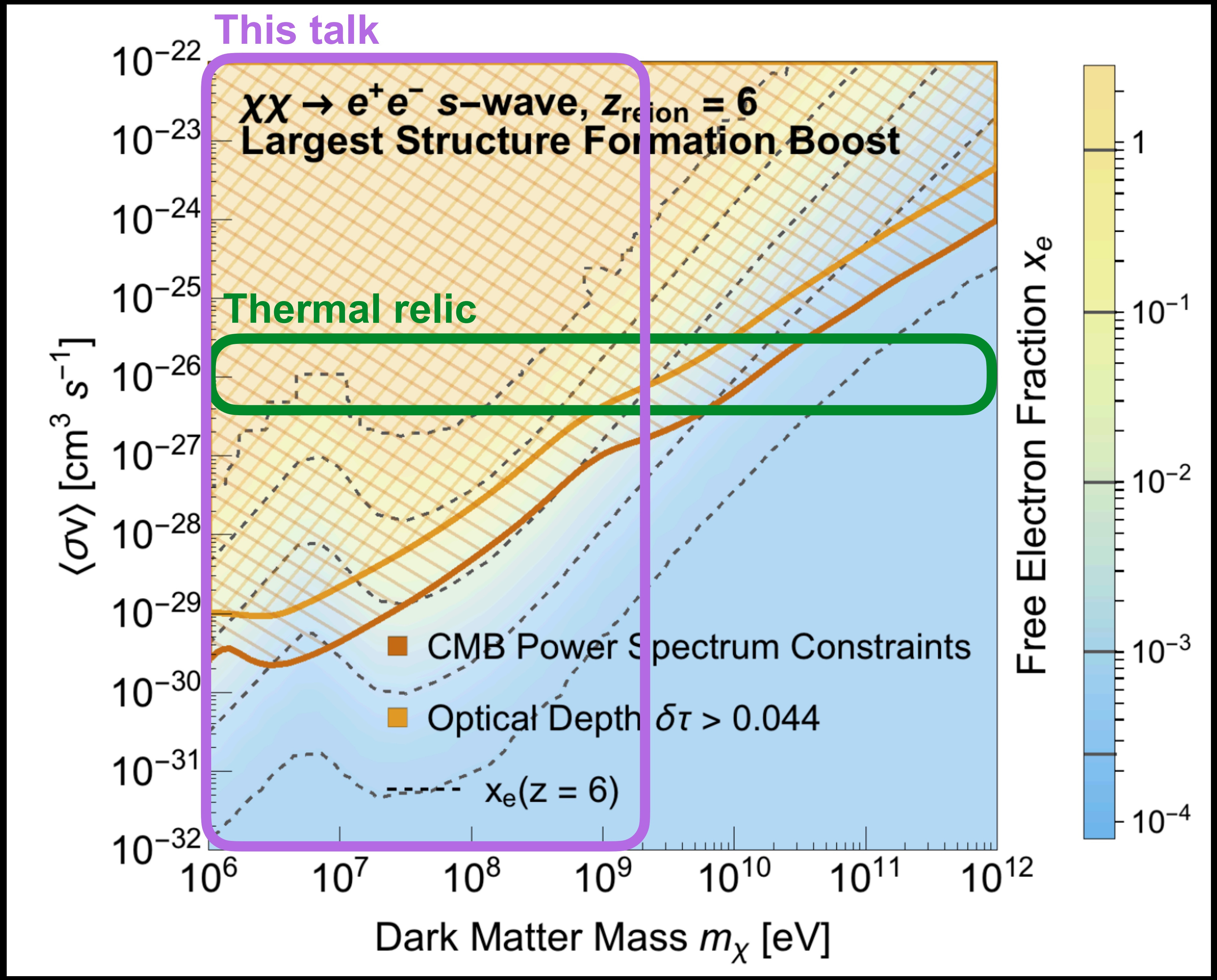


Light Dark Matter

Freeze-out and CMB limits

Self-annihilations inject energy into CMB at late times (H/He ionization)

H. Liu, T. Slatyer, J. Zavala, 1604.02457



Solution 1) no charged states are produced,

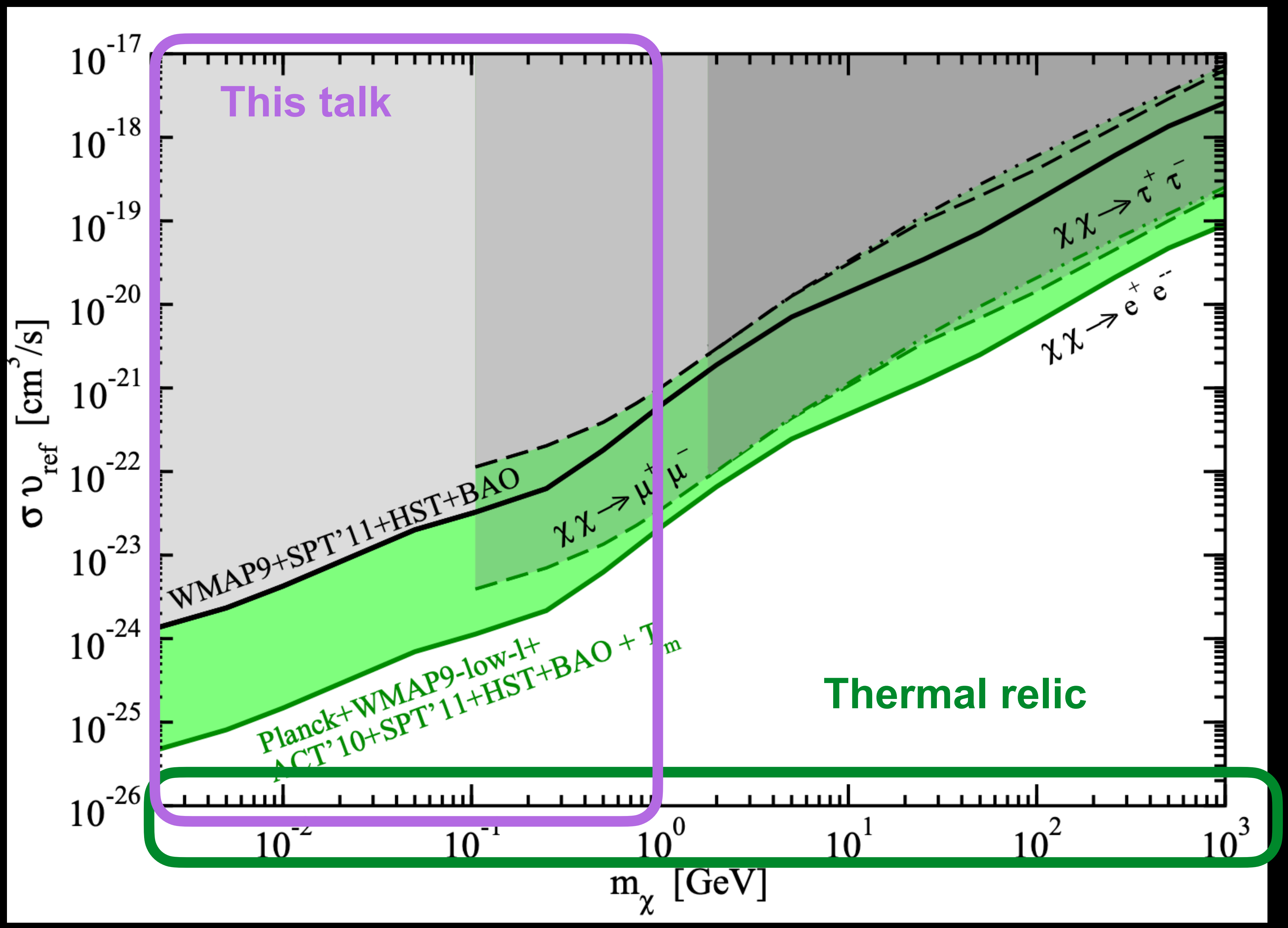
- “Neutrinophilic" dark matter
- Annihilations to dark states (secluded)

Light Dark Matter

Freeze-out and CMB limits

Self-annihilations inject energy into CMB at late times (H/He ionization)

Diamanti et al, arXiv:1308.2578



Solution 1) no charged states are produced,

- "Neutrinophilic" dark matter
- Annihilations to dark states (secluded)

Solution 2) late annihilation $\neq$ freeze-out annihilation,

- p-wave annihilation, $\langle \sigma v \rangle \sim bv^2$
- Resonantly-enhanced annihilations
- Asymmetric dark matter
- Forbidden annihilation
- **Co-annihilation ("inelastic" Dark Matter)**

$$\frac{n_2}{n_1} \propto e^{-(m_2 - m_1)/T}$$

Heavy partner becomes non-relativistic sooner and eventually decays away ($\psi_2 \to \psi_1 + \ldots$).

Inelastic Dark Matter

Direct detection

For inelastic scattering to take place, mass splitting should be sufficiently small.

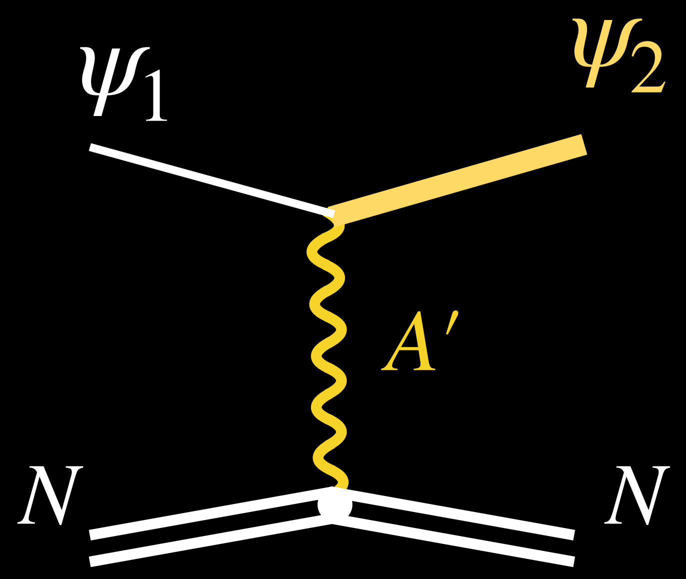
$$\Delta \equiv \frac{m_2 - m_1}{m_1} < \beta^2 \frac{m_N}{2(m_{\chi_1} + m_N)}$$

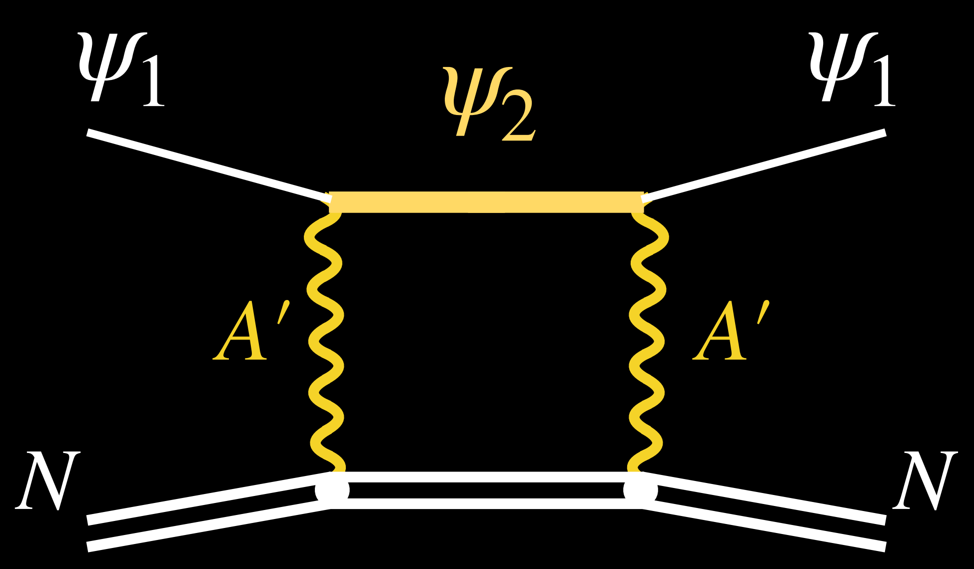
Velocity (β) thresholds are larger for lighter nuclei:

DAMA (Iodine 127) vs CDMS (Germanium 73)

D. Smith and N. Weiner, arXiv:0101138.

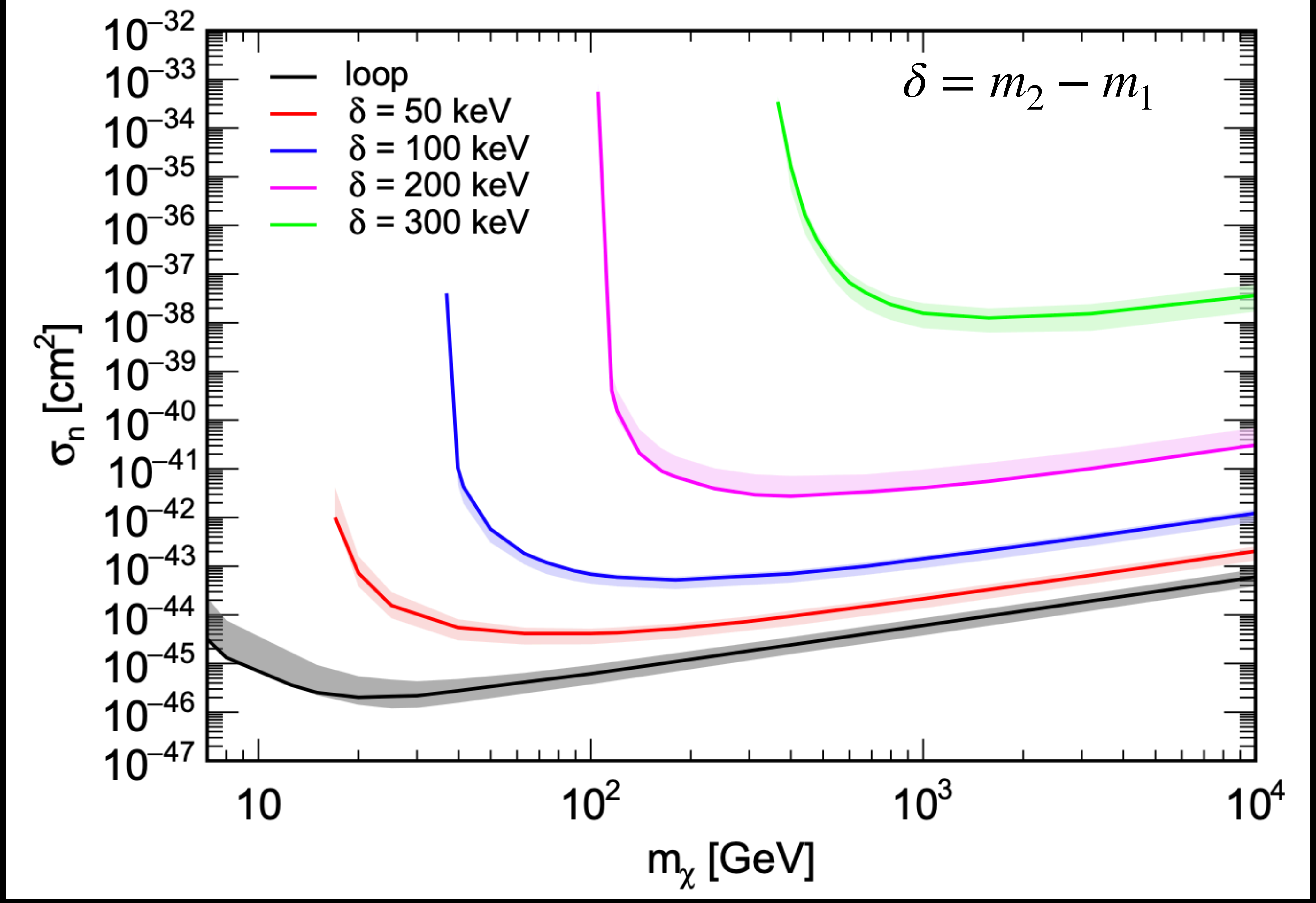
Later excluded by CDMS and XENON.





Challenging target for direct detection when the mass splitting is large.

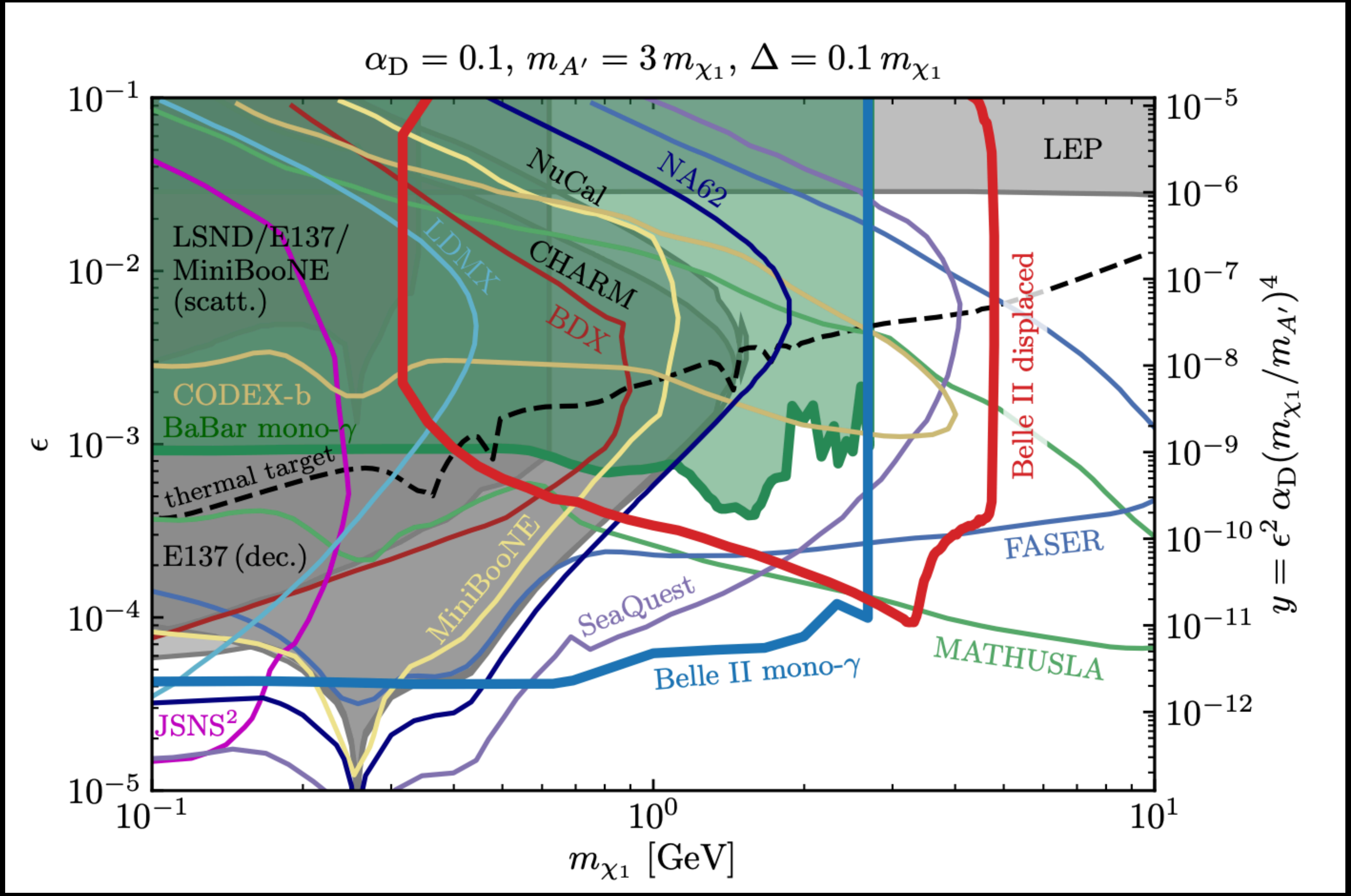
Limits from PandaX-II, arXiv:2205.08066



Inelastic Dark Matter

Accelerator searches

M. Duerr et al, arXiv:1911.03176

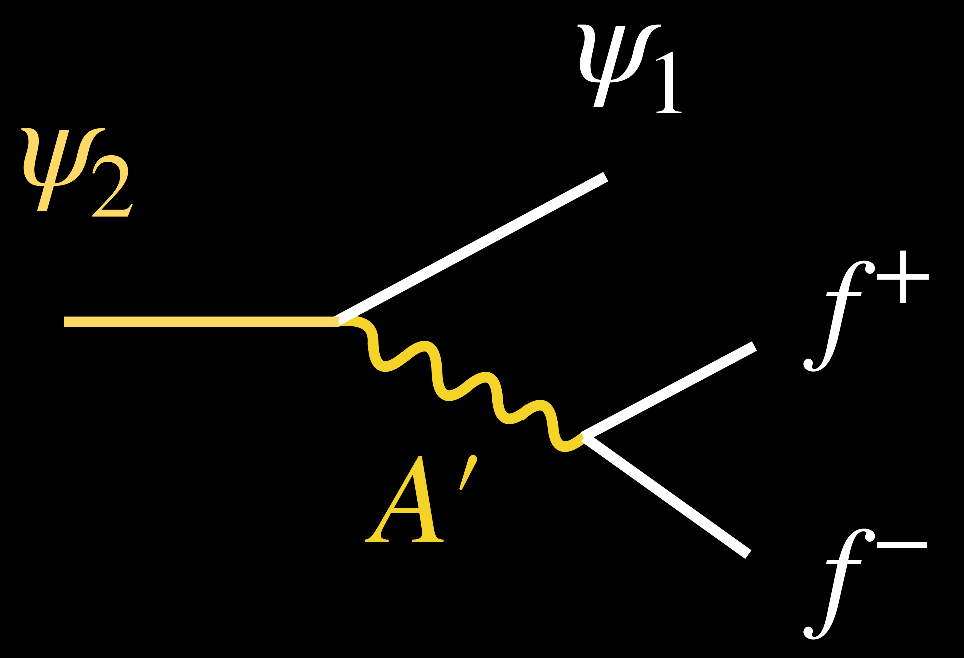


Heavy partner is now unstable.

Lifetime has strong dependence on $\Delta \equiv \dfrac{m_2 - m_1}{m_1}$.

Strong predictions for intensity frontier experiments.

$$\Gamma_{\psi_2 \to \psi_1 e^+ e^-} \sim \alpha \epsilon^2 \alpha_D \times \frac{\Delta^5}{m_{Z'}^4} m_1^5$$



- At small Δ and $m_{A'}$ — displaced decays dominate.
- At large Δ and $m_{A'}$ — fixed-target and colliders dominate.

Models of Semi-Visible Dark Photons

QED is rather boring...

Charge conservation overconstrains the theory:
Feinberg, Kabir, Weinberg, (1959)

1) All Weyl fermions form exact Dirac pairs, $Q(e_L) = Q(e_R)$.

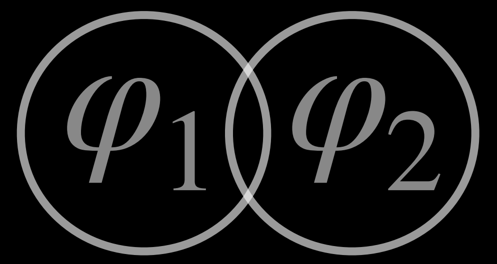
2) Flavor is conserved, fermions do not mix. No $\mu \to e$.

3) C, P, and T always conserved.

But that need not be the case in a (spontaneously) broken $U(1)$ theory.

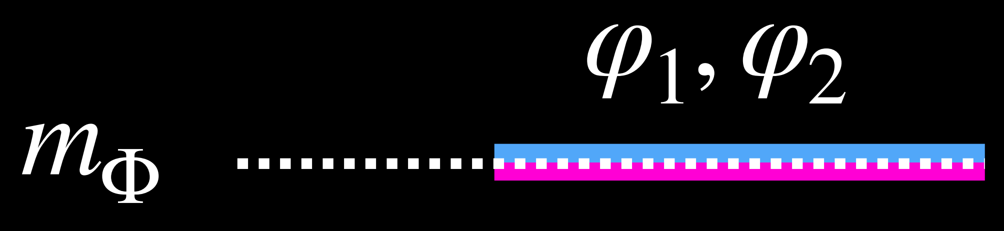
Light Dark Matter

Minimal example — complex scalar

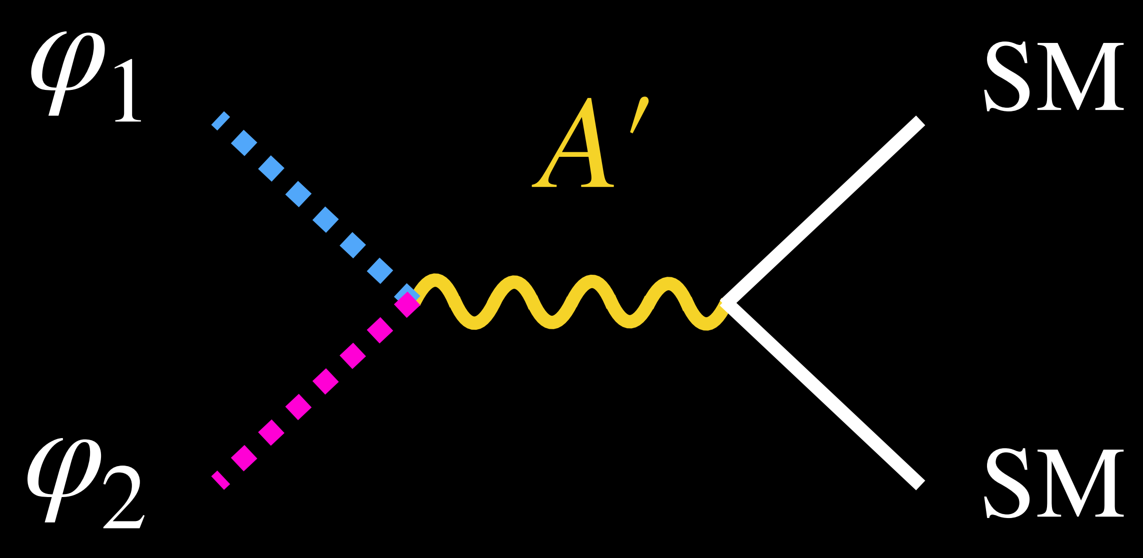


$U(1)_X$ charged complex scalar

$$\Phi \sim \varphi_1 + i\varphi_2$$



$$-\mathscr{L} \supset m_\Phi^2 |\Phi|^2$$



$$J_D^\mu = \Phi^* \, i\overleftrightarrow{\partial^\mu} \, \Phi$$

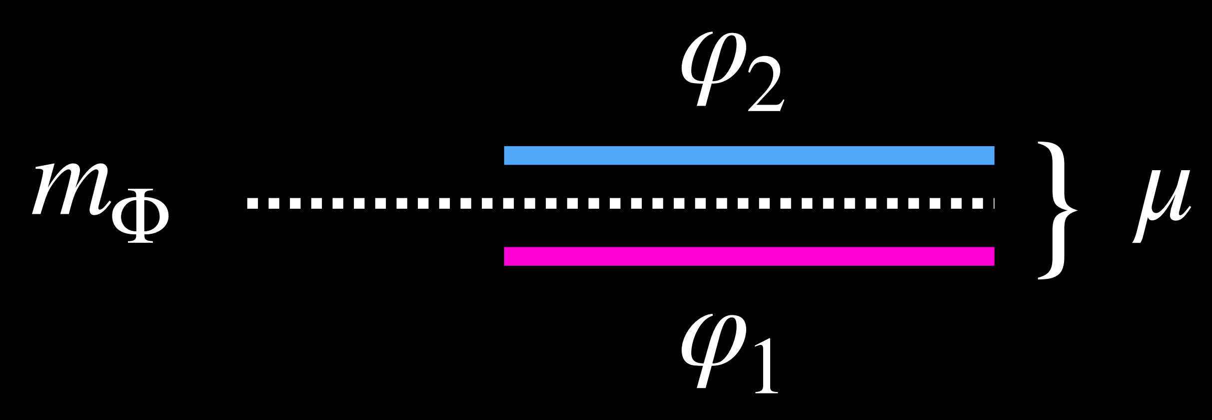
Light Dark Matter

Minimal example — complex scalar

$U(1)_X$ charged complex scalar

$$\Phi \sim \varphi_1 + i\varphi_2$$

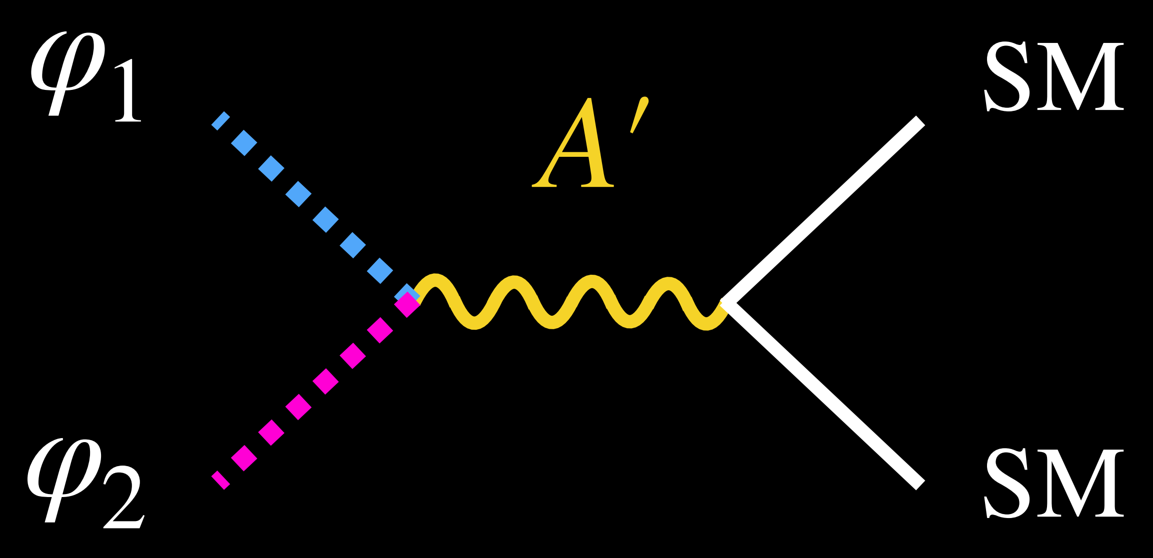
$$-\mathscr{L} \supset m_\Phi^2 |\Phi|^2 + \frac{\mu}{2}(\Phi^2 + h.c.)$$



The term Φ^2 breaks the $U(1)_X$ by 2 units and splits the scalar components.

The dark current is purely off-diagonal:

$$J_D^\mu = \Phi^* \, i\overleftrightarrow{\partial^\mu} \, \Phi = i(\varphi_2 \partial^\mu \varphi_1 - \varphi_1 \partial^\mu \varphi_2)$$



Models of Semi-Visible Dark Photons

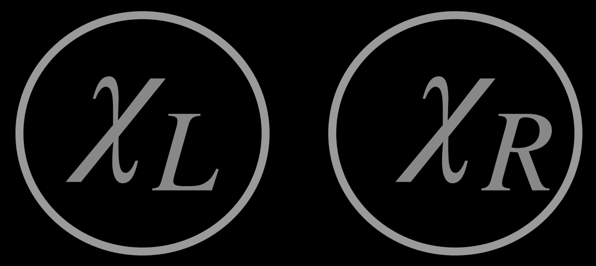
Model 1 — Inelastic Dark Matter

D. Smith and N. Weiner, arXiv:0101138.

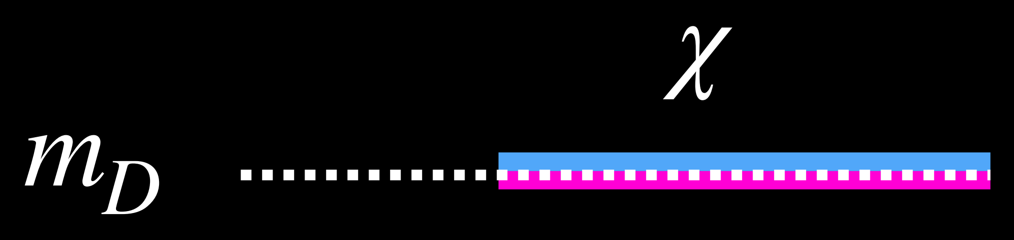
χ_L χ_R

Light Dark Matter

Models of Co-Annihilation — inelastic Dark Matter



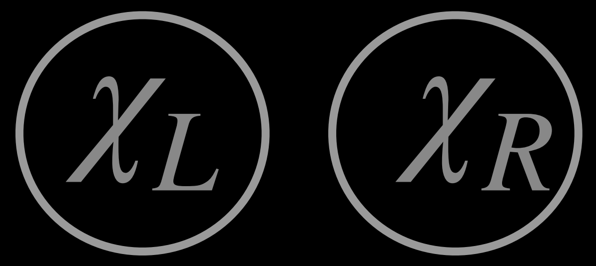
$U(1)_X$ charged fermion: $\chi = \chi_L + \chi_R$.



$$-\mathscr{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & 0 \end{pmatrix} \begin{pmatrix} \chi_L^c \\ \chi_R \end{pmatrix}$$

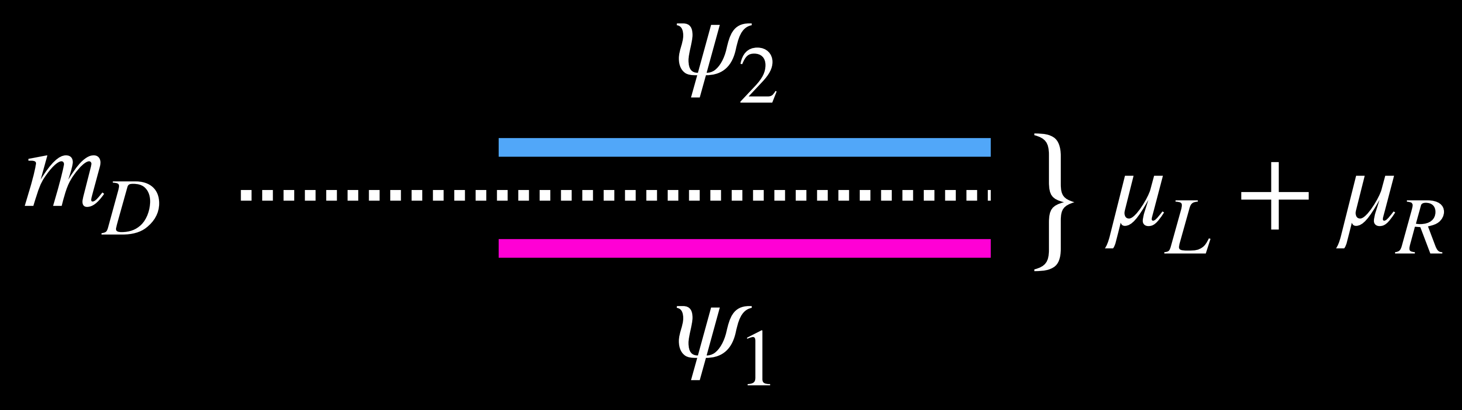
Light Dark Matter

Models of Co-Annihilation — inelastic Dark Matter



$U(1)_X$ charged fermion: $\chi = \chi_L + \chi_R$.

Majorana masses break the $U(1)_X$ by 2 units.



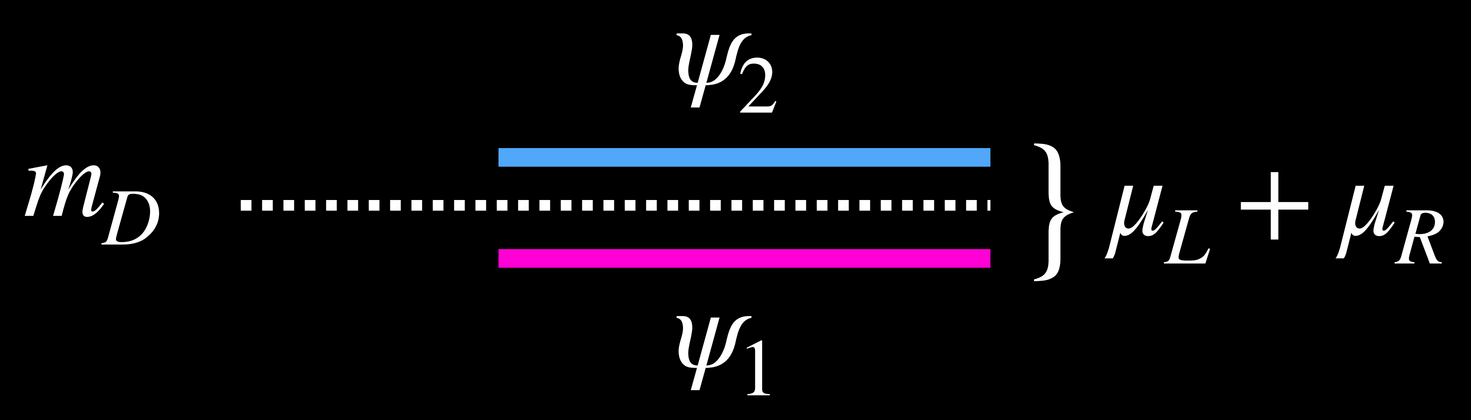
$$-\mathscr{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} \mu_L & m_D \\ m_D & \mu_R \end{pmatrix} \begin{pmatrix} \chi_L^c \\ \chi_R \end{pmatrix} \qquad \tan 2\theta = \frac{2m_D}{\mu_R - \mu_L}$$

Two Majorana fermions, forming a pseudo-Dirac pair.

Light Dark Matter

Models of Co-Annihilation — inelastic Dark Matter

χ_L χ_R



$U(1)_X$ charged fermion: $\chi = \chi_L + \chi_R$.

Majorana masses break the $U(1)_X$ by 2 units.

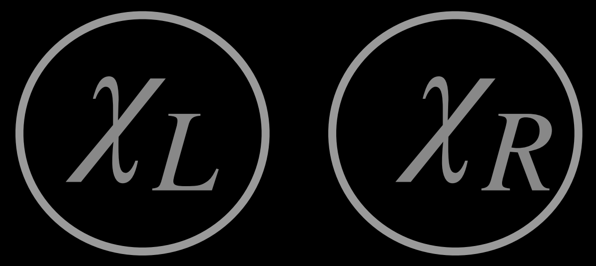
$$-\mathscr{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} \mu_L & m_D \\ m_D & \mu_R \end{pmatrix} \begin{pmatrix} \chi_L^c \\ \chi_R \end{pmatrix} \qquad \tan 2\theta = \frac{2m_D}{\mu_R - \mu_L} \to \infty$$

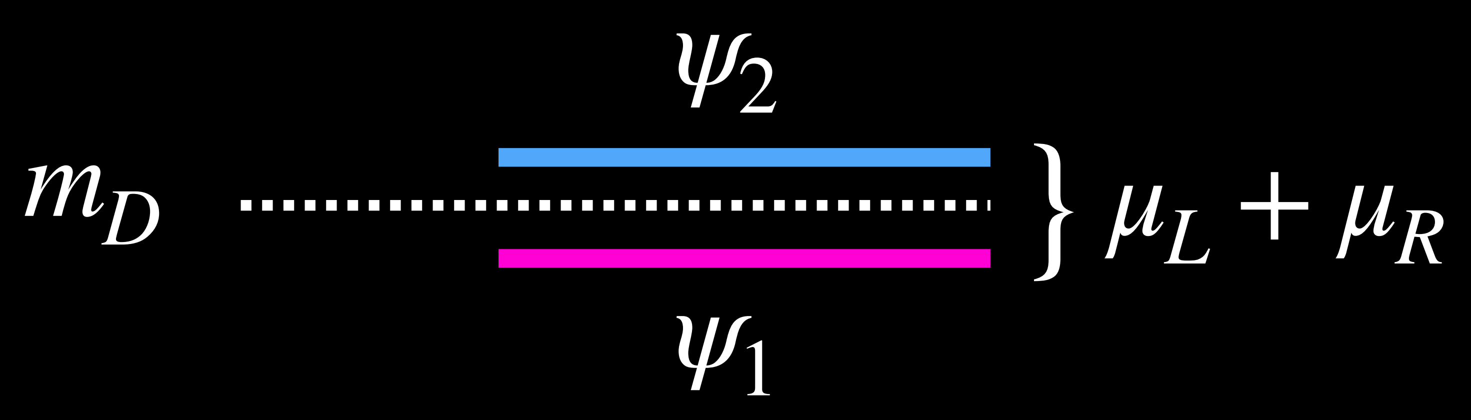
If $\mu \equiv \mu_L = \mu_R$, fermions maximally mix, and the mass basis is:

$$\psi_+ \equiv \frac{\chi_L^c + \chi_R}{\sqrt{2}}, \quad \psi_- \equiv \frac{\chi_L^c - \chi_R}{\sqrt{2}}$$

Light Dark Matter

Models of Co-Annihilation — inelastic Dark Matter





$U(1)_X$ charged fermion: $\chi = \chi_L + \chi_R$.

Majorana masses break the $U(1)_X$ by 2 units.

$$-\mathscr{L} \supset \frac{1}{2}\left(\overline{\chi_L} \quad \overline{\chi_R^c}\right)\begin{pmatrix}\mu_L & m_D \\ m_D & \mu_R\end{pmatrix}\begin{pmatrix}\chi_L^c \\ \chi_R\end{pmatrix} \qquad \tan 2\theta = \frac{2m_D}{\mu_R - \mu_L} \to \infty$$

If $\mu \equiv \mu_L = \mu_R$, fermions maximally mix, and the mass basis is:

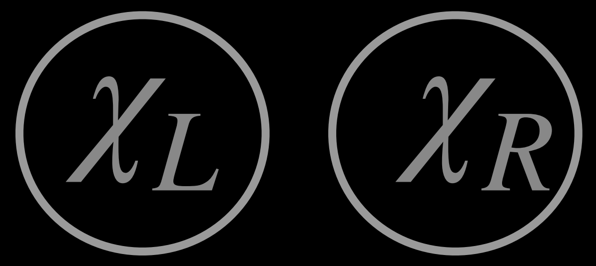
$$\psi_+ \equiv \frac{\chi_L^c + \chi_R}{\sqrt{2}}, \quad \psi_- \equiv \frac{\chi_L^c - \chi_R}{\sqrt{2}}$$

$$C(\psi_+) = +1, \quad C(\psi_-) = -1, \quad C(A') = -1.$$

These are the eigenstates of C conjugation under which $\chi_L^c \leftrightarrow \chi_R$.

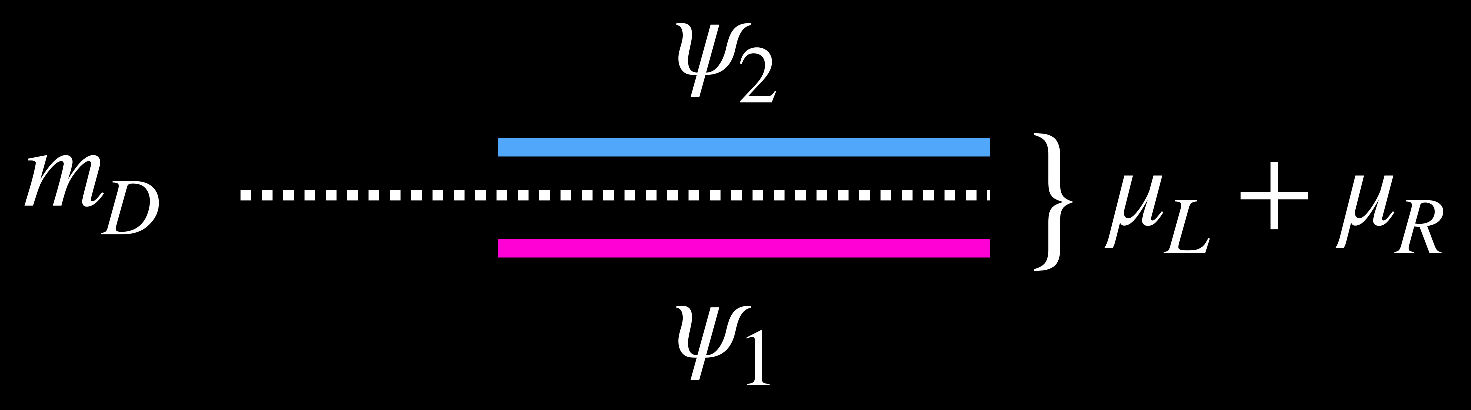
Light Dark Matter

Models of Co-Annihilation — inelastic Dark Matter



$U(1)_X$ charged fermion: $\chi = \chi_L + \chi_R$.

Majorana masses break the $U(1)_X$ by 2 units.



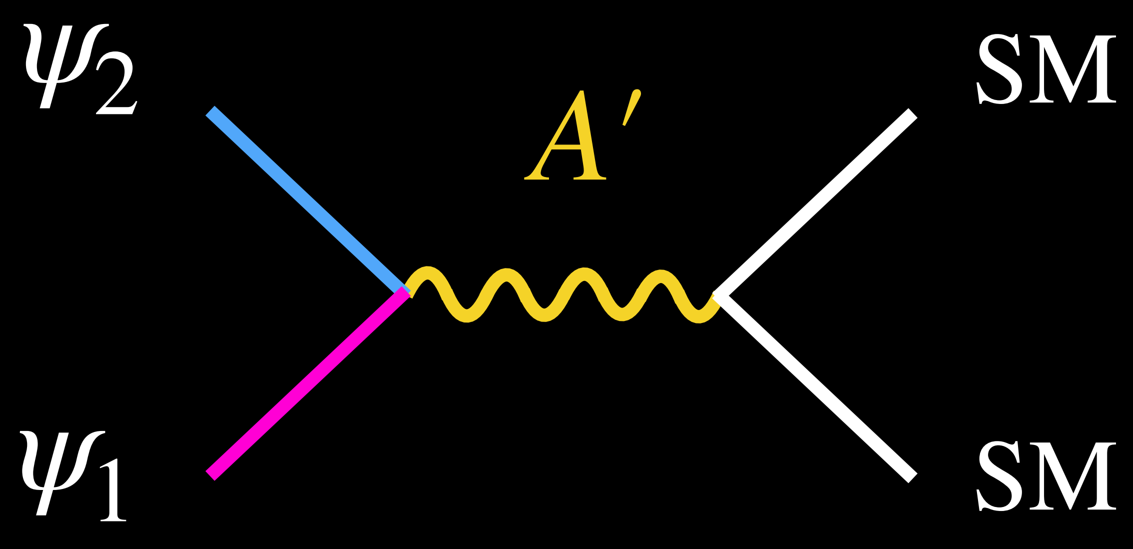
$$-\mathscr{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} \mu_L & m_D \\ m_D & \mu_R \end{pmatrix} \begin{pmatrix} \chi_L^c \\ \chi_R \end{pmatrix} \qquad \tan 2\theta = \frac{2m_D}{\mu_R - \mu_L} \to \infty$$

If $\mu \equiv \mu_L = \mu_R$, fermions maximally mix, and the mass basis is:

$$\psi_+ \equiv \frac{\chi_L^c + \chi_R}{\sqrt{2}}, \quad \psi_- \equiv \frac{\chi_L^c - \chi_R}{\sqrt{2}}$$

$$C(\psi_+) = +1, \quad C(\psi_-) = -1, \quad C(A') = -1.$$

These are the eigenstates of C conjugation under which $\chi_L^c \leftrightarrow \chi_R$.



$$J_X^\mu = \overline{\psi_+}\gamma^\mu\psi_- = \overline{\psi_2}\gamma^\mu\psi_1$$

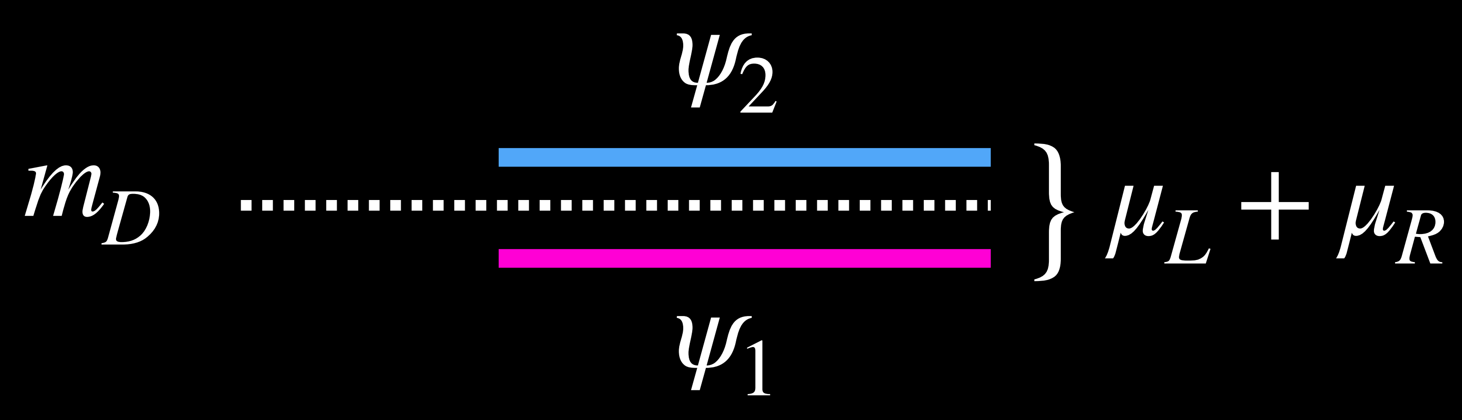
Light Dark Matter

Models of Co-Annihilation — inelastic Dark Matter

χ_L χ_R

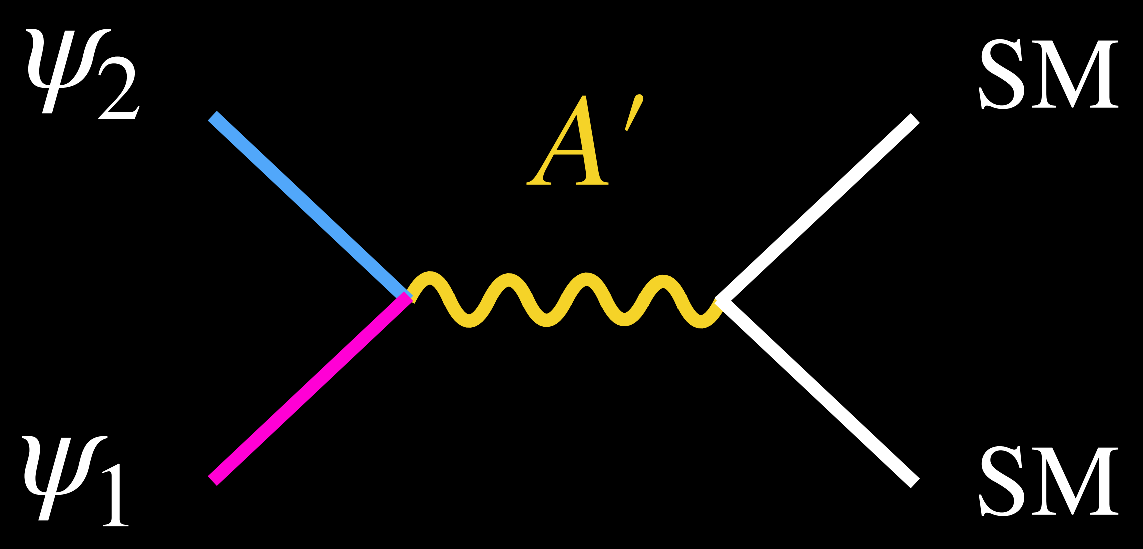
$U(1)_X$ charged fermion: $\chi = \chi_L + \chi_R$.

Majorana masses break the $U(1)_X$ by 2 units.



Dark photon decay
branching ratios:

1	$A' \to \psi_2 \psi_1$
$(e\varepsilon)^2/g_D^2$	$A' \to f^+ f^-$

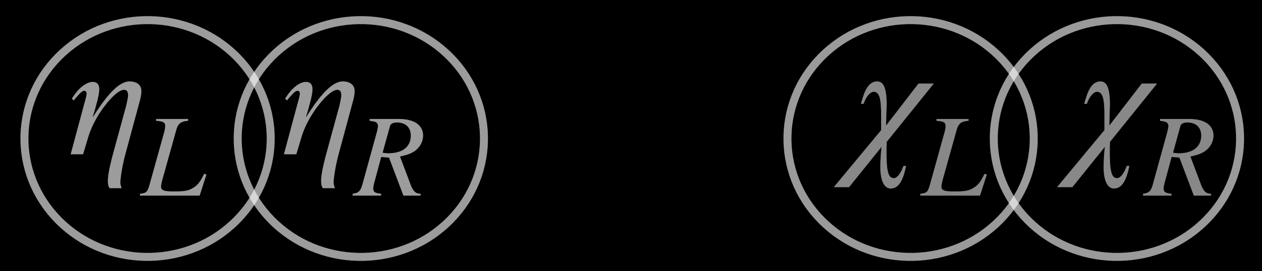


$$J_X^\mu = \overline{\psi_+}\gamma^\mu\psi_- = \overline{\psi_2}\gamma^\mu\psi_1$$

Models of Semi-Visible Dark Photons

Model 2 — Inelastic Dirac Dark Matter

A. Filomonova et al, arXiv:2201.08409



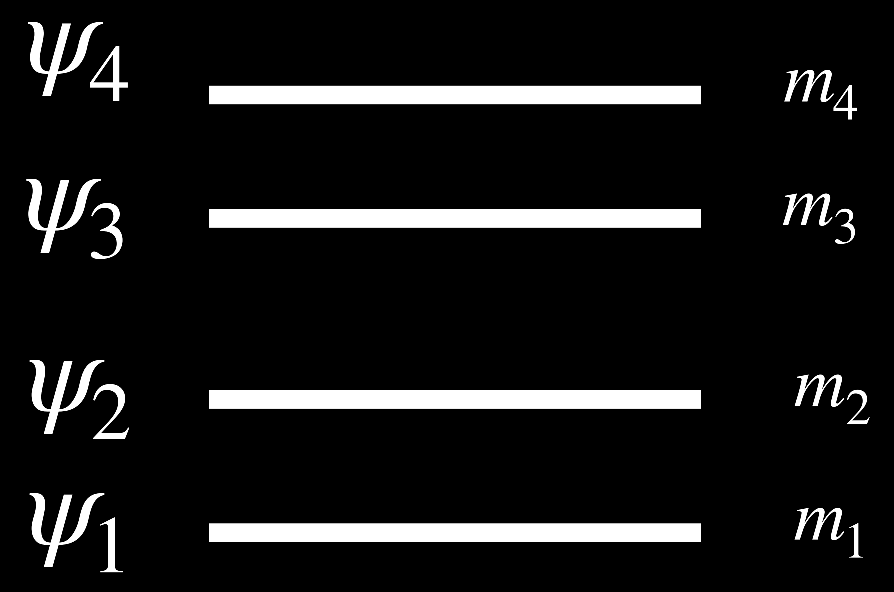
Light Dark Matter

Inelastid Dirac Dark Matter — i2DM

η_L η_R χ_L χ_R

$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral $\eta = \eta_L + \eta_R$.
Breaking of the $U(1)_X$ by one unit.

$$-\mathscr{L} \supset \frac{1}{2}\left(\overline{\eta_L} \quad \overline{\eta_R^c} \quad \overline{\chi_L} \quad \overline{\chi_R^c}\right) \begin{pmatrix} 0 & M_1 & 0 & M_L \\ M_1 & 0 & M_R & 0 \\ 0 & M_R & 0 & M_2 \\ M_L & 0 & M_2 & 0 \end{pmatrix} \begin{pmatrix} \eta_L^c \\ \eta_R \\ \chi_L^c \\ \chi_R \end{pmatrix}$$



In all generality: four Majorana fermions.

Light Dark Matter

Inelastid Dirac Dark Matter — i2DM

$\eta_L \eta_R$ $\chi_L \chi_R$

$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral $\eta = \eta_L + \eta_R$.
Breaking of the $U(1)_X$ by one unit.

Ψ_2 $\sim \chi + \beta\eta$

Ψ_1 $\sim \eta + \beta\chi$

$$-\mathscr{L} \supset \frac{1}{2}\left(\overline{\eta_L} \quad \overline{\chi_L}\right)\begin{pmatrix} M_1 & M_R \\ M_L & M_2 \end{pmatrix}\begin{pmatrix} \eta_R \\ \chi_R \end{pmatrix}$$

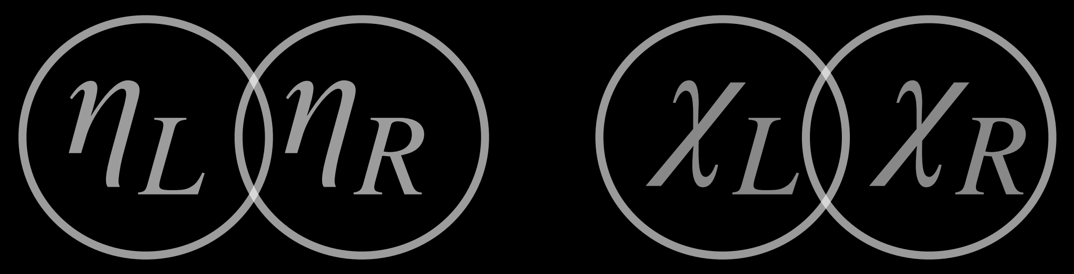
Imposing C symmetry again, we can then collapse to a Dirac fermion matrix

Working in the limit of two (pseudo-)Dirac fermions.

In this case, we ignore the "pseudo-Diracness" of each state.

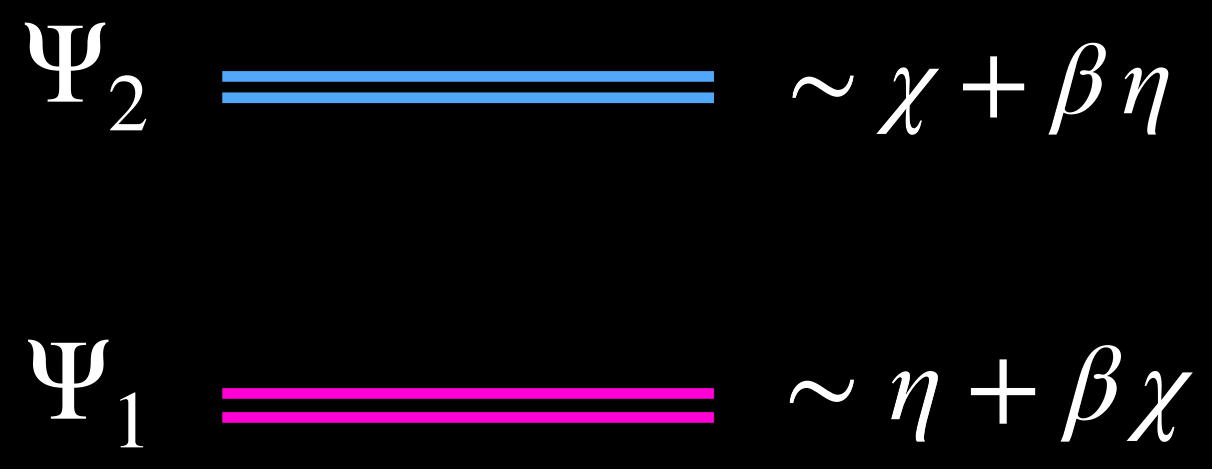
Light Dark Matter

Inelastid Dirac Dark Matter — i2DM



$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral $\eta = \eta_L + \eta_R$.

Breaking of the $U(1)_X$ by one unit.



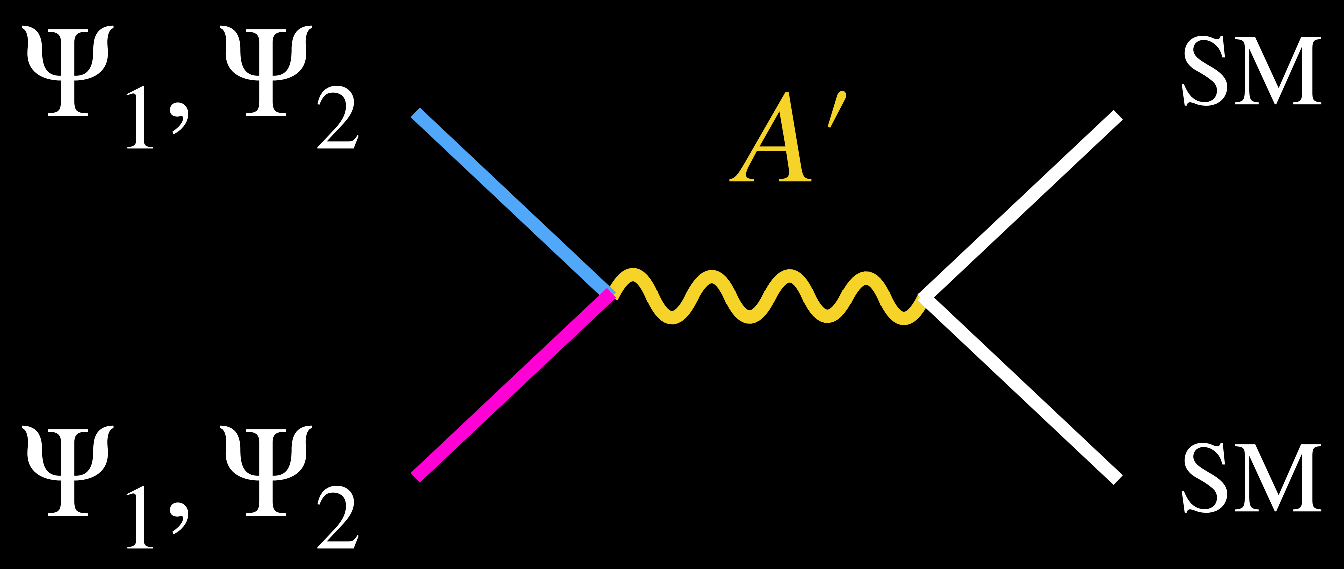
Dark photon decay branching ratios:

1 $A' \to \Psi_2\Psi_2$

β^2 $A' \to \Psi_1\Psi_2$

β^4 $A' \to \Psi_1\Psi_1$

$(e\varepsilon)^2/g_D^2$ $A' \to f^+f^-$

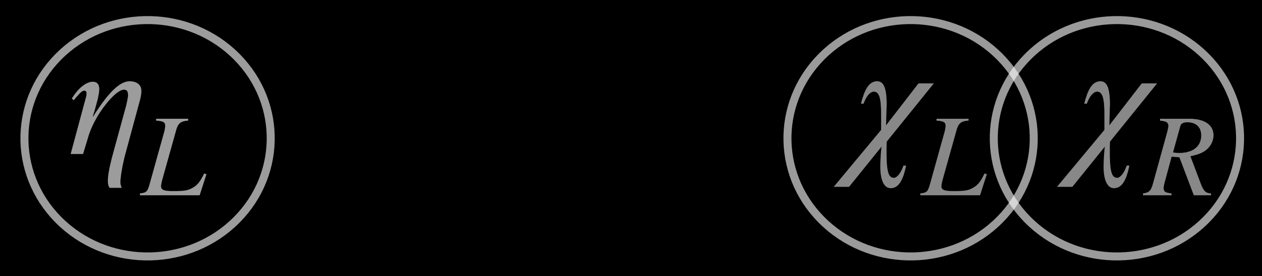


$$J_X^\mu = \left(\beta^2\,\overline{\Psi_1}\gamma^\mu\Psi_1 + \beta\,\overline{\Psi_2}\gamma^\mu\Psi_1 + \overline{\Psi_2}\gamma^\mu\Psi_2\right)$$

Mixing angle β

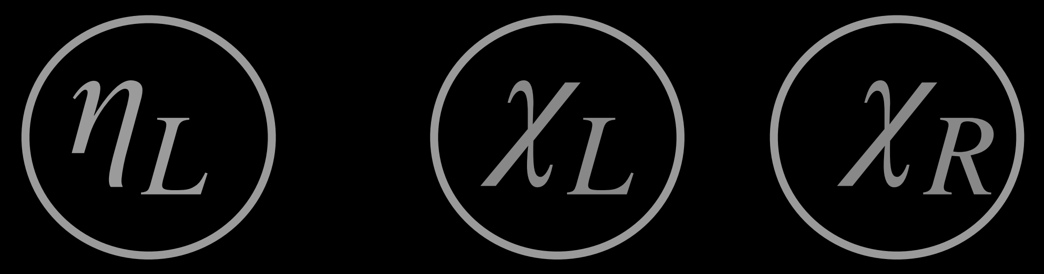
Models of Semi-Visible Dark Photons

Model 3 — Mixed Inelastic Dark Matter



Light Dark Matter

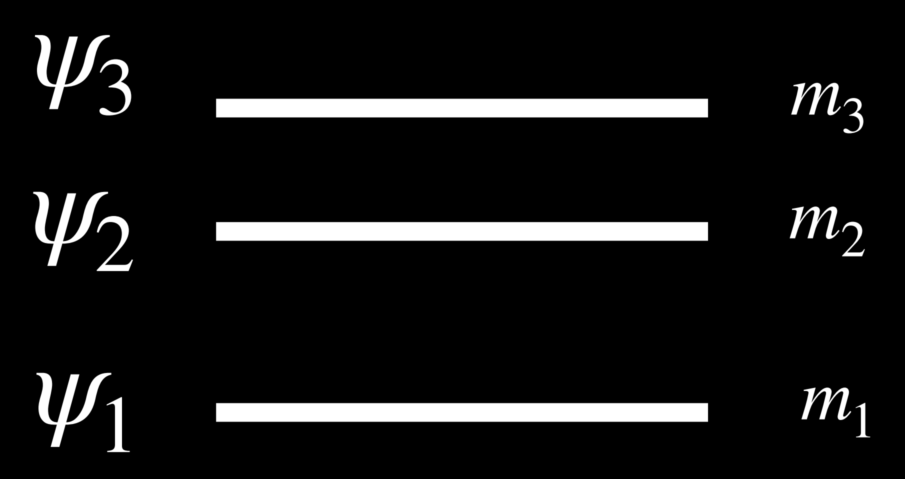
Mixed Inelastic Dark Matter — mixed iDM



$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral η_L

$\Lambda_{L,R}$ terms break the $U(1)_X$ by 1 units.

$$-\mathscr{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\eta_L} & \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} \mu_L & \Lambda_L & \Lambda_R \\ \Lambda_L & 0 & M_X \\ \Lambda_R & M_X & 0 \end{pmatrix} \begin{pmatrix} \eta_L^c \\ \chi_L^c \\ \chi_R \end{pmatrix}$$

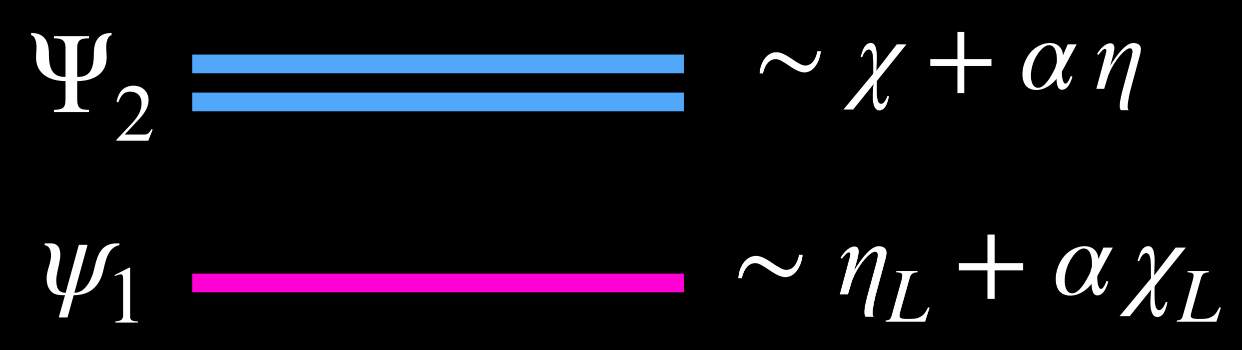


Light Dark Matter

Mixed Inelastic Dark Matter — mixed iDM

$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral η_L

$\Lambda_{L,R}$ terms break the $U(1)_X$ by 1 units.



$$-\mathscr{L} \supset \frac{1}{2}\begin{pmatrix}\overline{\eta_L} & \overline{\chi_L} & \overline{\chi_R^c}\end{pmatrix}\begin{pmatrix}\mu_L & \Lambda & \Lambda \\ \Lambda & 0 & M_X \\ \Lambda & M_X & 0\end{pmatrix}\begin{pmatrix}\eta_L^c \\ \chi_L^c \\ \chi_R\end{pmatrix} \longrightarrow \begin{pmatrix}\mu_L & \Lambda & 0 \\ \Lambda & M_X & 0 \\ 0 & 0 & -M_X\end{pmatrix}\begin{pmatrix}\eta_L^c \\ \psi_+ \\ \psi_-\end{pmatrix}$$

If $\Lambda \equiv \Lambda_L = \Lambda_R$, dark fermions maximally mix again.

$$\psi_+ \equiv \frac{\chi_L^c + \chi_R}{\sqrt{2}}, \quad \psi_- \equiv \frac{\chi_L^c - \chi_R}{\sqrt{2}}$$

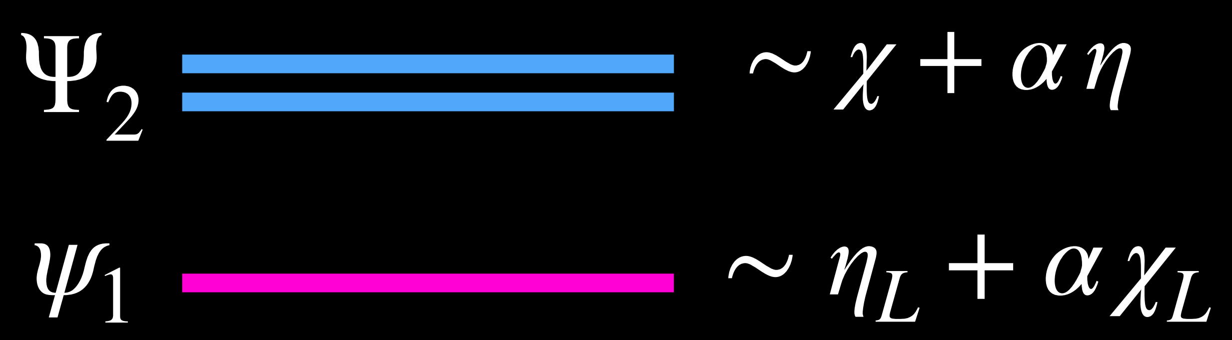
$$C(\eta_L) = +1, \quad C(\psi_+) = +1, \quad C(\psi_-) = -1, \quad C(A') = -1.$$

Light Dark Matter

Mixed Inelastic Dark Matter — mixed iDM

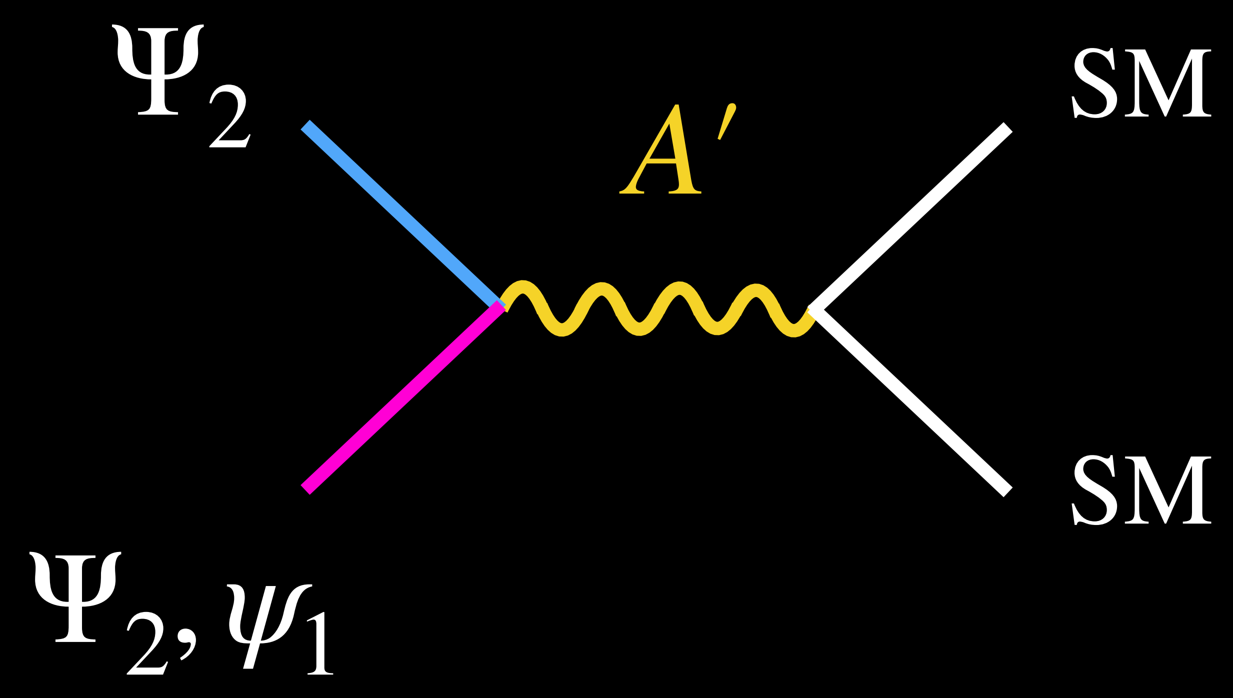
$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral η_L

$\Lambda_{L,R}$ terms break the $U(1)_X$ by 1 units.



Dark photon decay branching ratios:

1	$A' \to \Psi_2\Psi_2$
α^2	$A' \to \psi_1\Psi_2$
0	$A' \not\to \psi_1\psi_1$
$(e\varepsilon)^2/g_D^2$	$A' \to f^+f^-$



$$J_X^\mu = \overline{\Psi_2}\gamma^\mu\left(\Psi_2 + \alpha\,\psi_1\right)$$

Mixing angle α

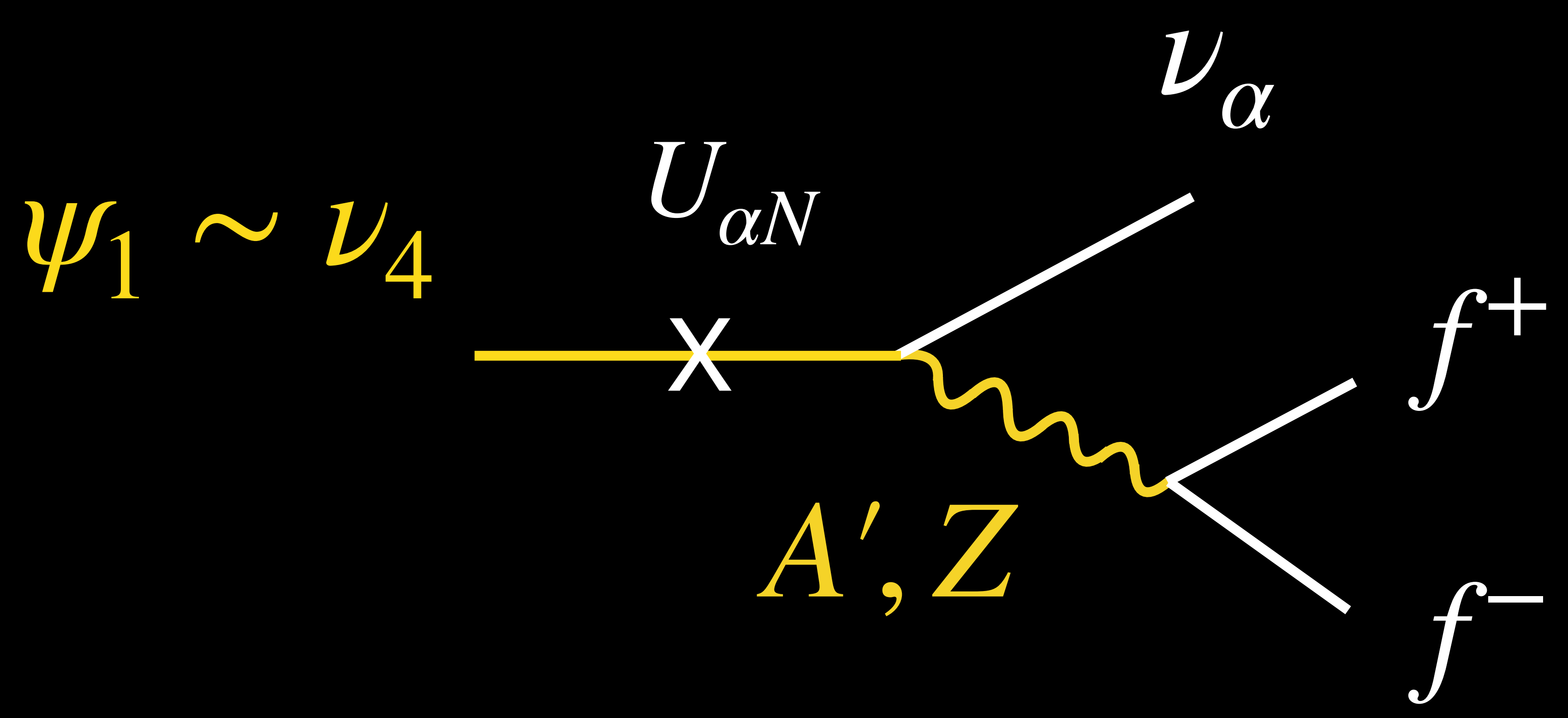
Heavy Neutral Leptons

Connection to neutrino masses

A. Abdullahi, MH, S. Pascoli arxiv:2007.11813

The singlet fermions η_L and η_R can mix with SM neutrinos:

$$\mathscr{L} \supset y\,LH\eta_L^c + y'LH\eta_R$$



$$\propto U_{\alpha N} \sim y\frac{v_{\mathrm{EW}}}{m_N}$$

Neutrino mixing is constrained by other types of probes.

Not necessary for this talk, but if present, it would indicate the nature of HNFs as Heavy Neutral Leptons in a "dark" seesaw mechanism.

The lightest HNF (now a HNL) can decay to SM neutrinos, so it would not be DM.

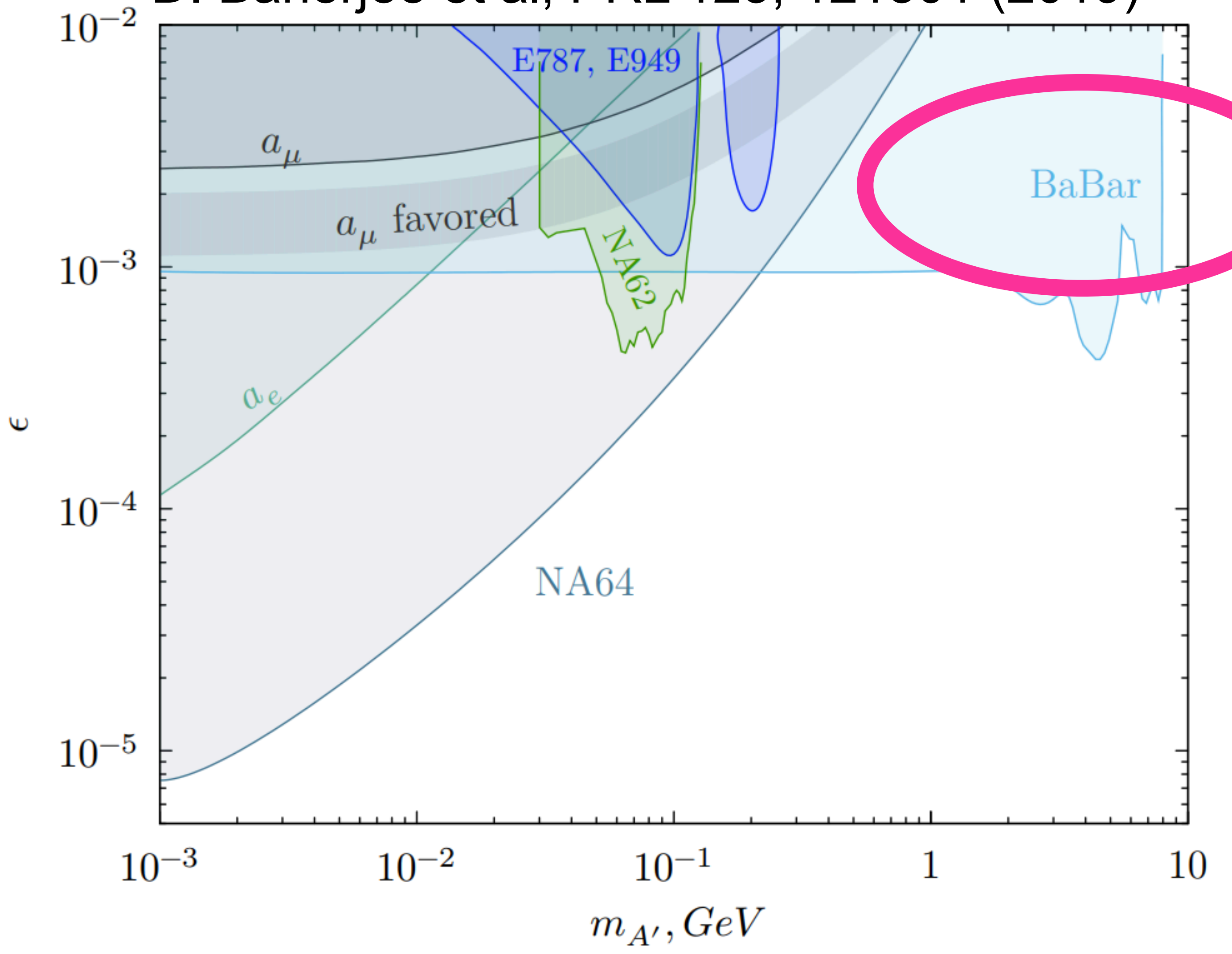
Experimental signatures

Semi-visible dark photons

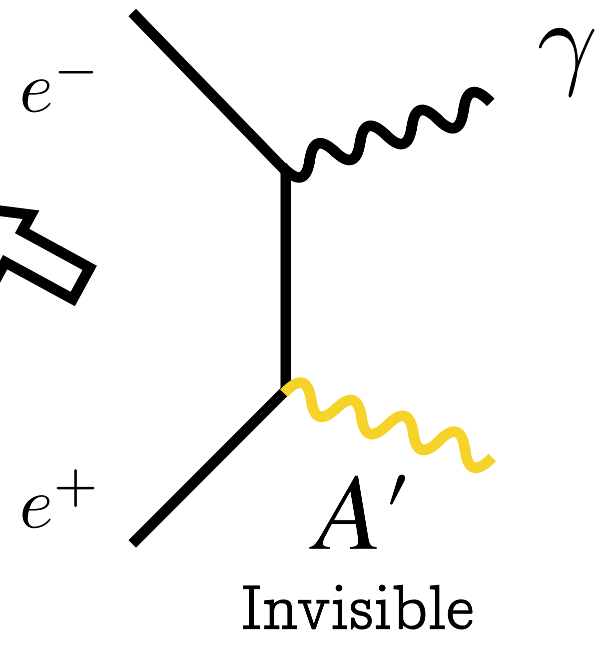
Dark Photons at BaBar

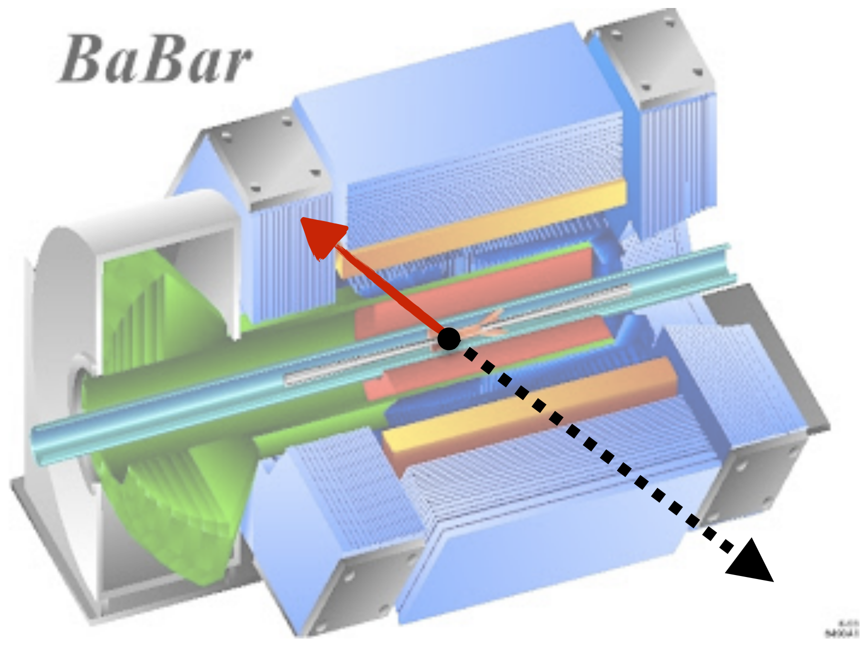
Initial state radiation searches (monophotons)

D. Banerjee et al, PRL 123, 121801 (2019)



ISR monophoton





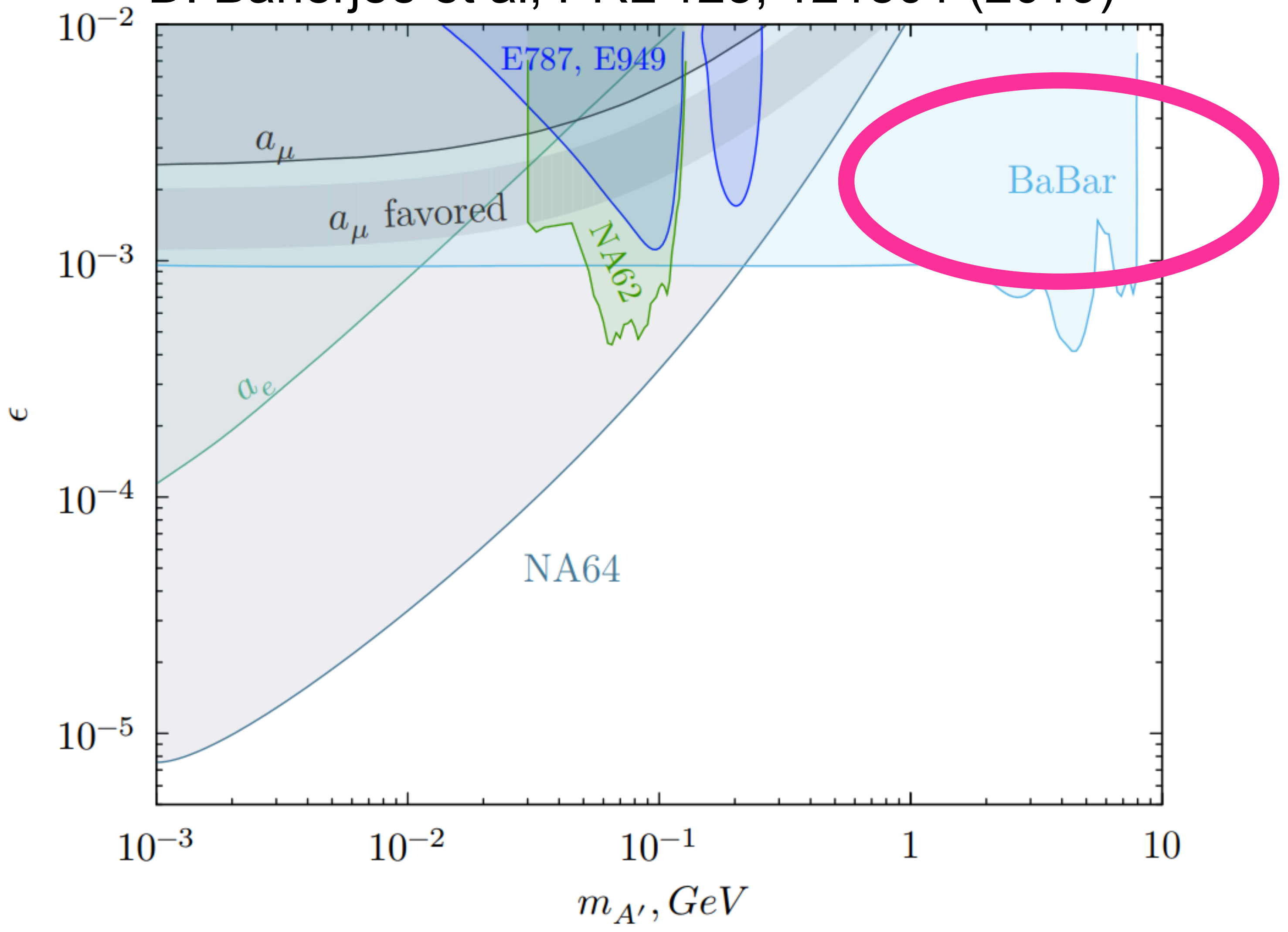
A single photon recoiling against an invisible massive particle. Dark photon mass reconstructed as:

$$M_X^2 = s - 2E_\gamma^{\mathrm{CM}}\sqrt{s}$$

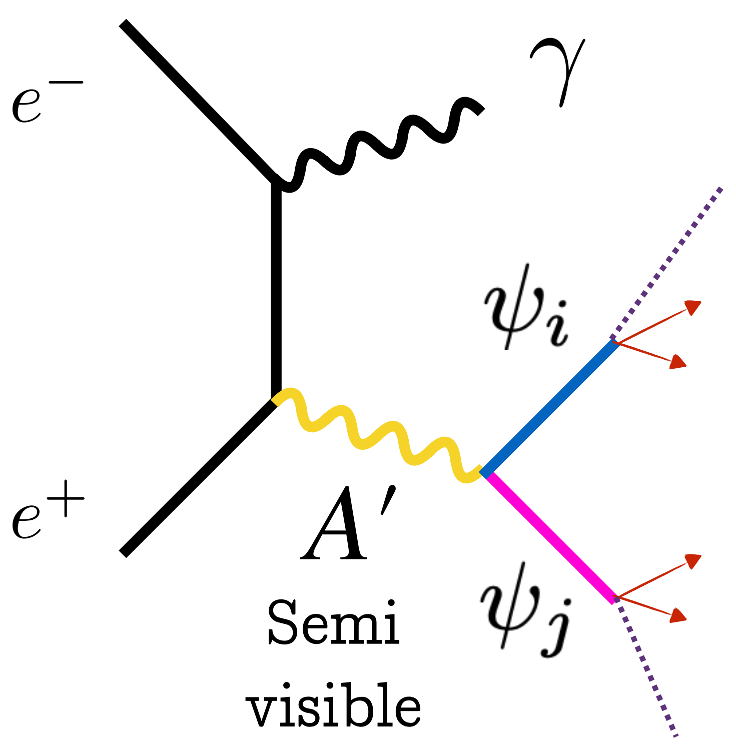
Dark Photons at BaBar

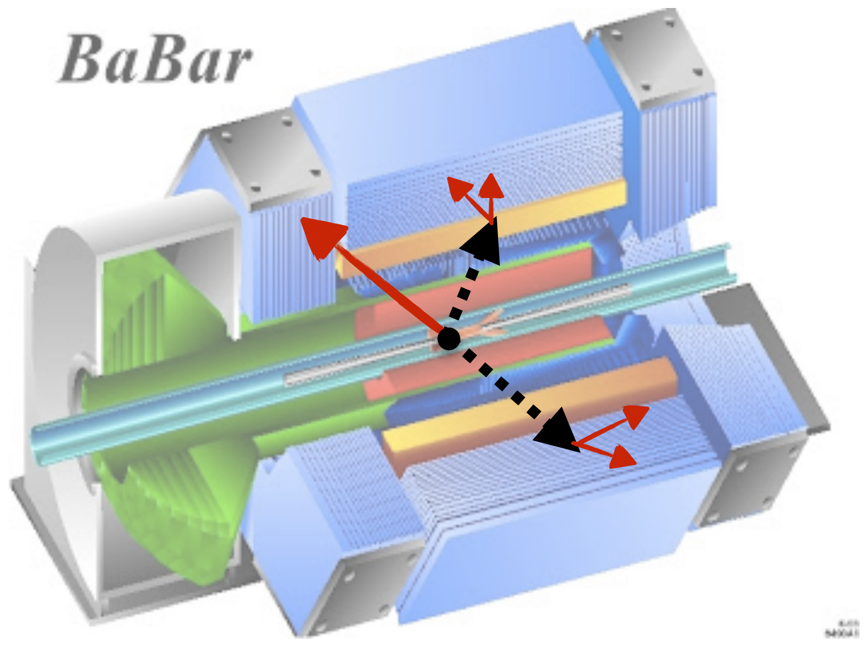
Initial state radiation searches (monophotons)

D. Banerjee et al, PRL 123, 121801 (2019)

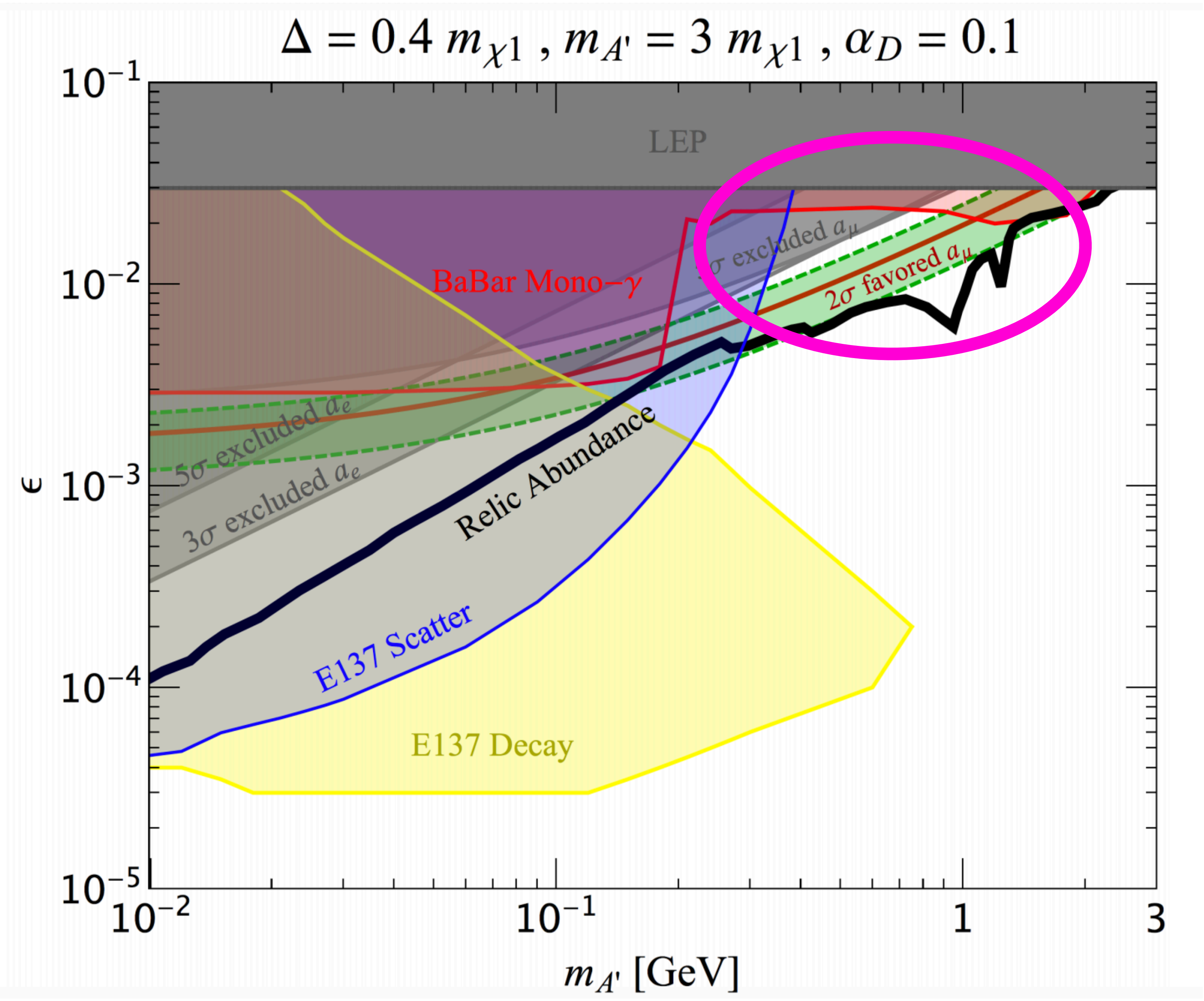


ISR monophoton





If A' decays semi-visibly, then additional tracks are vetoed in the mono photon selection.



G. Mohlabeng, Phys. Rev. D 99, 115001 (2019)

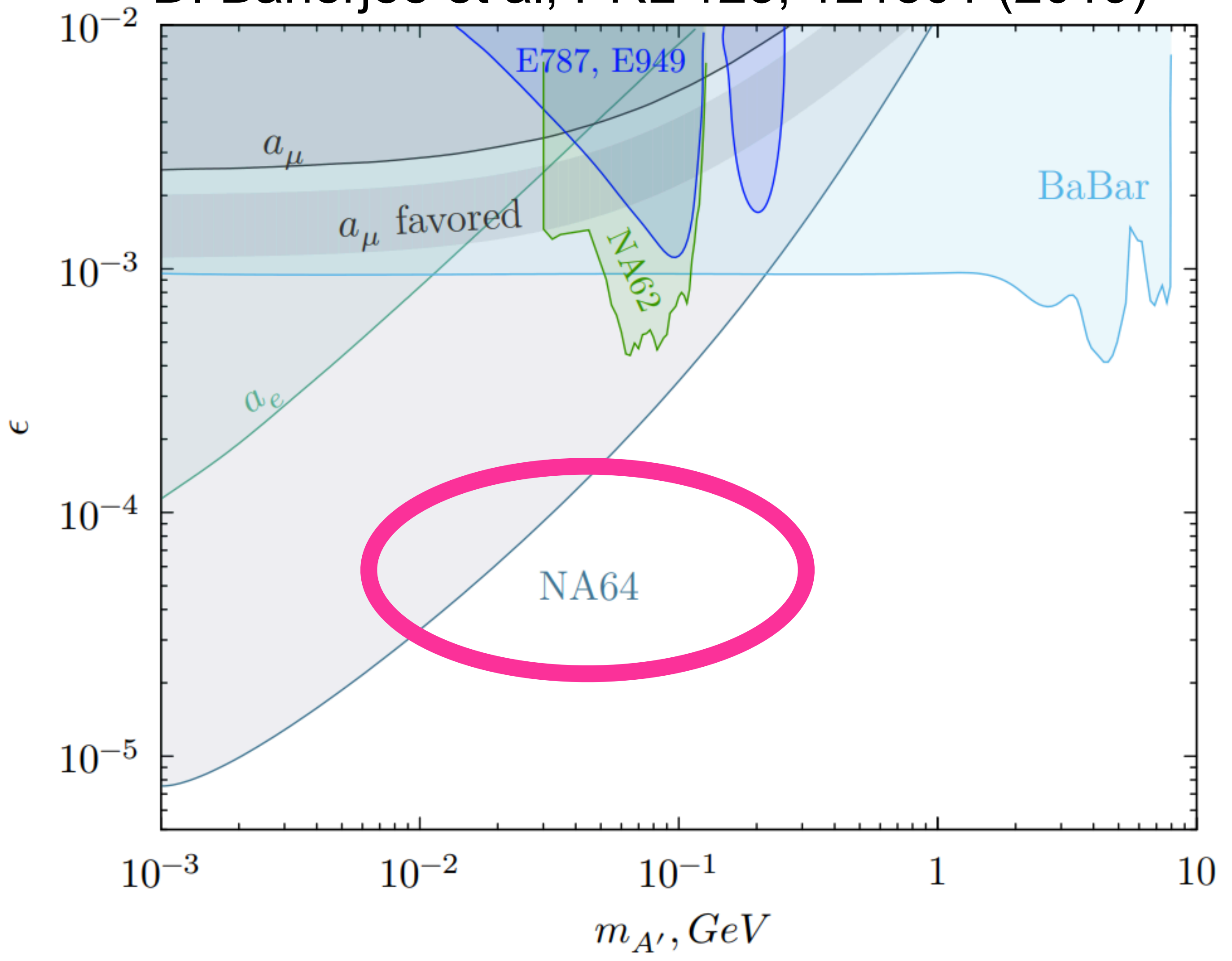
For example, taking $\quad \varepsilon \sim 0.02, \quad m_{A'} \sim 1\,\text{GeV} \quad$ we need $P_{\text{missing}\,A'} \lesssim 2.2 \times 10^{-3}$

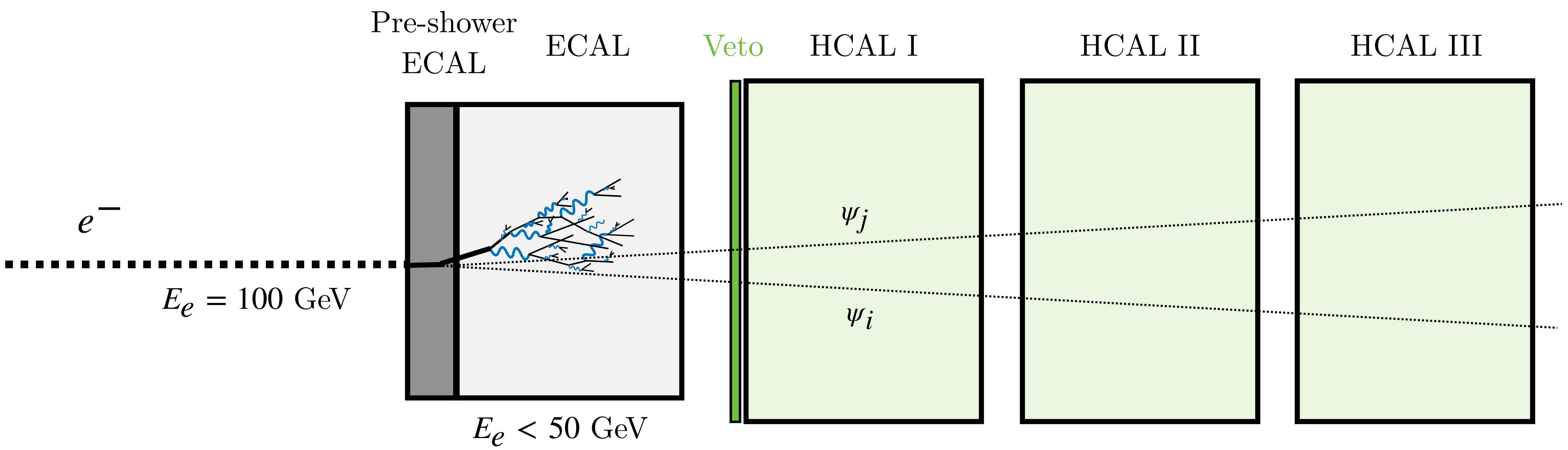
New $(g\text{-}2)_\mu$ region of interest around dark photon masses of 0.3 to 3 GeV.

Searches for invisible dark photons at NA64

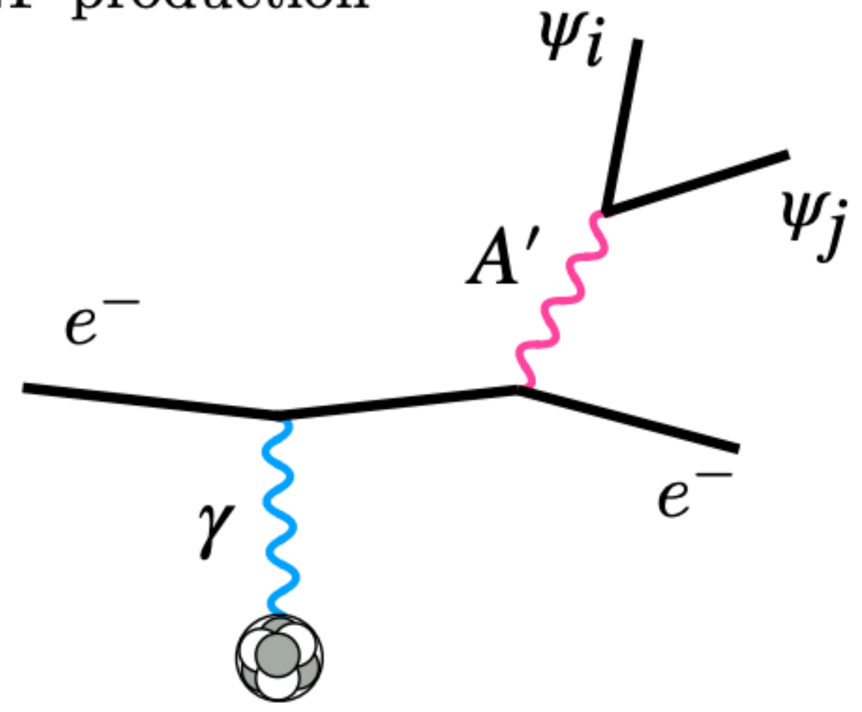
Electrons on target

D. Banerjee et al, PRL 123, 121801 (2019)





HNF production



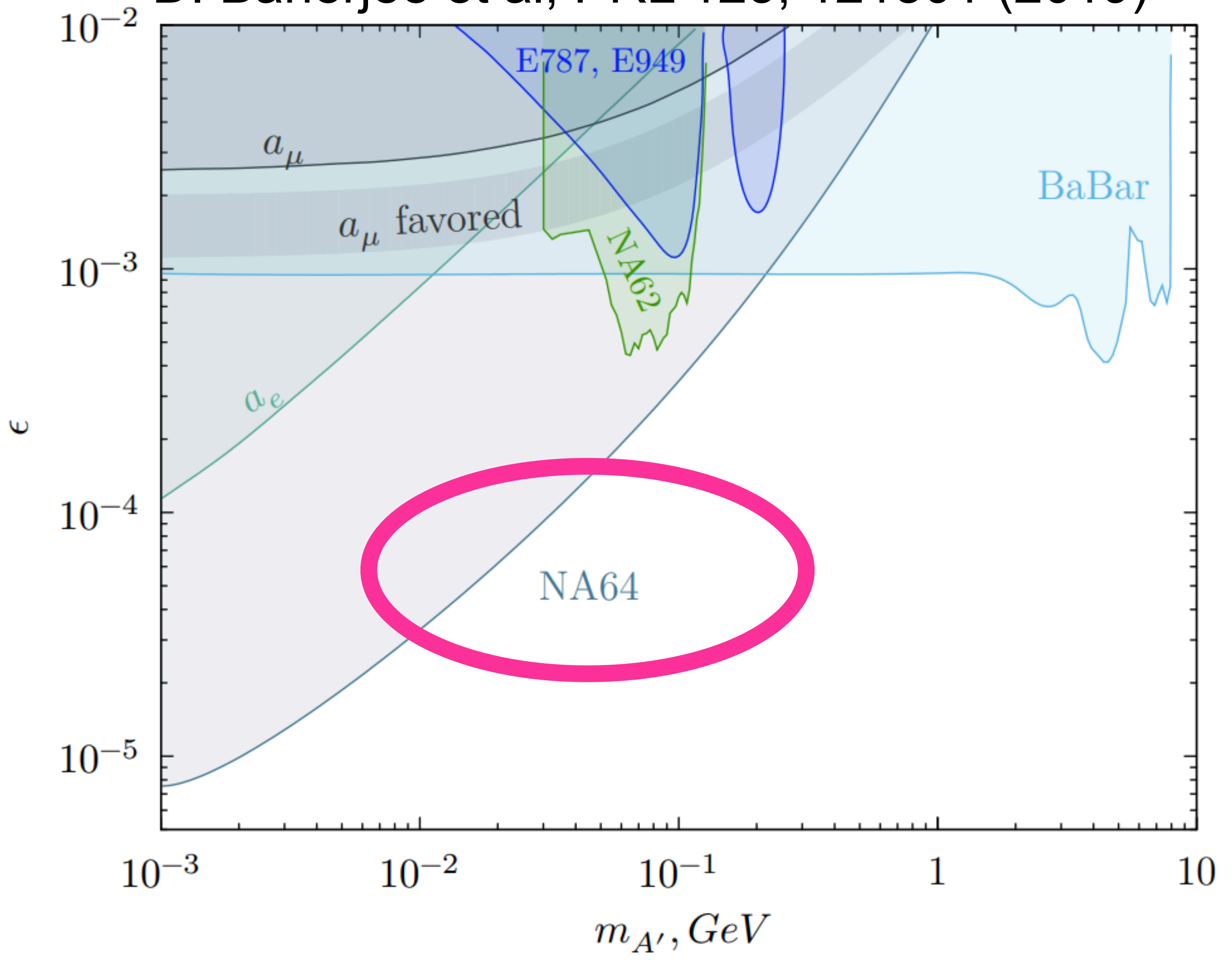
ψ particles fully invisible:

$$E_{\text{missing}} \sim (E_e - E_{\text{ECAL}}) \sim E_{A'}$$

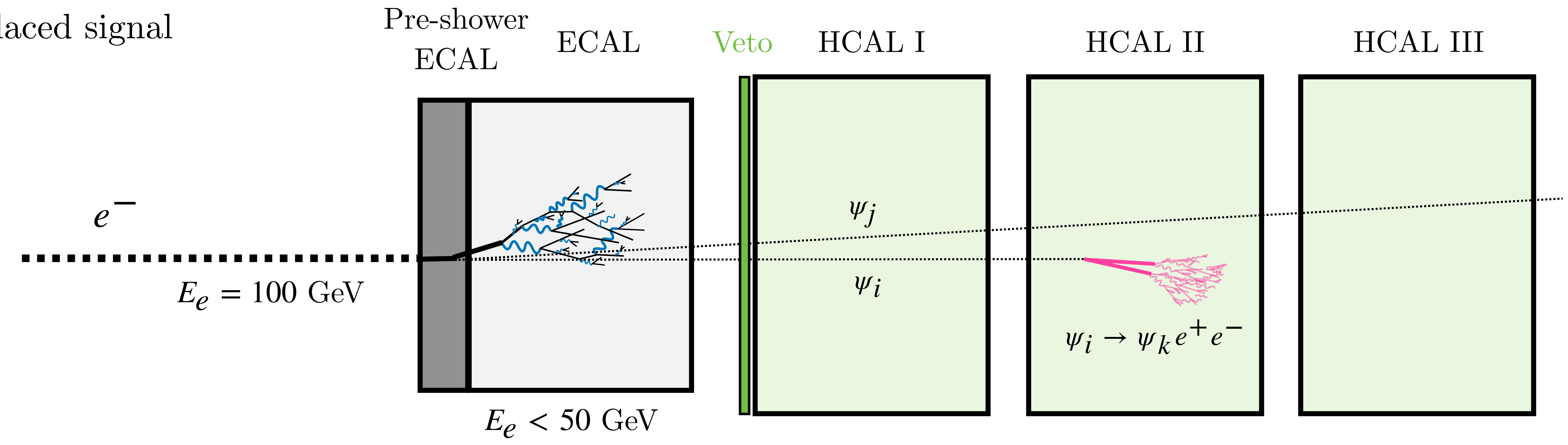
Searches for invisible dark photons at NA64

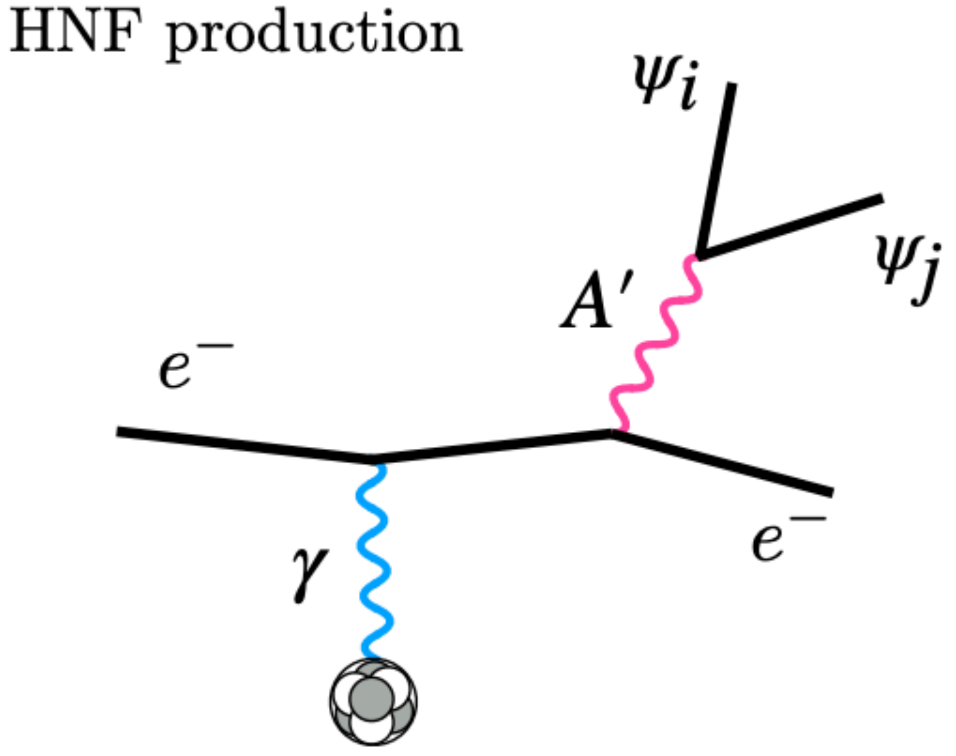
Electrons on target

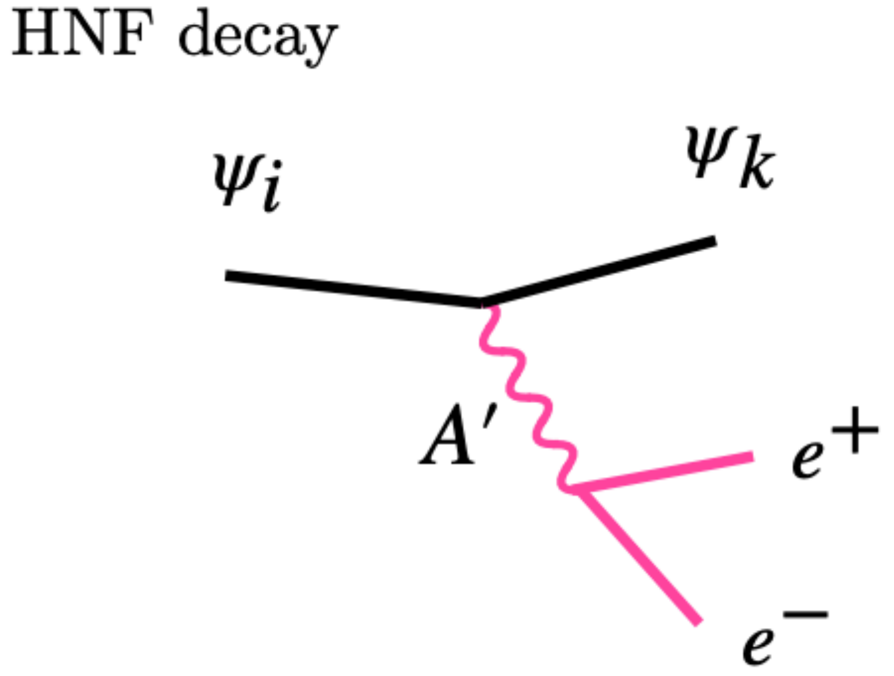
D. Banerjee et al, PRL 123, 121801 (2019)



Displaced signal (S1)







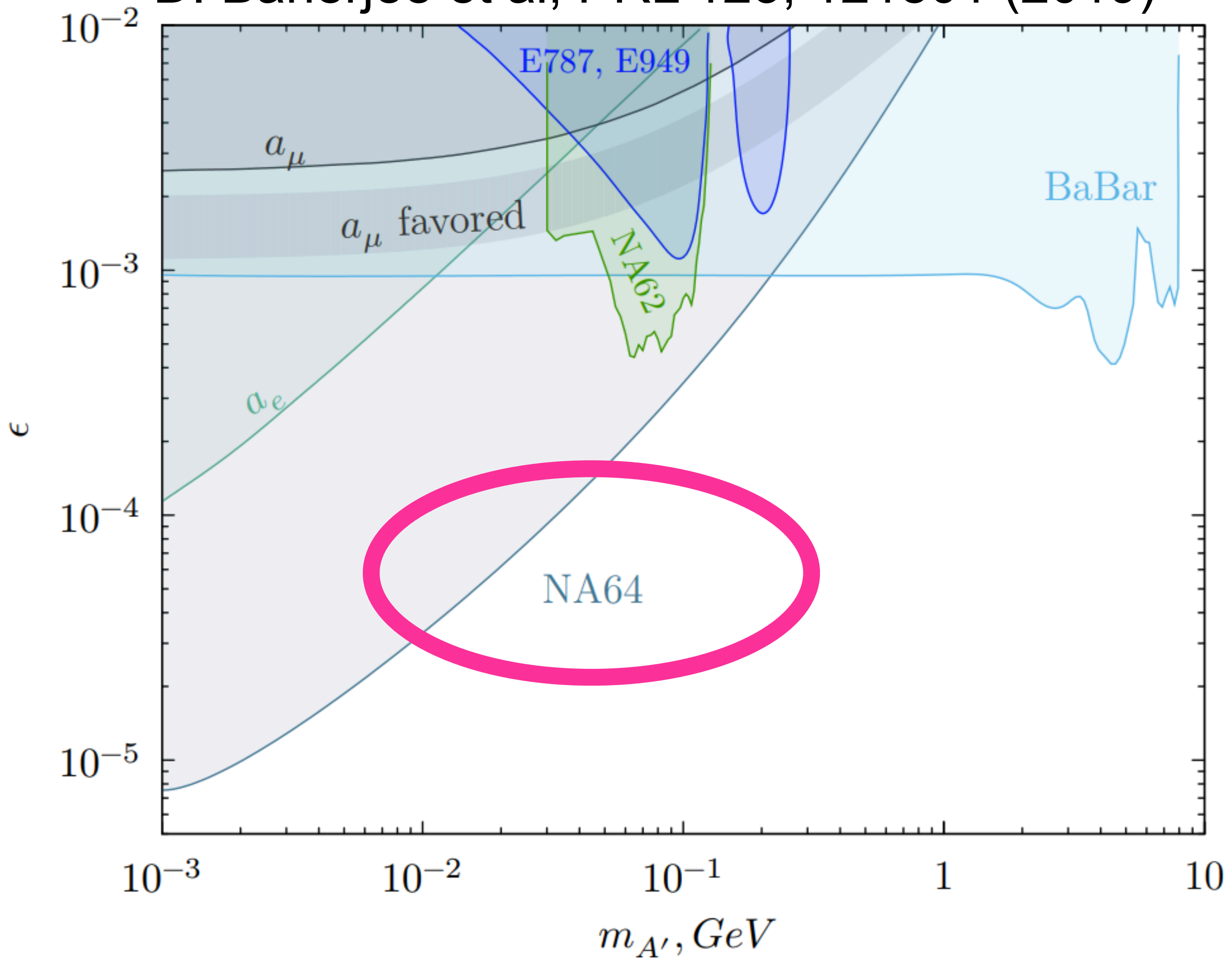
ψ particles semi-visible:

$$E_{\text{missing}} \sim E_e - E_{\text{ECAL}} \sim E_{A'}$$
$$+$$
$$E_{\text{HCAL}} \sim E_{e^+e^-}$$

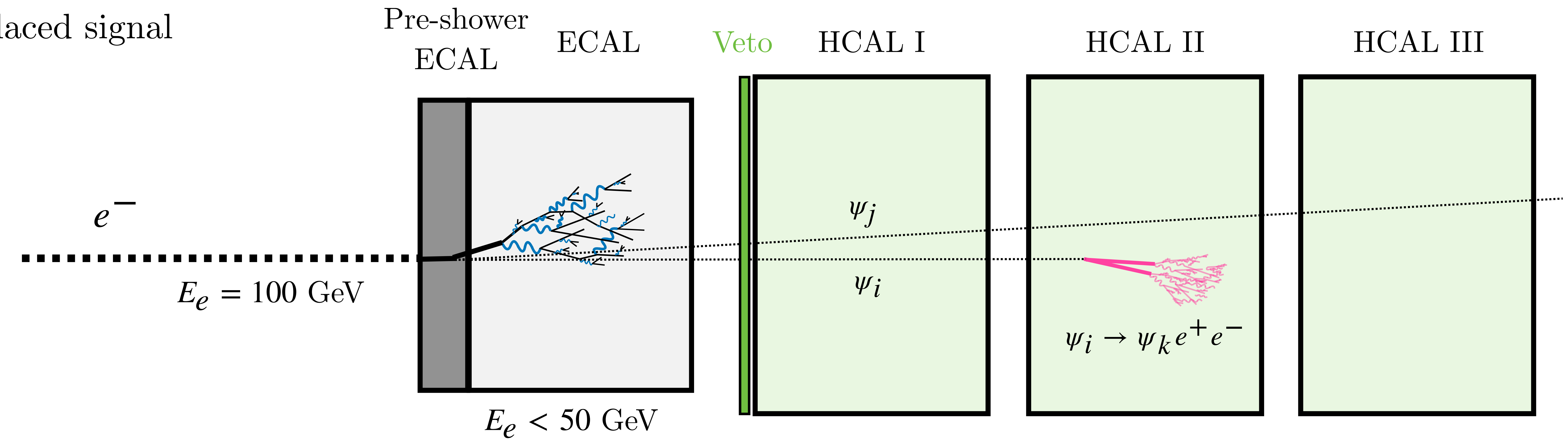
Searches for invisible dark photons at NA64

Electrons on target

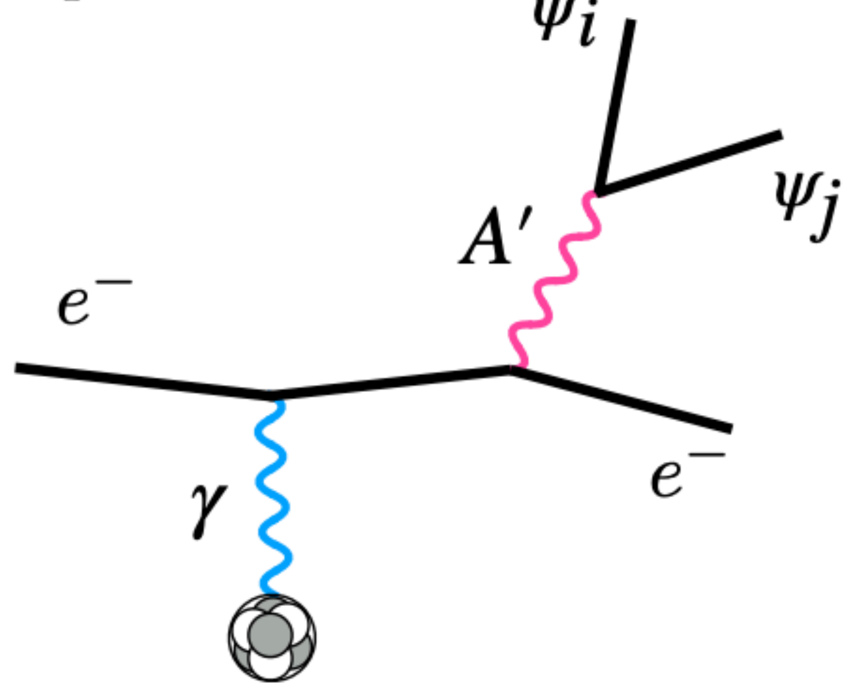
D. Banerjee et al, PRL 123, 121801 (2019)



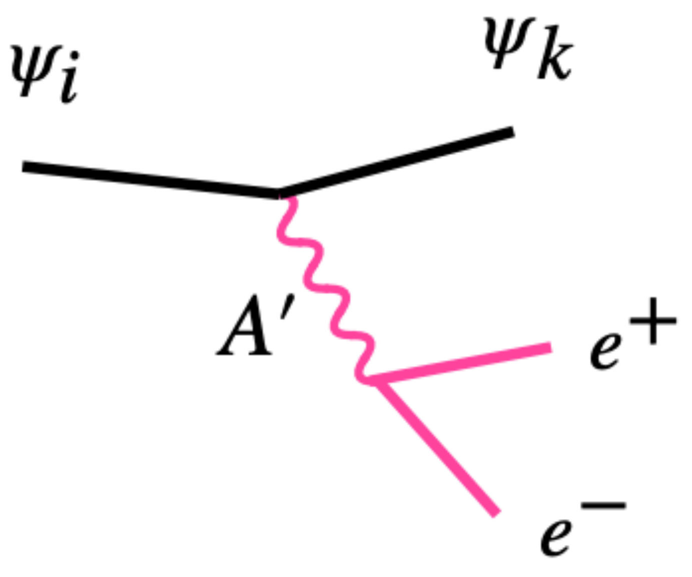
Displaced signal (S1)

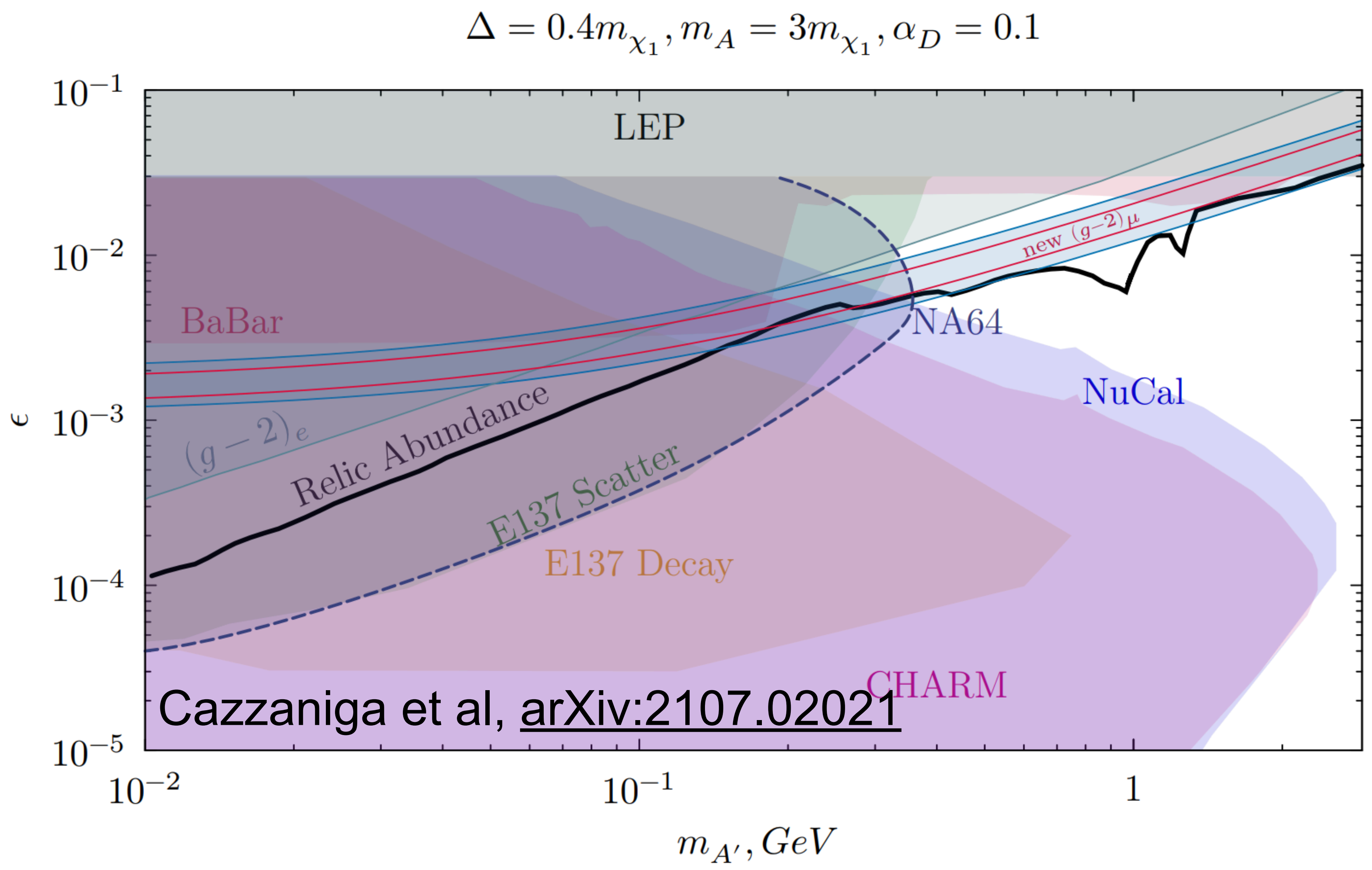


HNF production



HNF decay

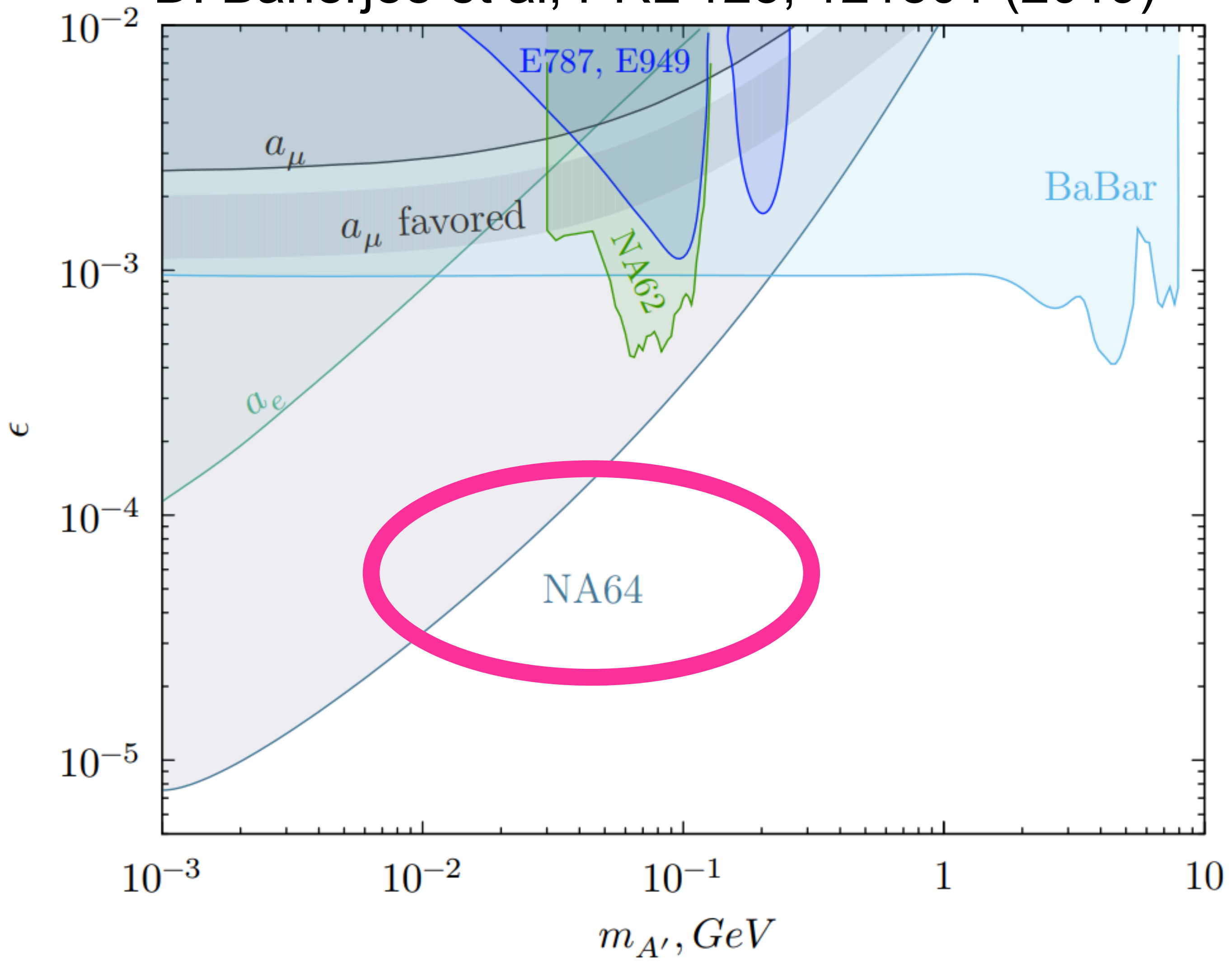




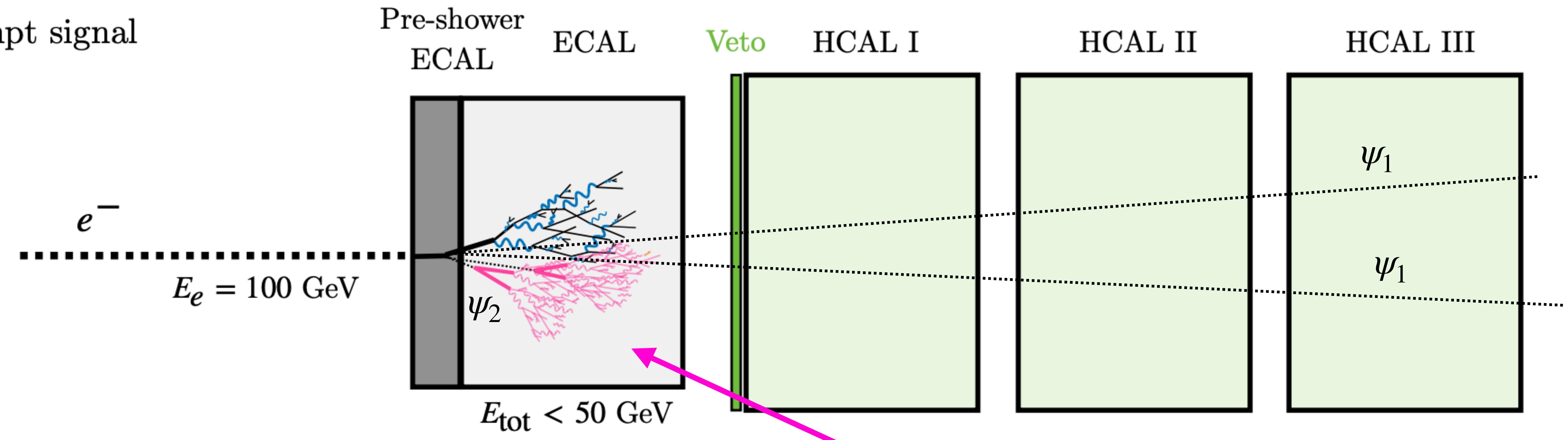
Searches for invisible dark photons at NA64

Electrons on target

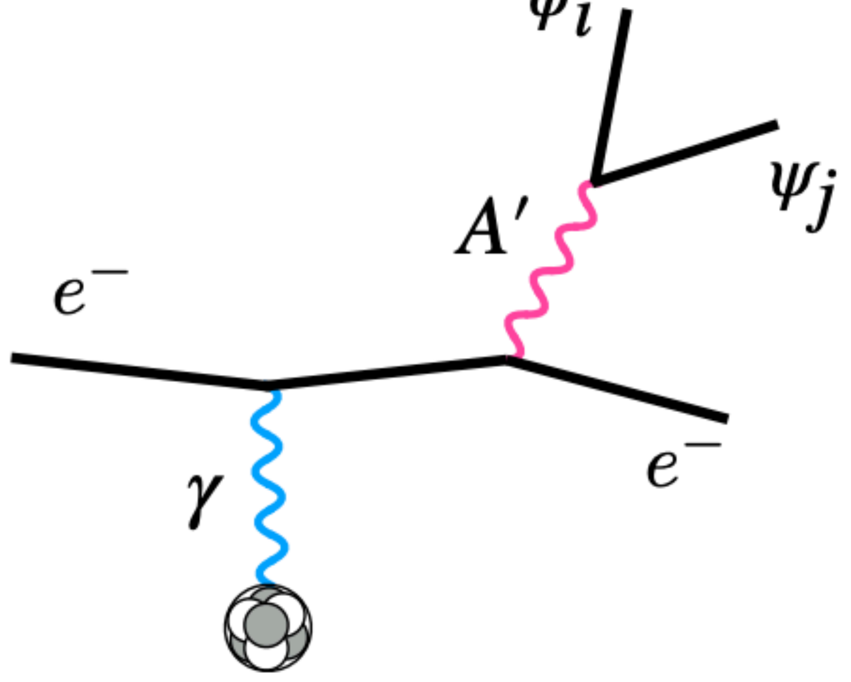
D. Banerjee et al, PRL 123, 121801 (2019)



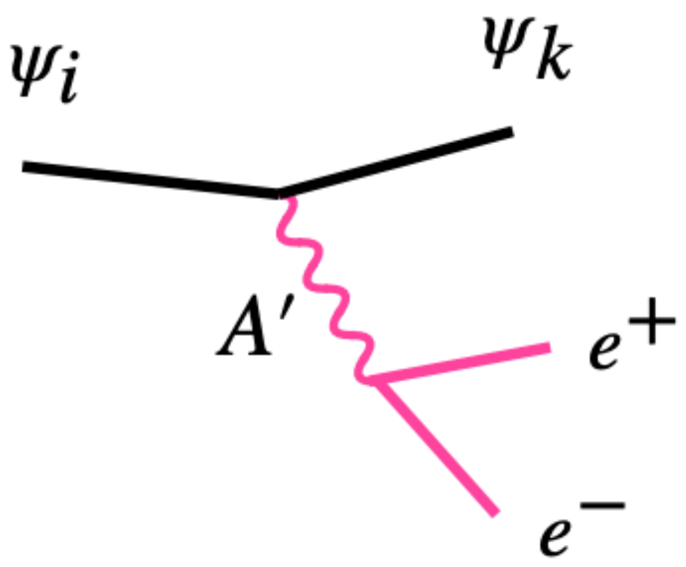
Prompt signal (S2)

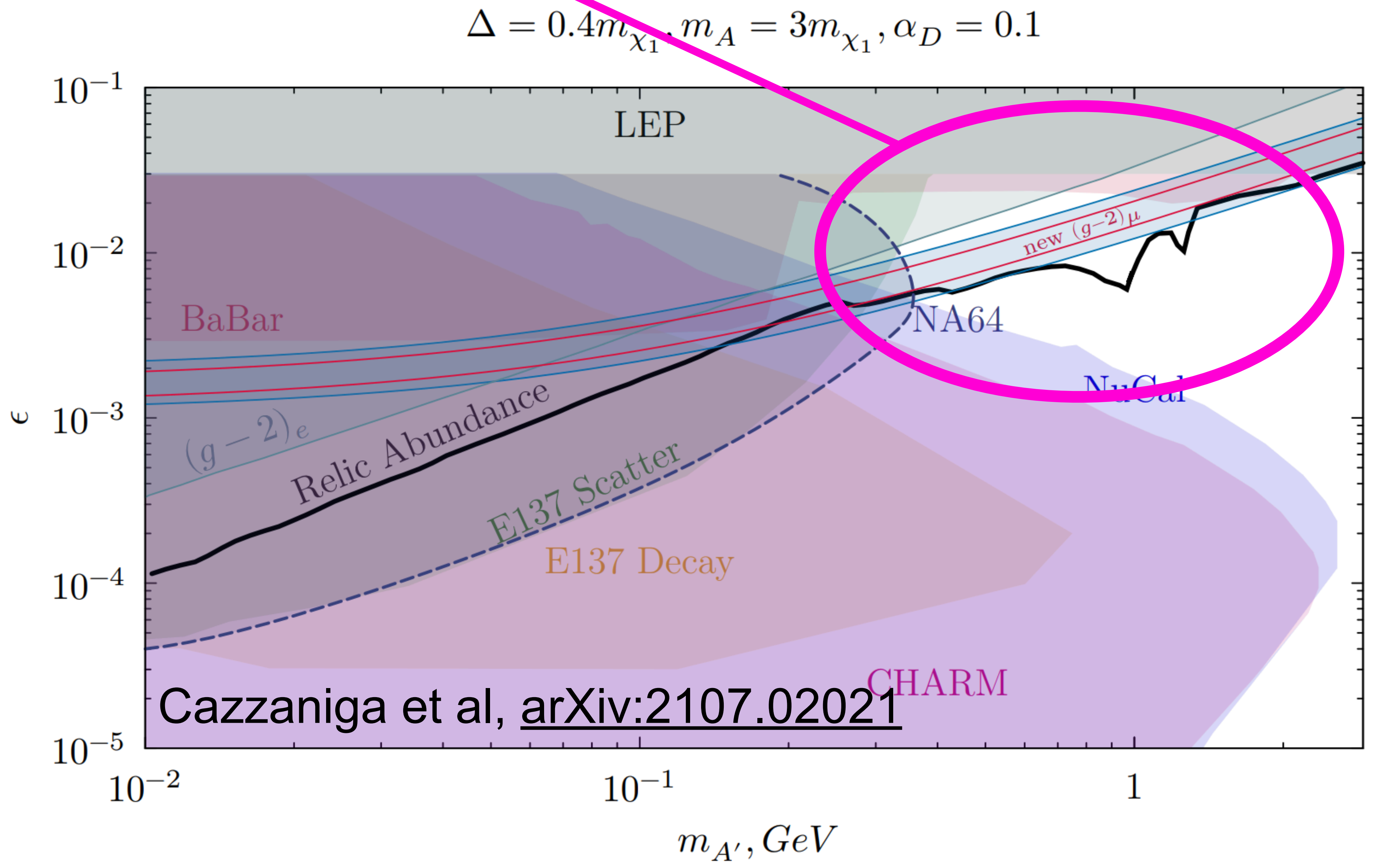


HNF production



HNF decay





Results

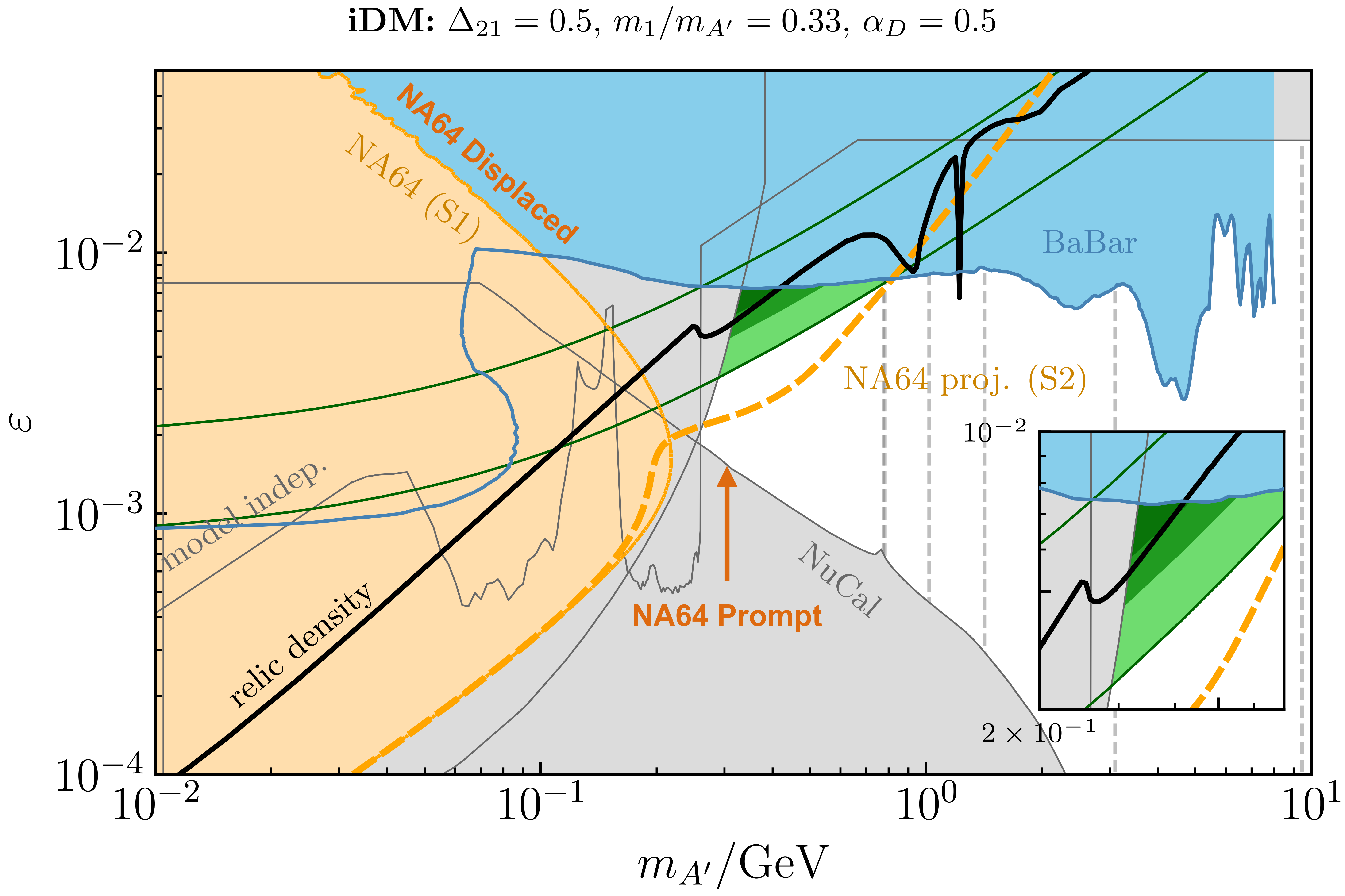
1) Pheno analysis:
    a. Re-evaluation of BaBar limits
    b. Recast of iDM displaced decay search at NA64
    c. Estimate NA64 sensitivity to prompt decays

2) In collaboration with NA64 members:
    a. New limits from recast of invisible A' search
       + future sensitivity

Results of our BaBar and NA64 simulations

Inelastic Dark Matter (iDM)

χ_L χ_R



Some parameter space that can explain $(g\text{-}2)_\mu$

Every A' decays to a single semi-visible state. Easily missed at BaBar when soft*.

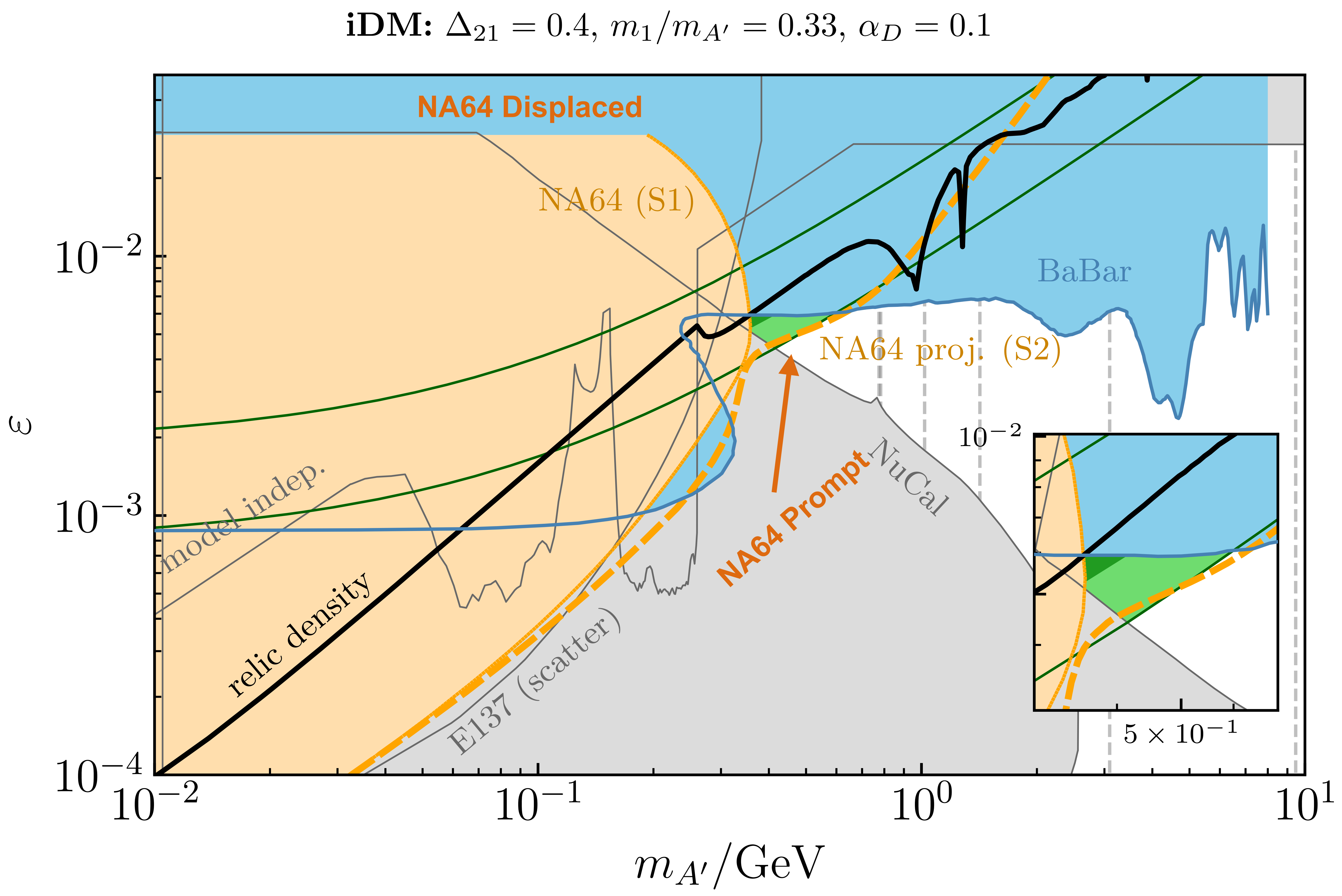
$$J_X^\mu = \overline{\psi_2}\gamma^\mu\psi_1$$

*Updated G. Mohlabeng (2019) with new energy thresholds and angular cuts. BaBar selection assumes E_e > 100 MeV for all tracks and less pessimistic assumptions than M. Duerr et al, arXiv:1911.03176.

Results of our BaBar and NA64 simulations

Inelastic Dark Matter (iDM)

χ_L χ_R



Some parameter space that can explain $(g\text{-}2)_\mu$

Every A' decays to a single semi-visible state. Easily missed at BaBar when soft*.

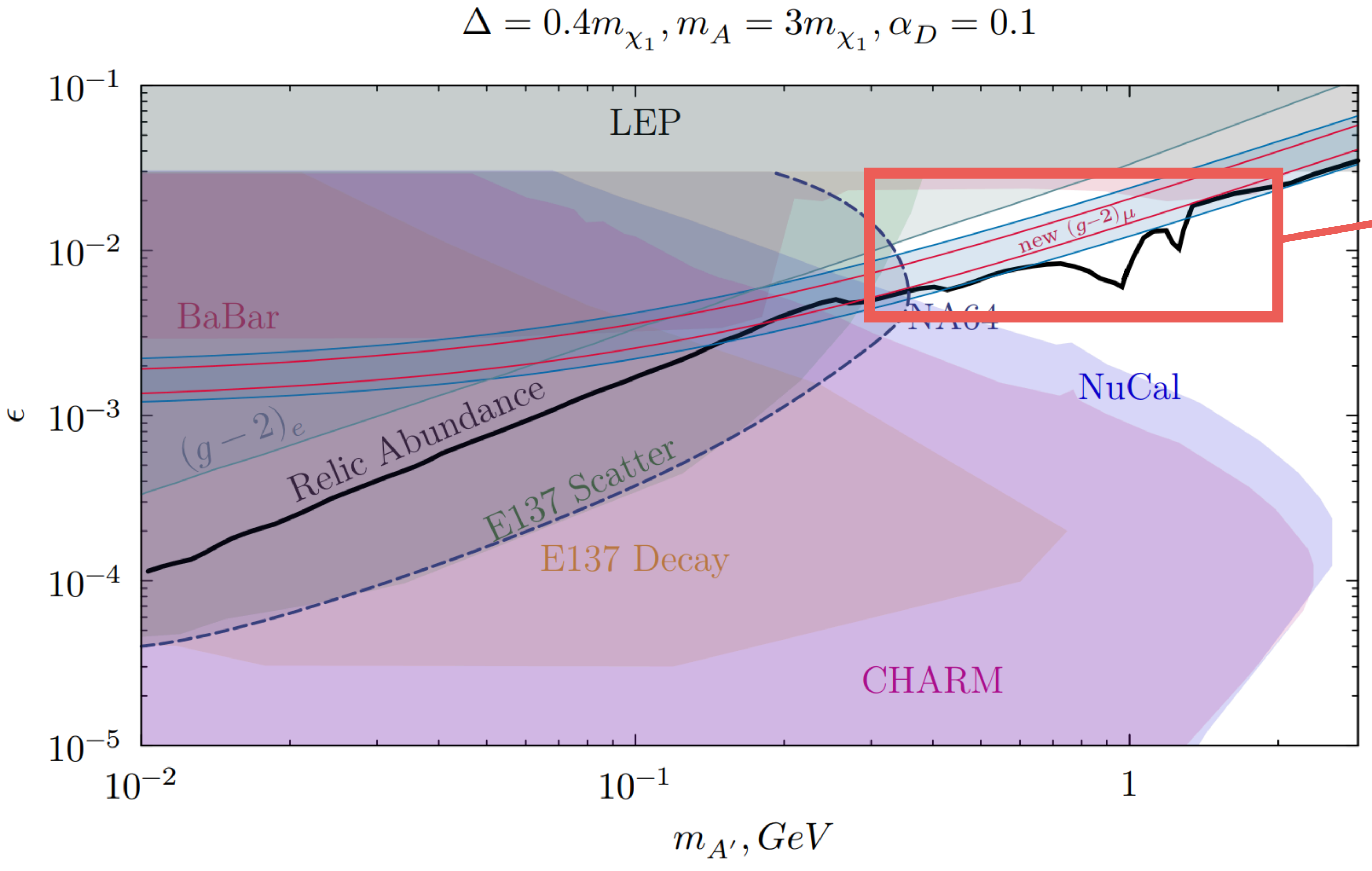
$$J_X^\mu = \overline{\psi_2}\gamma^\mu\psi_1$$

*Updated G. Mohlabeng (2019) with new energy thresholds and angular cuts. BaBar selection assumes E_e > 100 MeV for all tracks and less pessimistic assumptions than M. Duerr et al, arXiv:1911.03176.

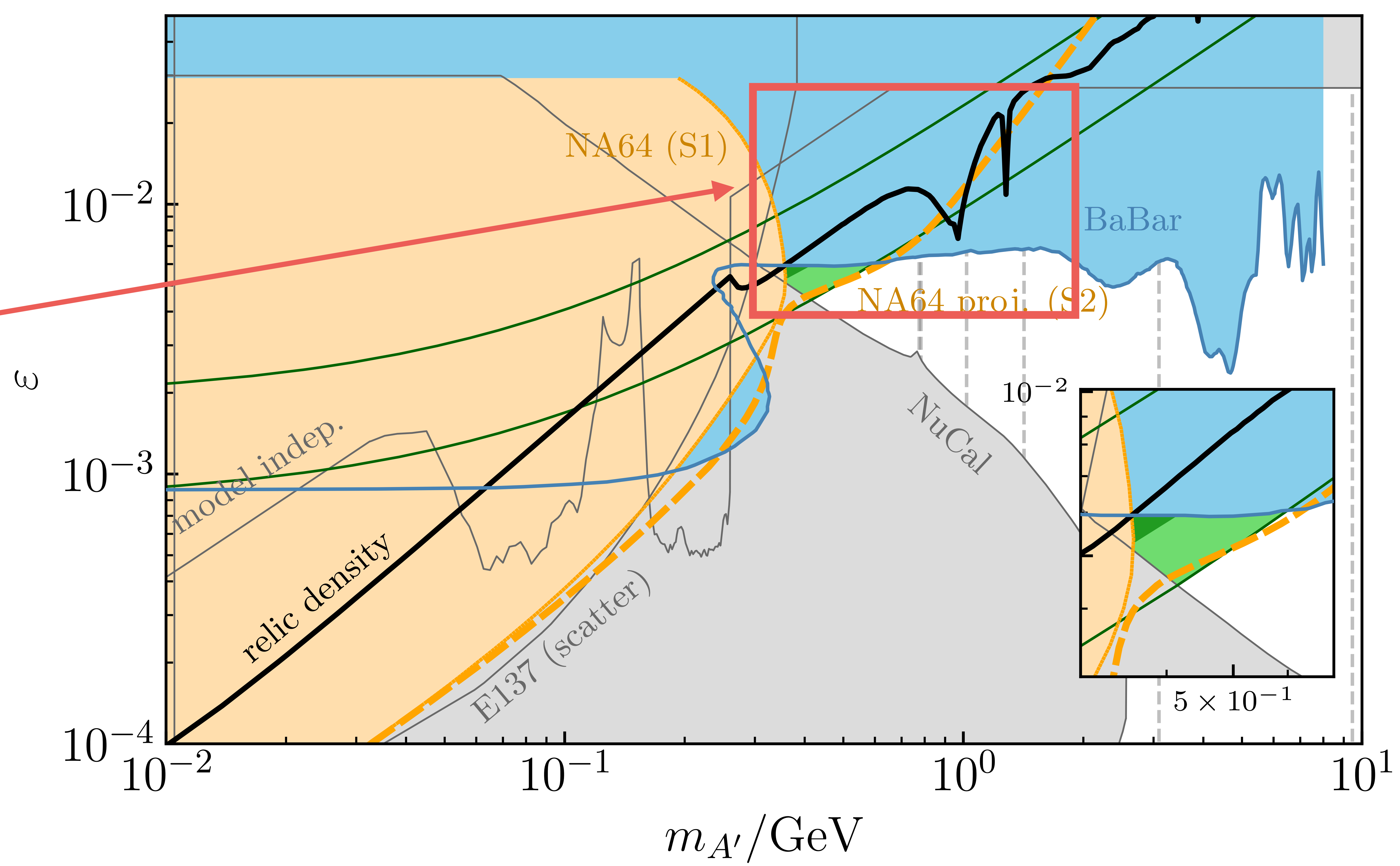
Results of our BaBar and NA64 simulations

Inelastic Dark Matter (iDM)

χ_L χ_R



Cazzaniga et al, arXiv:2107.02021

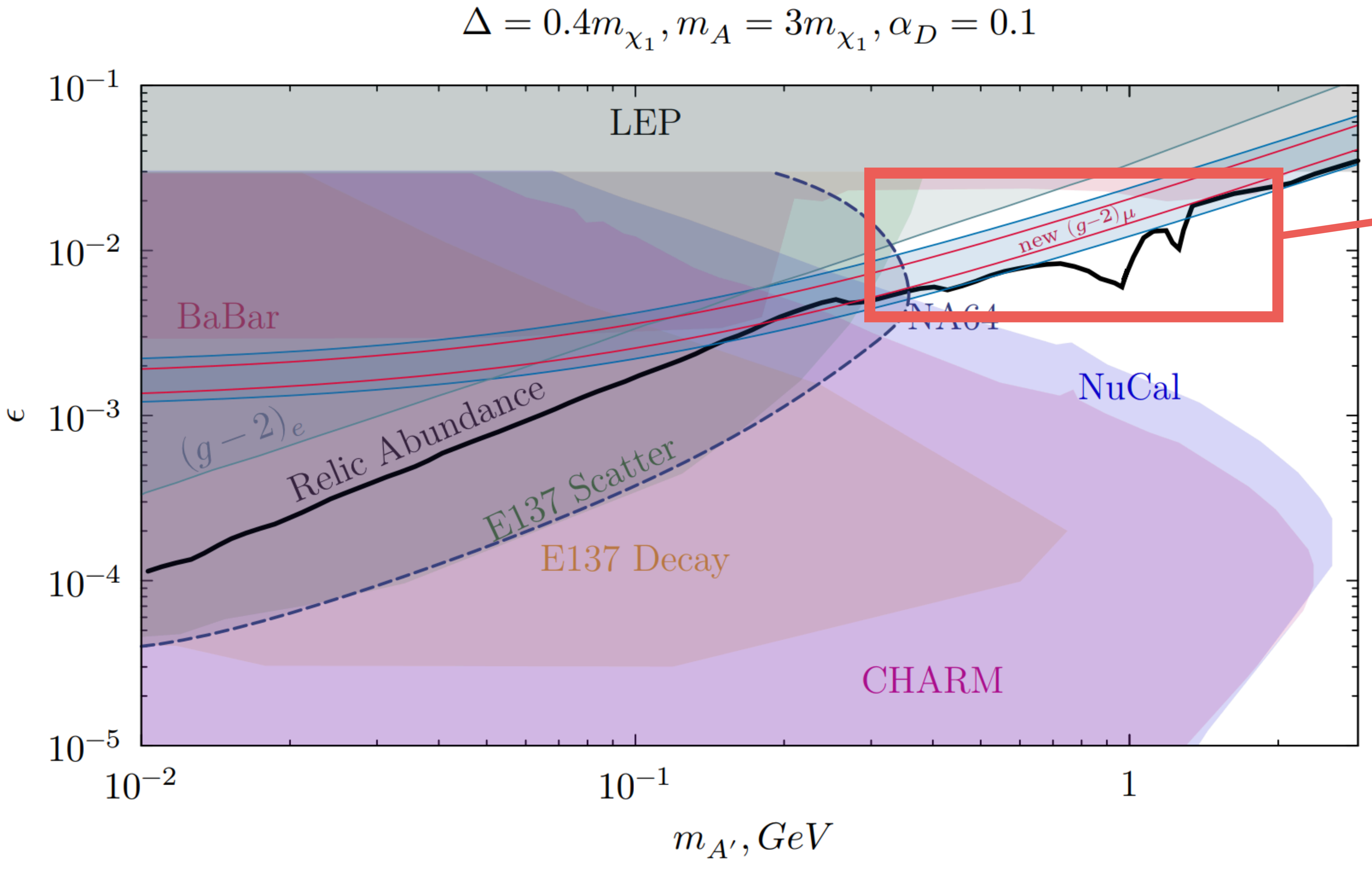


A. Abdullahi et al, arXiv:2302.05410

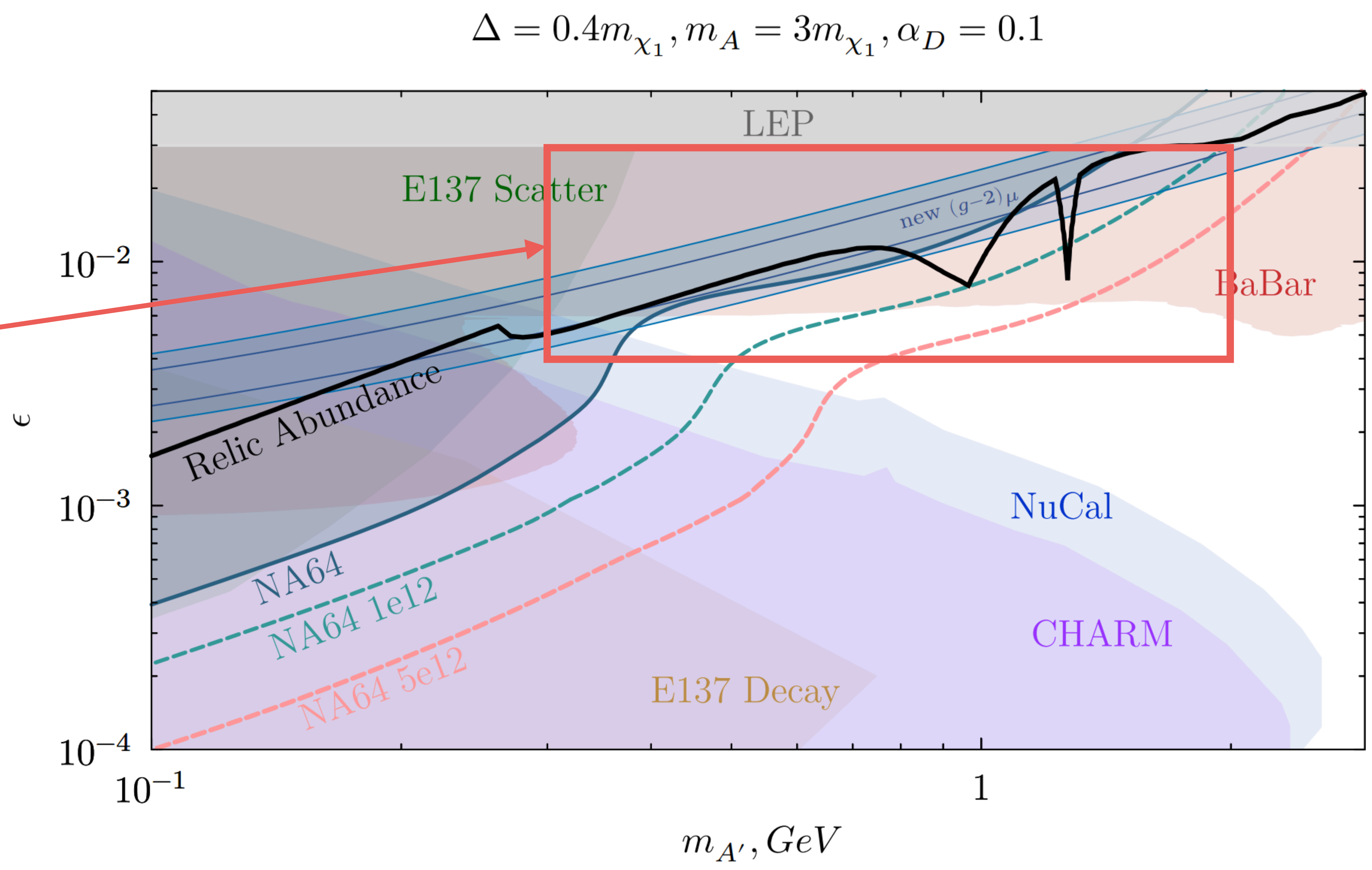
Results of our BaBar and NA64 simulations

Inelastic Dark Matter (iDM)

χ_L χ_R

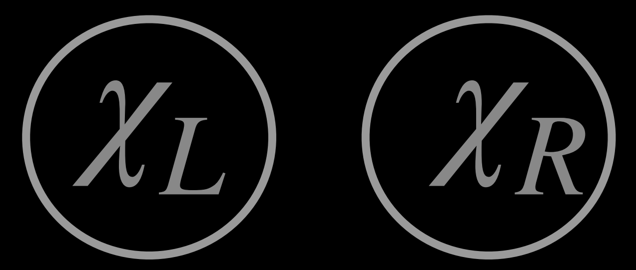


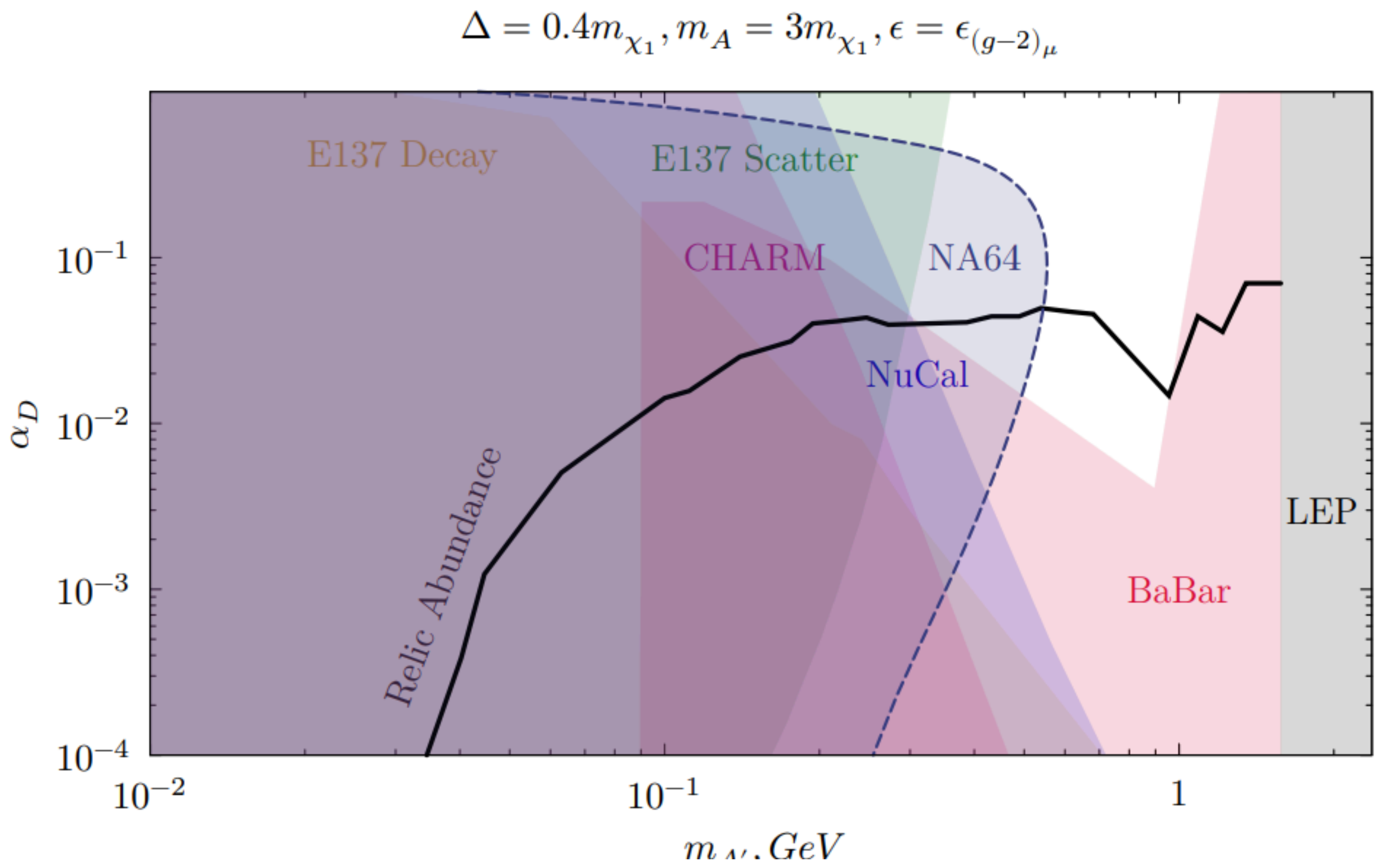
Cazzaniga et al, arXiv:2107.02021



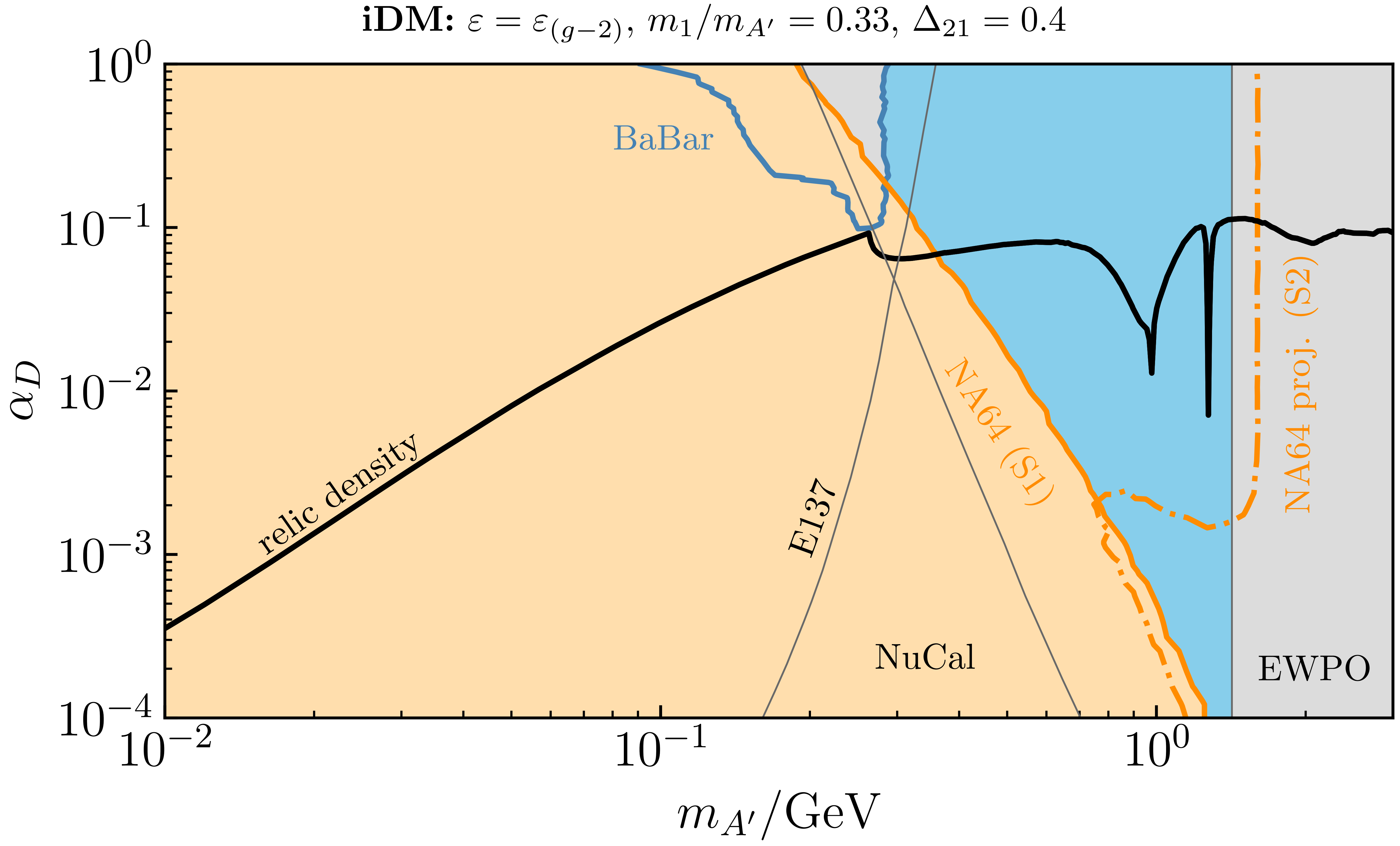
M. Mongillo et al, arXiv:2302.05414

Inelastic Dark Matter (iDM) — different plane





Cazzaniga et al, arXiv:2107.02021

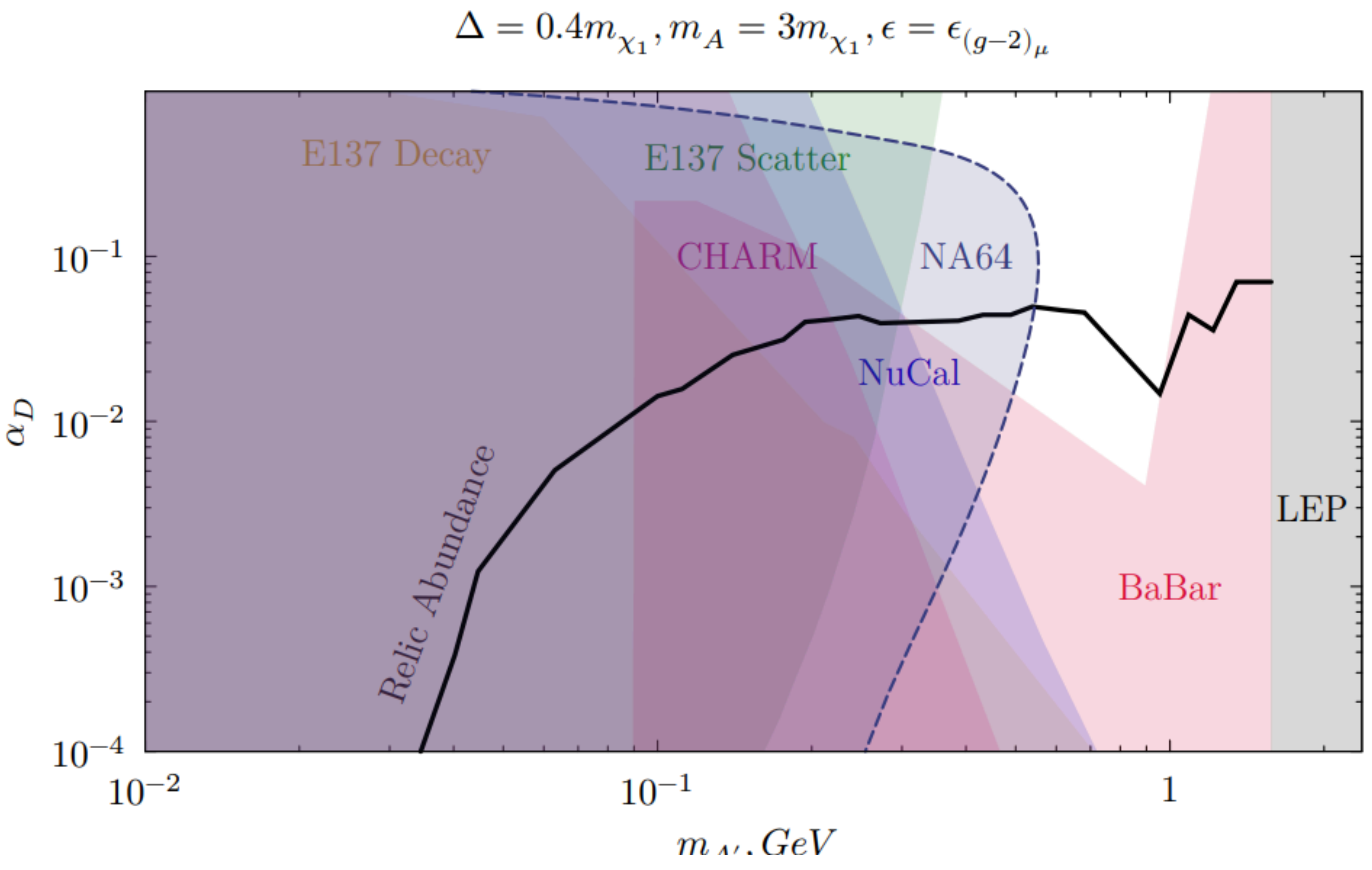


A. Abdullahi et al, arXiv:2302.05410

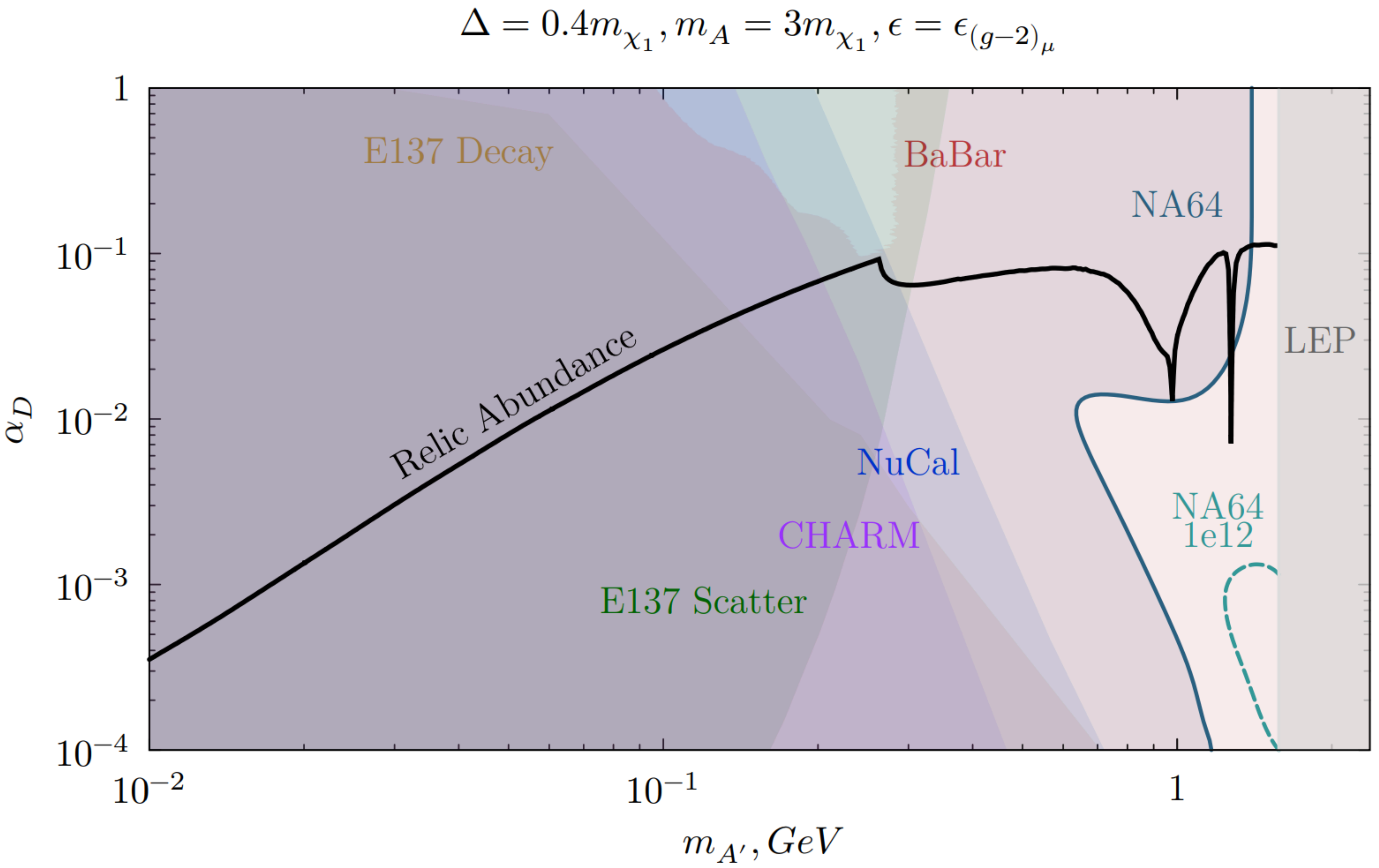
Results of our BaBar and NA64 simulations

Inelastic Dark Matter (iDM) — different plane

χ_L χ_R



Cazzaniga et al, arXiv:2107.02021



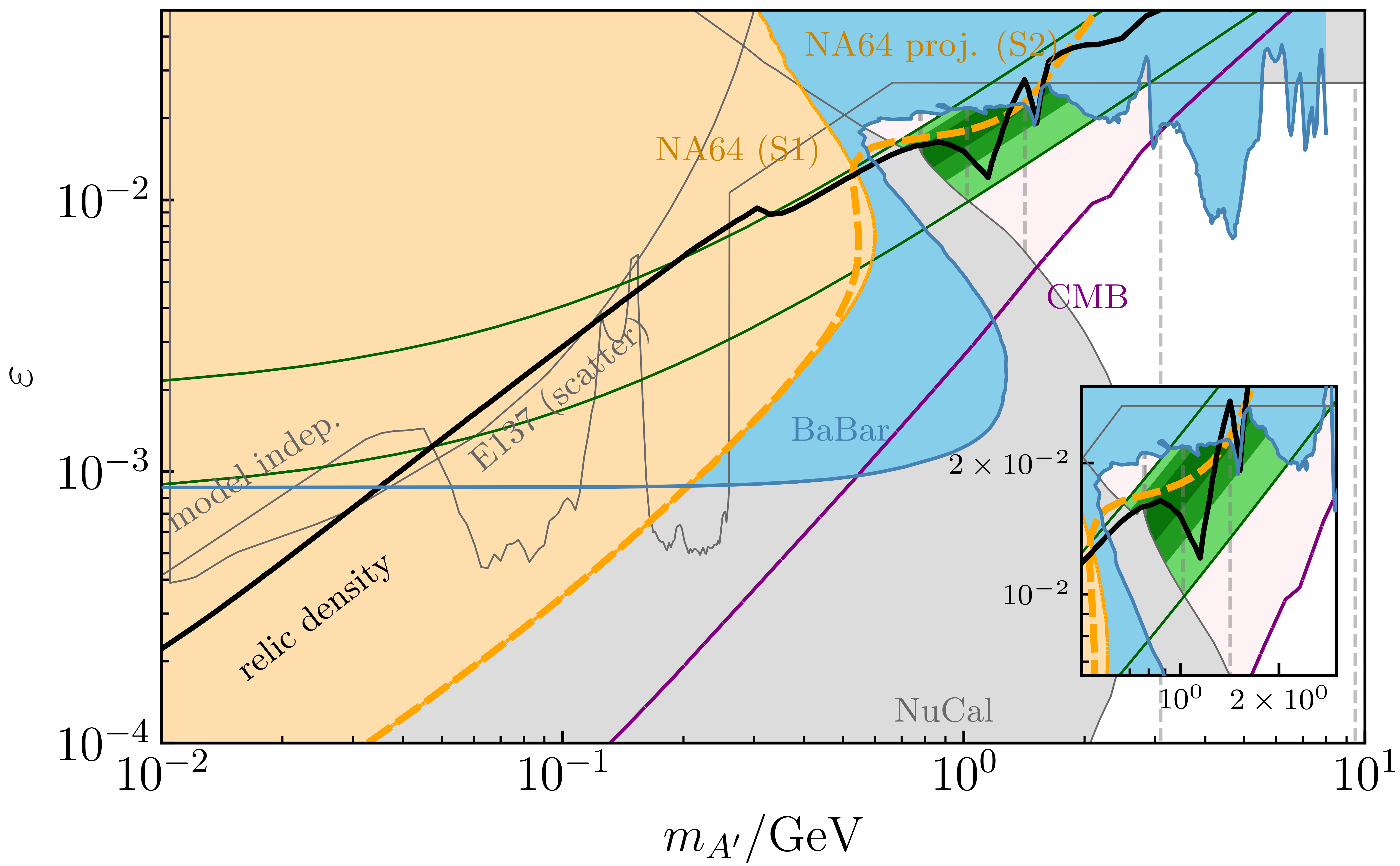
M. Mongillo et al, arXiv:2302.05414

Results of our BaBar and NA64 simulations

Inelastic Dirac Dark Matter (i2DM)

$\eta_L \; \eta_R \quad \chi_L \; \chi_R$

i2DM: $\Delta_{21} = 0.4$, $m_1/m_{A'} = 0.33$, $\alpha_D = 0.5$, $\beta = 4.6°$



If not dark matter, parameter space could explain $(g\text{-}2)_\mu$

$$J_X^\mu = \left(\theta^2\, \overline{\psi_1}\gamma^\mu\psi_1 + \theta\, \overline{\psi_2}\gamma^\mu\psi_1 + \overline{\psi_2}\gamma^\mu\psi_2\right)$$

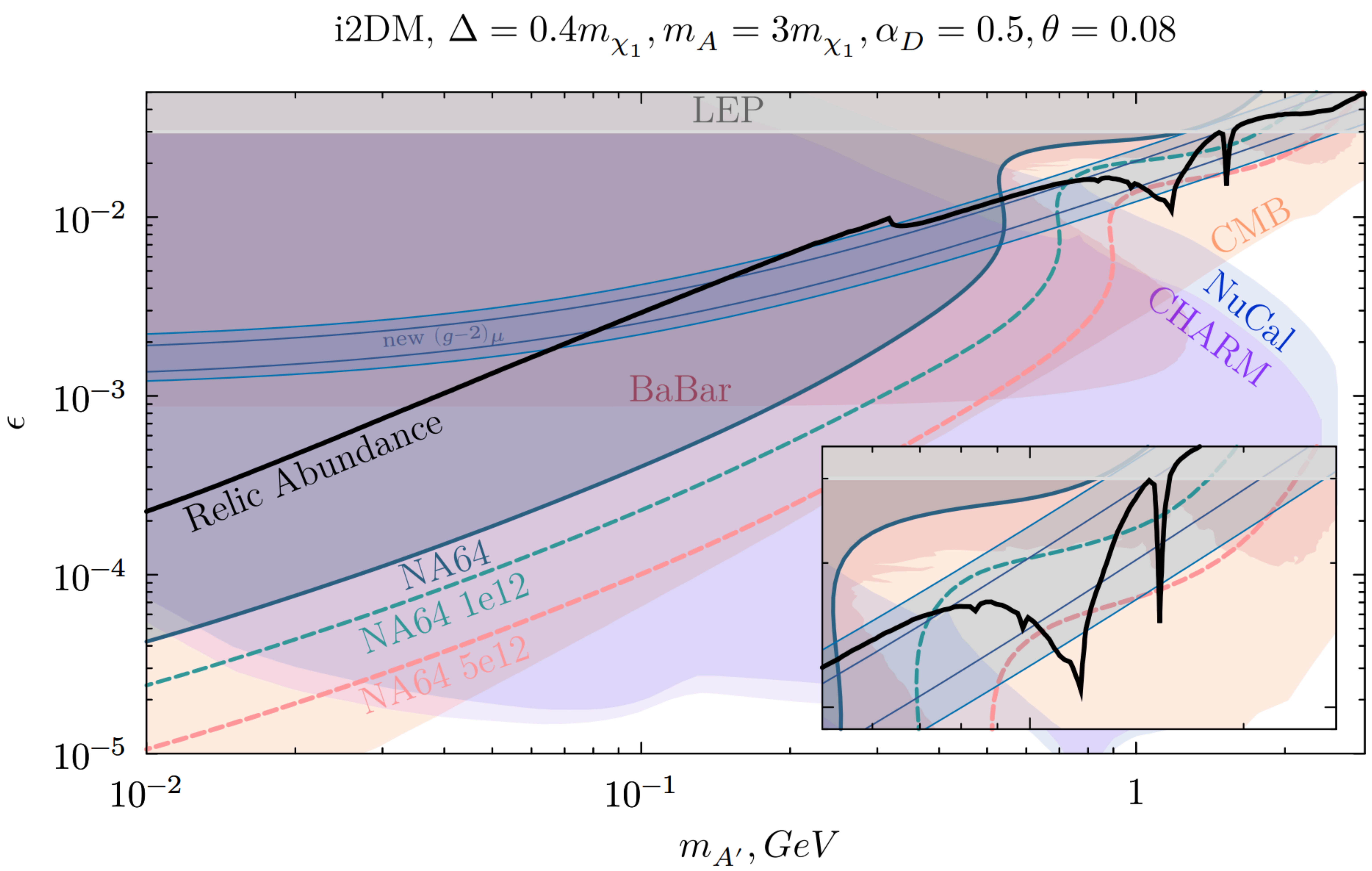
If ψ_1 is dark matter, it would be in tension with CMB.

Not an issue if ψ_1 mixes with neutrinos, as it decays $\psi_1 \to \nu e^+ e^-$.

Results of our BaBar and NA64 simulations

Inelastic Dirac Dark Matter (i2DM)

$\eta_L \eta_R$ $\chi_L \chi_R$



If not dark matter, parameter space could explain $(g\text{-}2)_\mu$

$$J_X^\mu = \left(\theta^2\, \overline{\psi_1}\gamma^\mu\psi_1 + \theta\, \overline{\psi_2}\gamma^\mu\psi_1 + \overline{\psi_2}\gamma^\mu\psi_2\right)$$

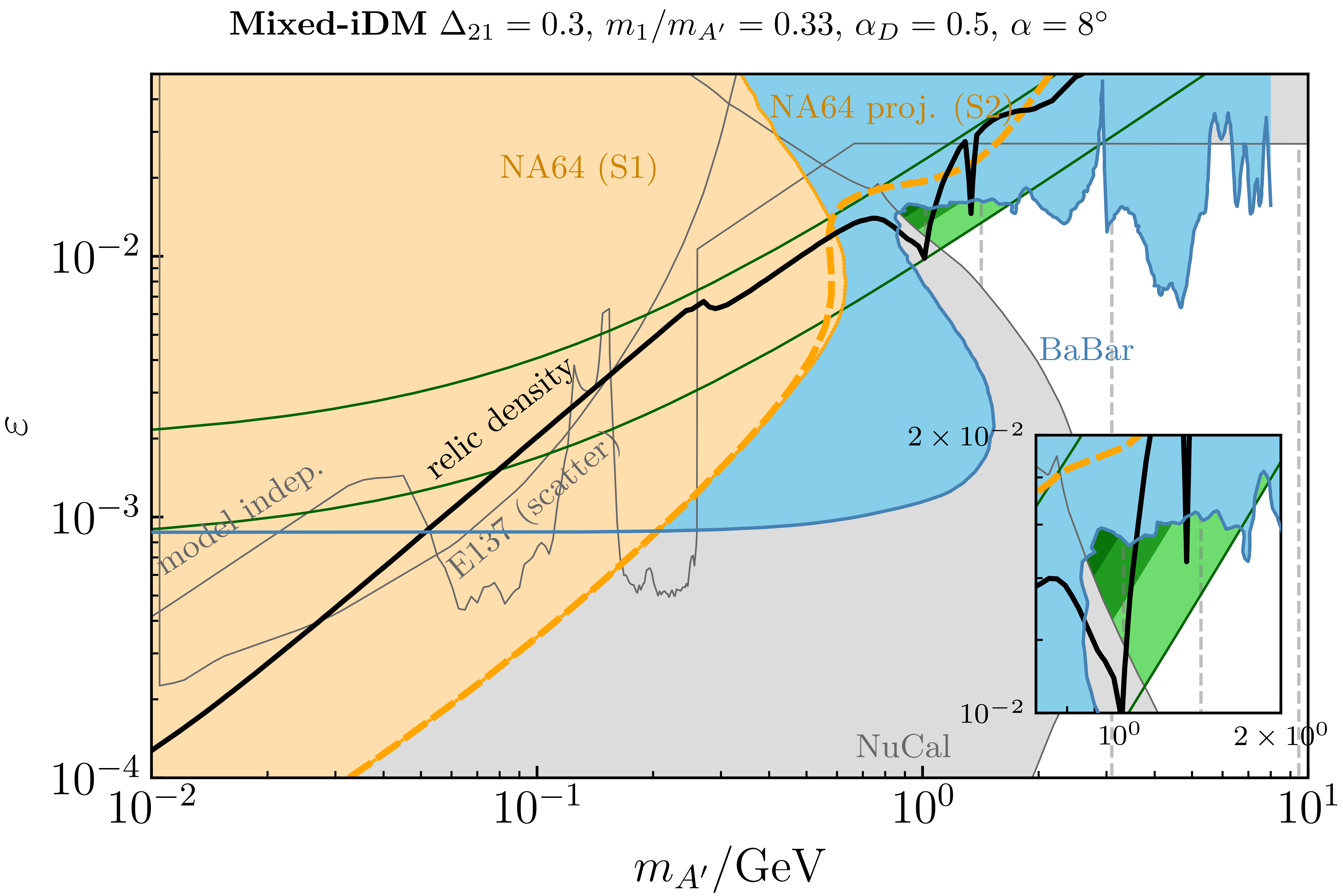
If ψ_1 is dark matter, it would be in tension with CMB.

Not an issue if ψ_1 mixes with neutrinos, as it decays $\psi_1 \to \nu e^+ e^-$.

Results of our BaBar and NA64 simulations

Mixed Inelastic Dark Matter

η_L χ_L χ_R



Parameter space that can explain $(g\text{-}2)_\mu$

$$J^\mu_X = \left(\theta\,\overline{\Psi_2}\gamma^\mu\psi_1 + \overline{\Psi_2}\gamma^\mu\Psi_2\right)$$

Now ψ_1 can easily be dark matter.

Weak CMB constraints as ψ_1 has no self-annihilations.

Results of our BaBar and NA64 simulations

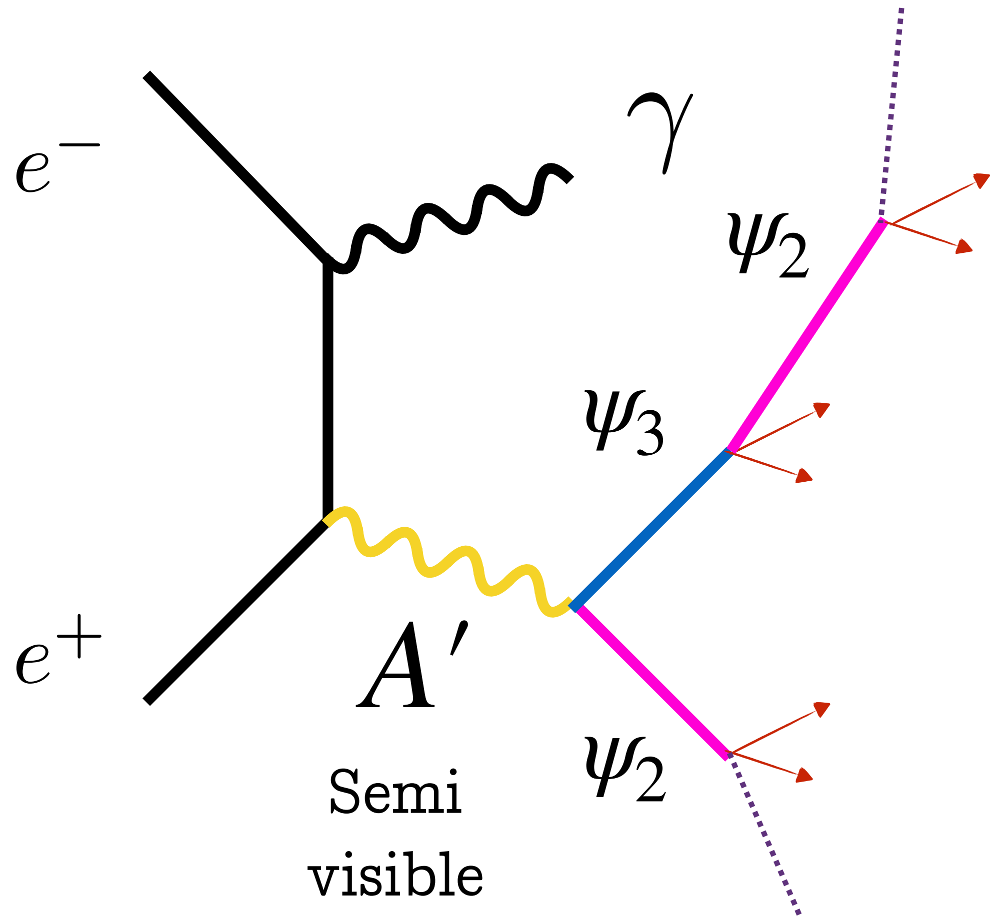
A dark Dirac fermion seesaw

η_L χ_L χ_R

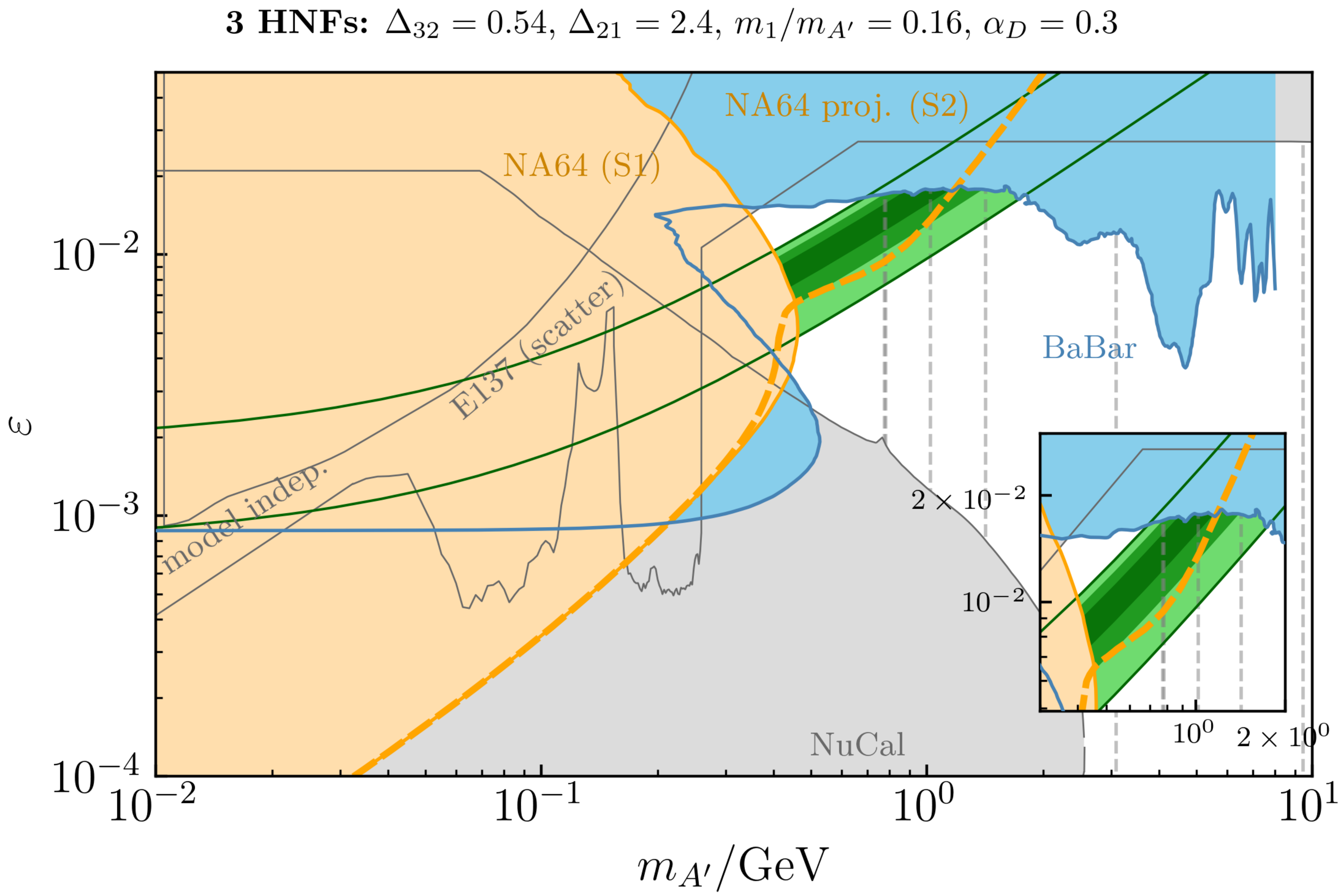
Model can explain $(g\text{-}2)_\mu$

(if HNF ≡ HNL)

ψ_i have to mix with neutrinos as otherwise, DM co-annihilation too inefficient.



$3\,(e^+e^-)$ *pairs*



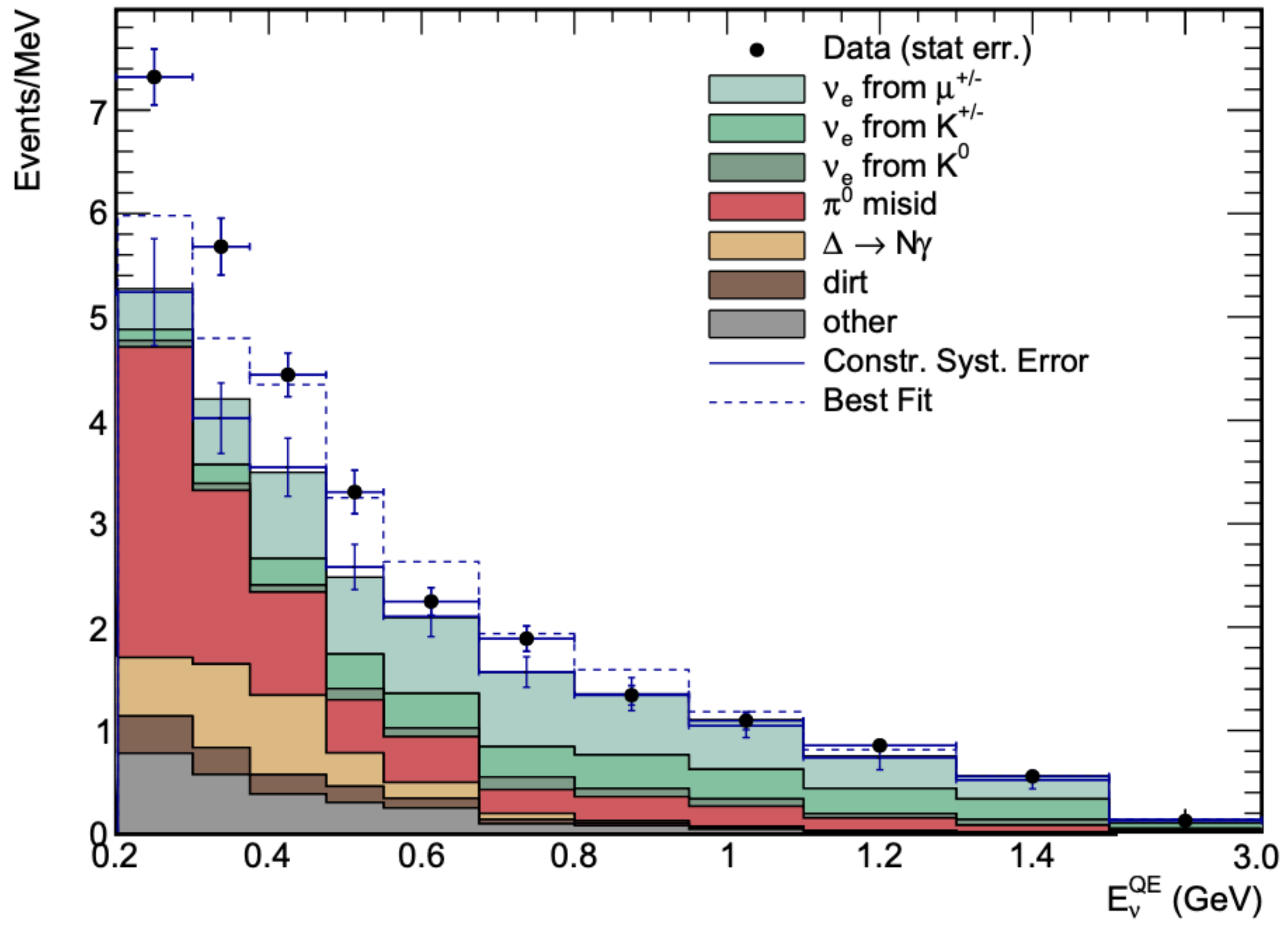
We choose benchmark points in [A. Abdullahi, MH, S. Pascoli, 2020], where anomalies in neutrino experiments, including the MiniBooNE excess, can be explained.

Prospects

Neutrino experiments

E. Bertuzzo et al., [arXiv:1807.09877]
P. Ballett et al, [arxiv:1808.02915]
C. Argüelles et al, [arXiv:1812.08768]
P. Ballett, MH, S. Pascoli [arxiv:1903.07589]
A. Abdullahi, MH, S. Pascoli, [arXiv:2007.11813]

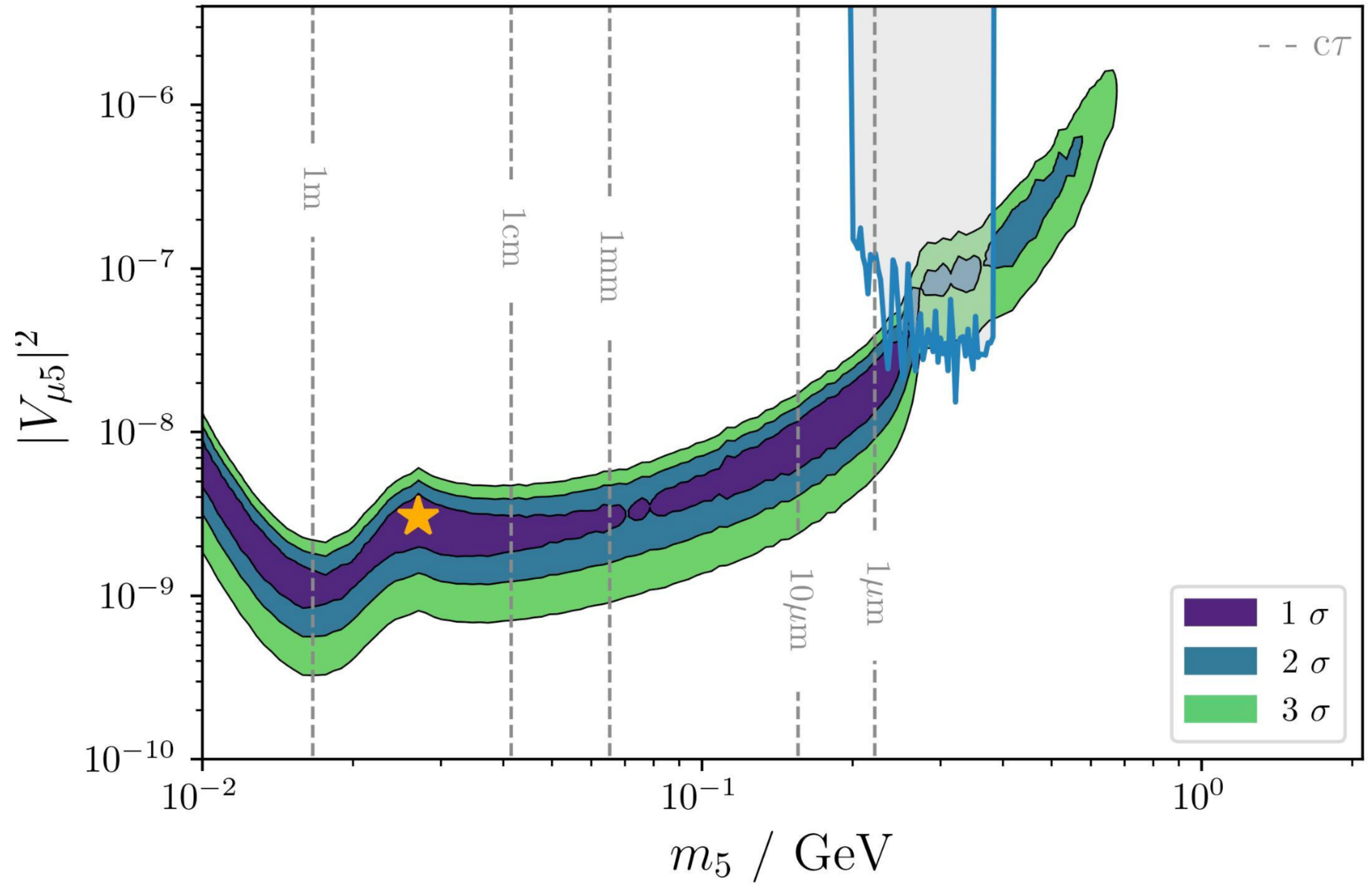
MiniBooNE Coll., [arXiv:2006.16883]



Large excess of electron-like events in MiniBooNE (4.8σ)

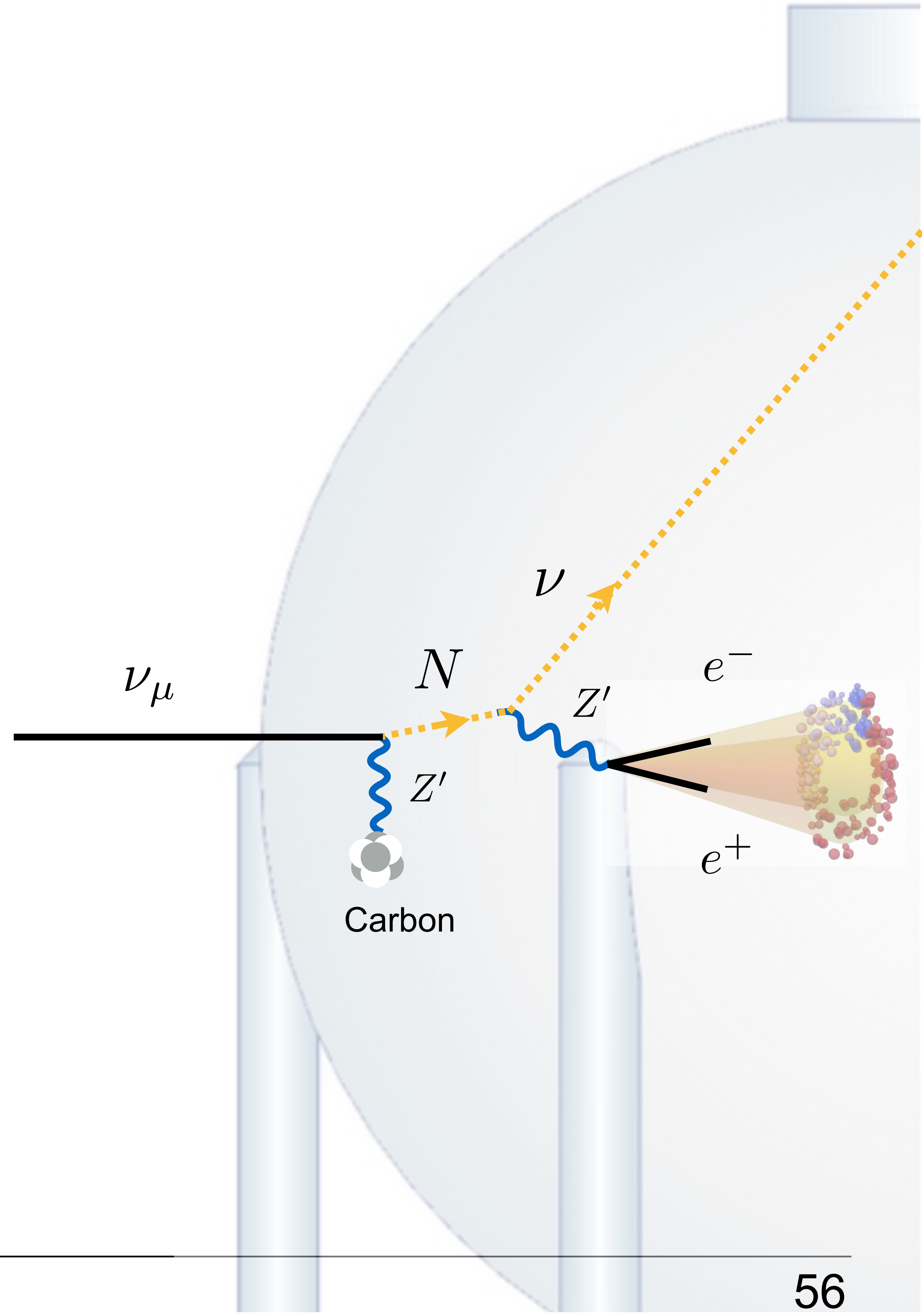
Dominated by systematic uncertainty on backgrounds.

Cherenkov signal can be single e^-, γ or overlapping e^+e^- or $\gamma\gamma$



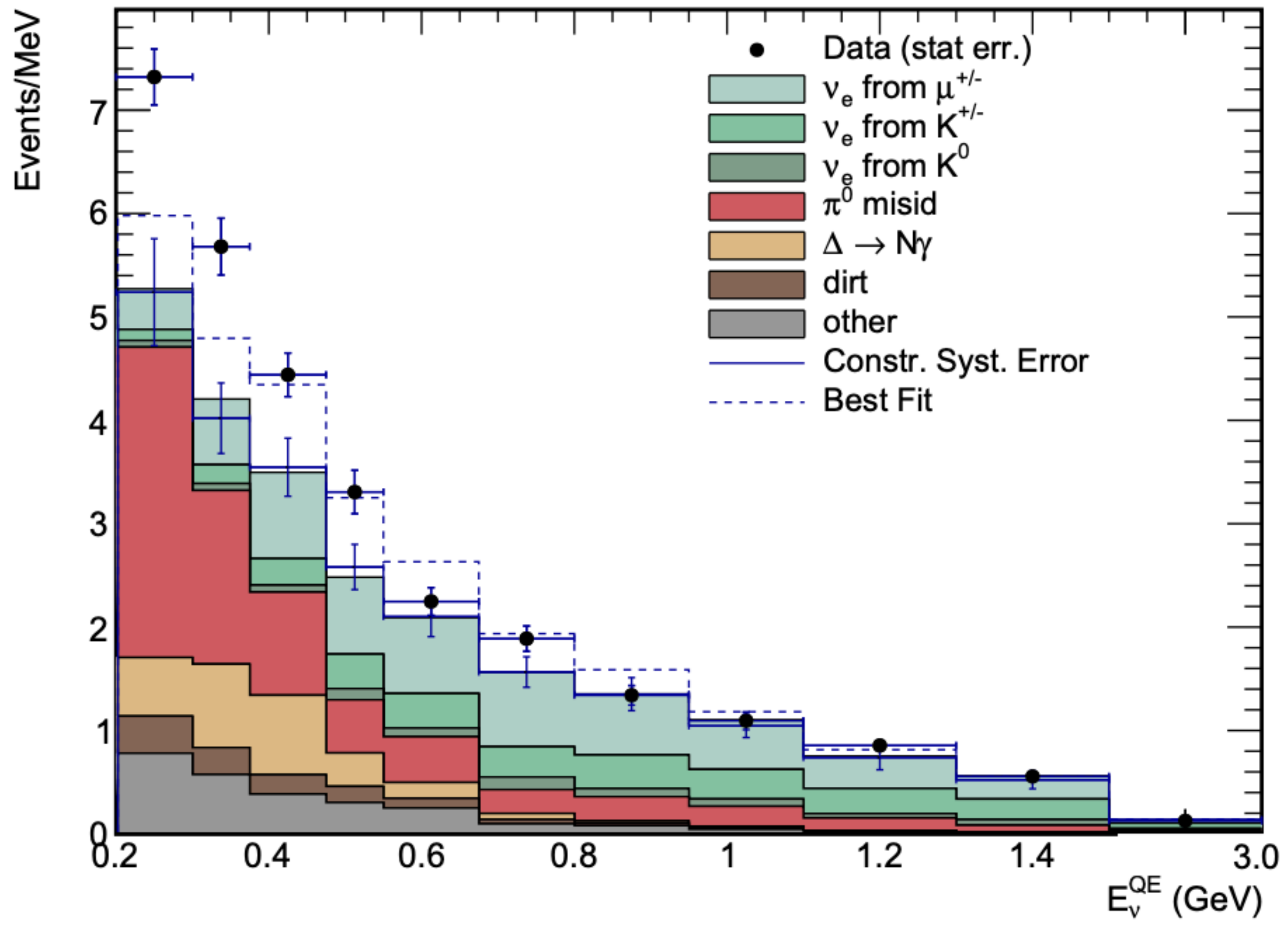
A. Abdullahi, J. Z. Hoefken, D. Massaro, MH, S. Pascoli, in preparation.

Detailed fits to excess in semi-visible dark photon parameter space.



E. Bertuzzo et al., [arXiv:1807.09877]
P. Ballett et al, [arxiv:1808.02915]
C. Argüelles et al, [arXiv:1812.08768]
P. Ballett, MH, S. Pascoli [arxiv:1903.07589]
A. Abdullahi, MH, S. Pascoli, [arXiv:2007.11813]

MiniBooNE Coll., [arXiv:2006.16883]



Large excess of electron-like events in MiniBooNE (4.8σ)

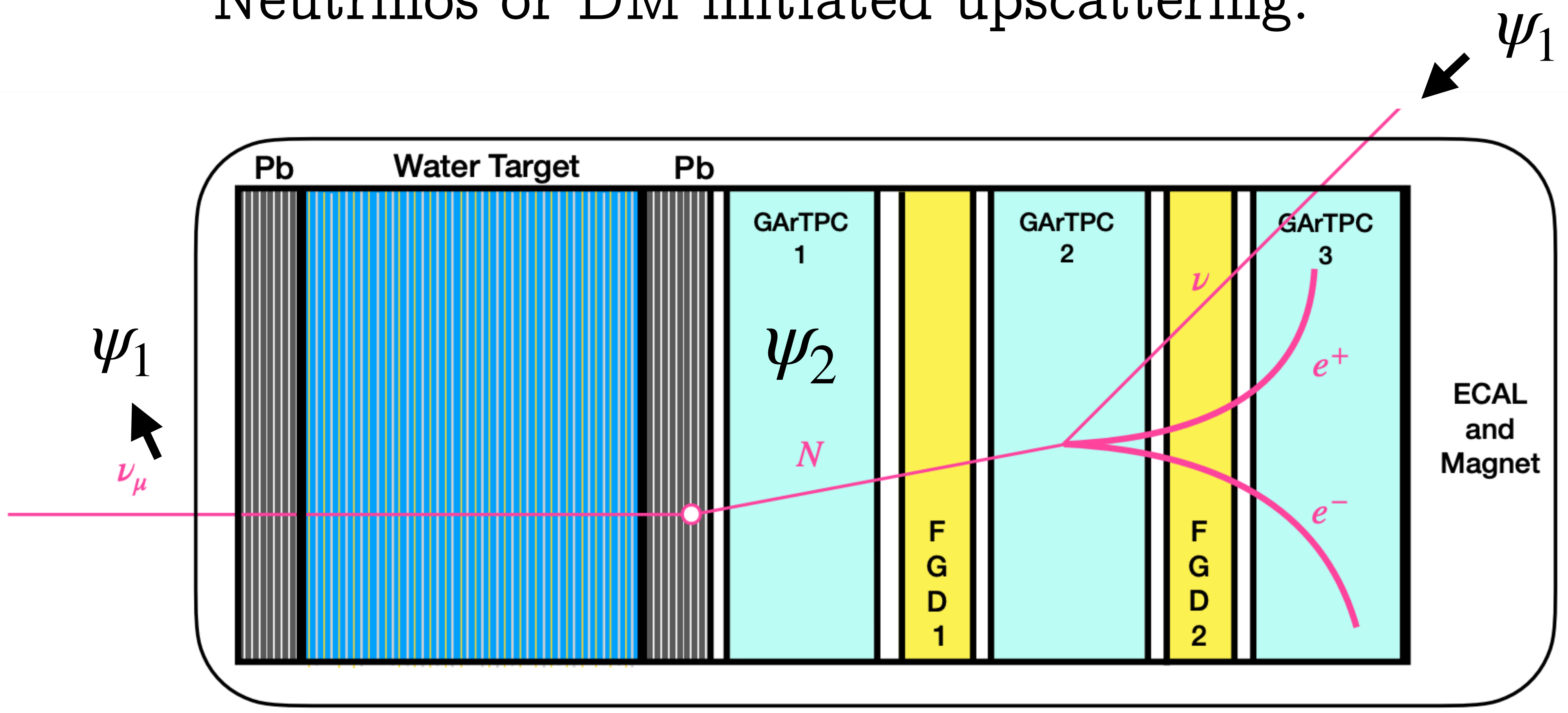
Dominated by systematic uncertainty on backgrounds.

Cherenkov signal can be single e^-, γ or overlapping e^+e^- or $\gamma\gamma$

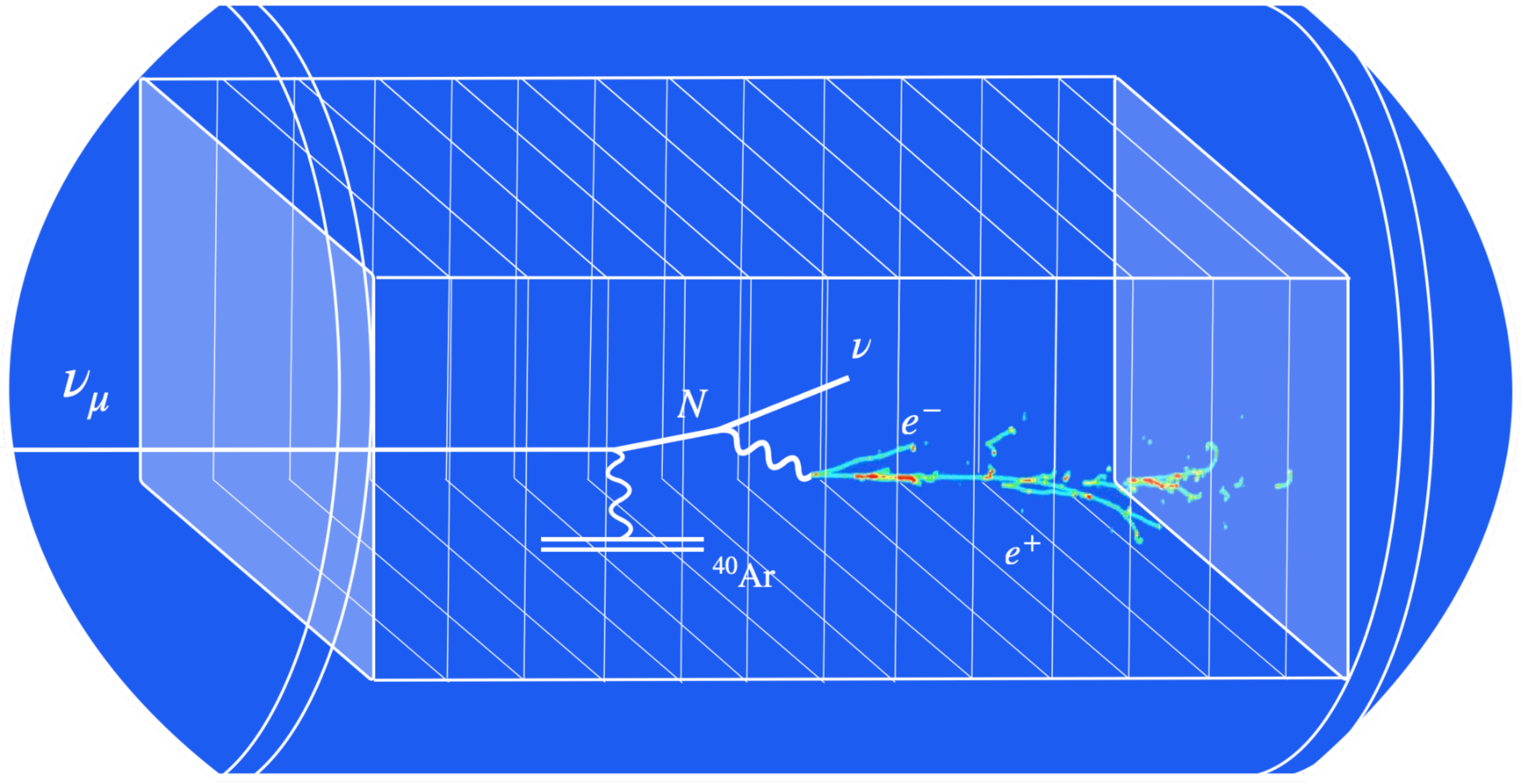
C. Arguelles, MH, N. Foppiani, arXiv:2205.12273

Searches at other neutrino detectors, such as T2K ND280.

Neutrinos or DM initiated upscattering.



Dedicated searches on-going at the LArTPC program at FNAL →



Summary

A semi-visible dark photon with $m_{A'} \sim 1$ GeV and $\varepsilon \sim 10^{-2}$ is an important target for experimental search
$\rightarrow$ naive one-loop prediction for kinetic mixing.

Applications to open problems in experimental data:
Solution to the $(g-2)_\mu$ puzzle
Connection to anomalies in short-baseline neutrino experiments (MiniBooNE)

Better understanding of the parameter space of semi-visible A':
Re-evaluation of the BaBar limits with fast MC.
Sensitivity study and recast of NA64 limits
New models and benchmarks — in addition to iDM and i2DM, we can move to mixed-iDM and HNLs.

Prospects

Extend our coverage of semi-visible mediators:

1. **Dedicated** searches for A' in CERN's fixed target program:

    a. Targeting prompt decay signature
    b. Targeting multi-chain decays, such as $\psi_3 \to \psi_2 \to \psi_1$ in a HNL context (connection to SBL anomalies)

    c. Include resonant $e^+e^- \to A'$ production @ $m_{A'} \sim 2E_e m_e \sim 300\,\mathrm{MeV}$ — $\Gamma_{A'}/m_{A'}$ can be sizable.
    d. Muon beam also relevant — A' energy distribution can be higher E, offering complementary reach.

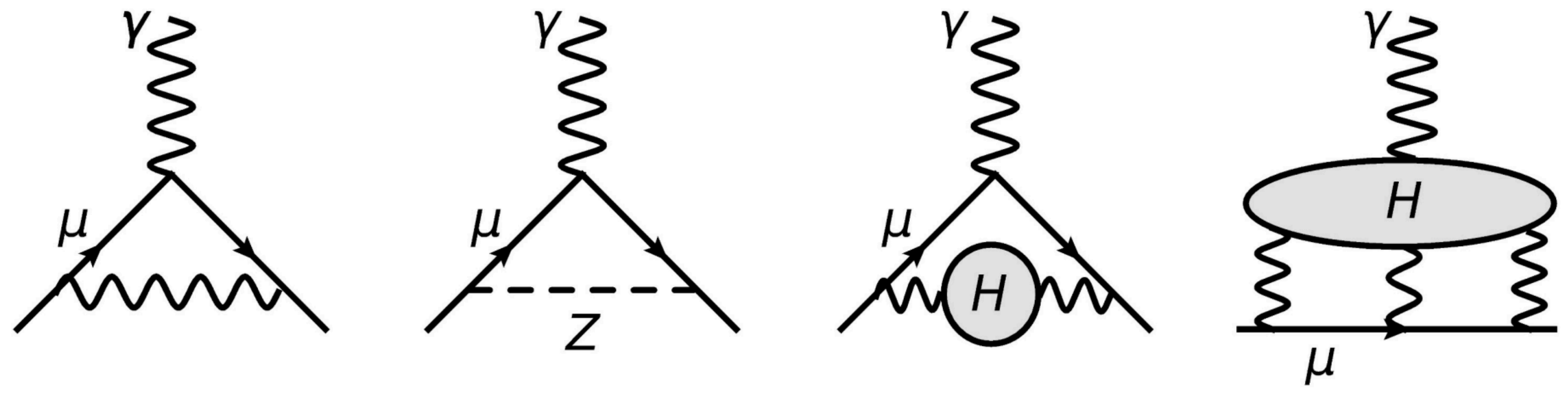
2. Searches for monophotons and displaced vertices at Belle-II.
3. Make use of $\psi_1 \to \psi_2 \to \psi_1 e^+e^-$ upscattering signatures at neutrino experiments.
4. Eventually, LDMX could weigh in with a missing **momentum** technique — resolve tracks of e^+e^-.

Back-up slides

Dark forces contributing to (g-2)μ

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HVP,\,LO} + a_\mu^{\rm HVP,\,NLO} + a_\mu^{\rm HVP,\,NNLO} + a_\mu^{\rm HLbL} + a_\mu^{\rm HLbL,\,NLO}$$
$$= 116\,591\,810(43) \times 10^{-11}\,.$$

Phys. Rept. 887 (2020) 1–166



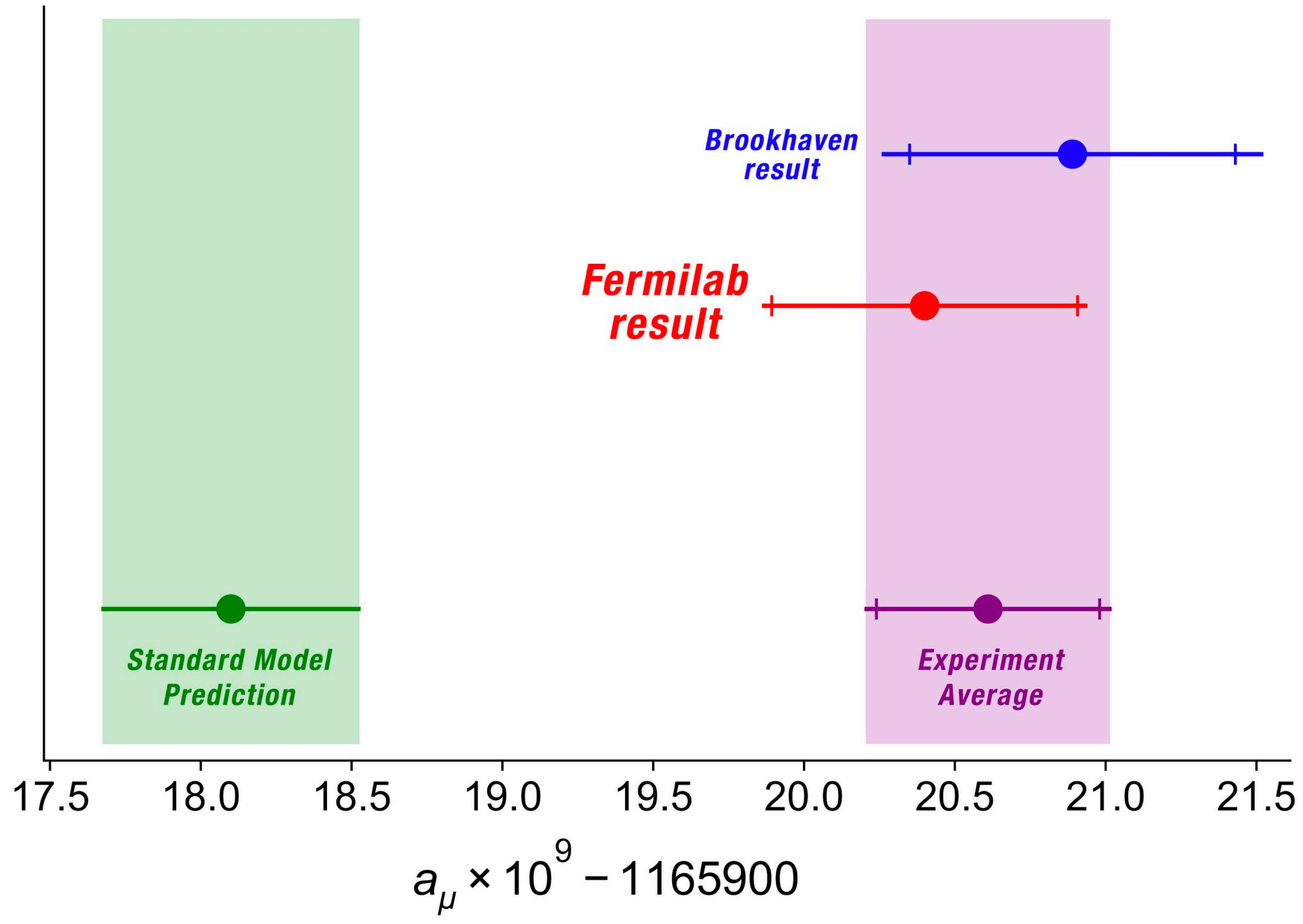
$$a_\mu^{\rm EXP} = 116592061(41) \times 10^{-11}$$

Muon (g-2) BNL., PRD73:072003,2006

Muon (g-2) FNAL 10.1103/PhysRevLett.126.141801

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 251 \times 10^{-11}$$

Combination of BNL and FNAL results stands at a 4.2 σ discrepancy with theory white-paper calculations (see also, lattice results).



If theory predictions are indeed under control, then new physics must not be too far out of reach

$$\Delta a_\mu^{\rm NP} \sim \frac{g^2}{16\pi^2}\frac{m_\mu^2}{\Lambda^2}$$

$$\frac{\Lambda}{g} \sim \text{ few 100s of GeV}$$

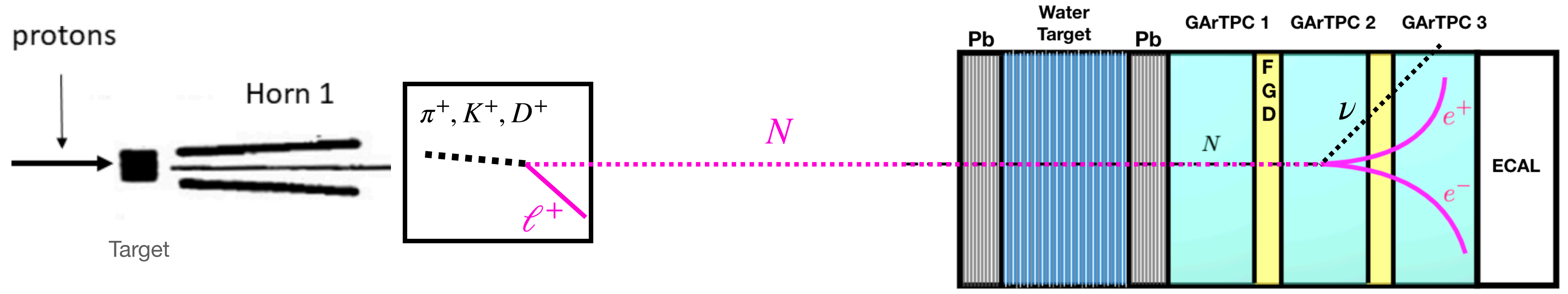
Dark Neutrino Sectors
Upscattering at the T2K near detector

T2K Collaboration, Phys. Rev. D 100, 052006 (2019)

See also, Vedran Brdar et al, arXiv:2007.14411

C. Arguelles, MH, N. Foppiani, arXiv:2205.12273

T2K search:



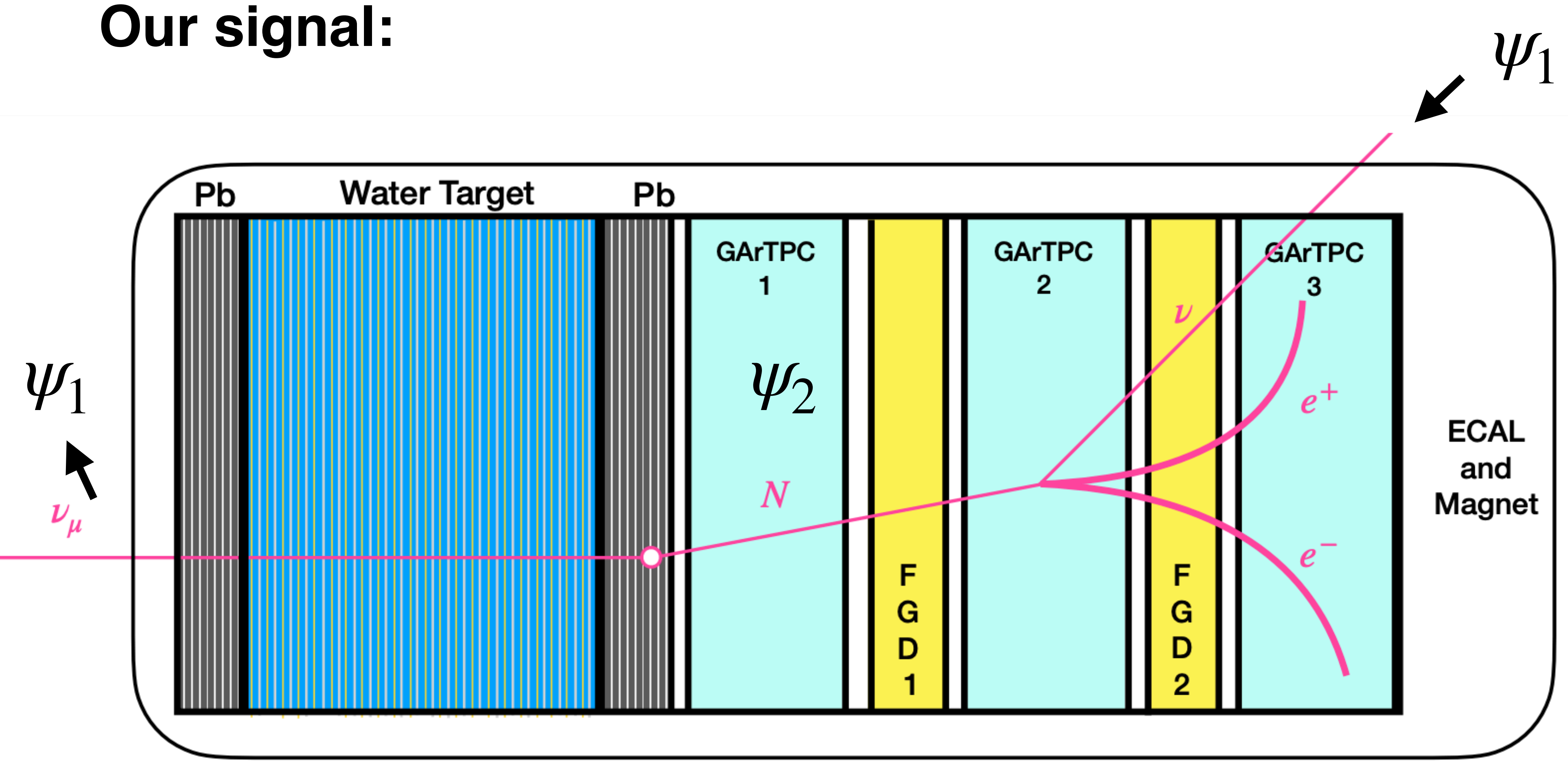
+ Heavy **lead** plates

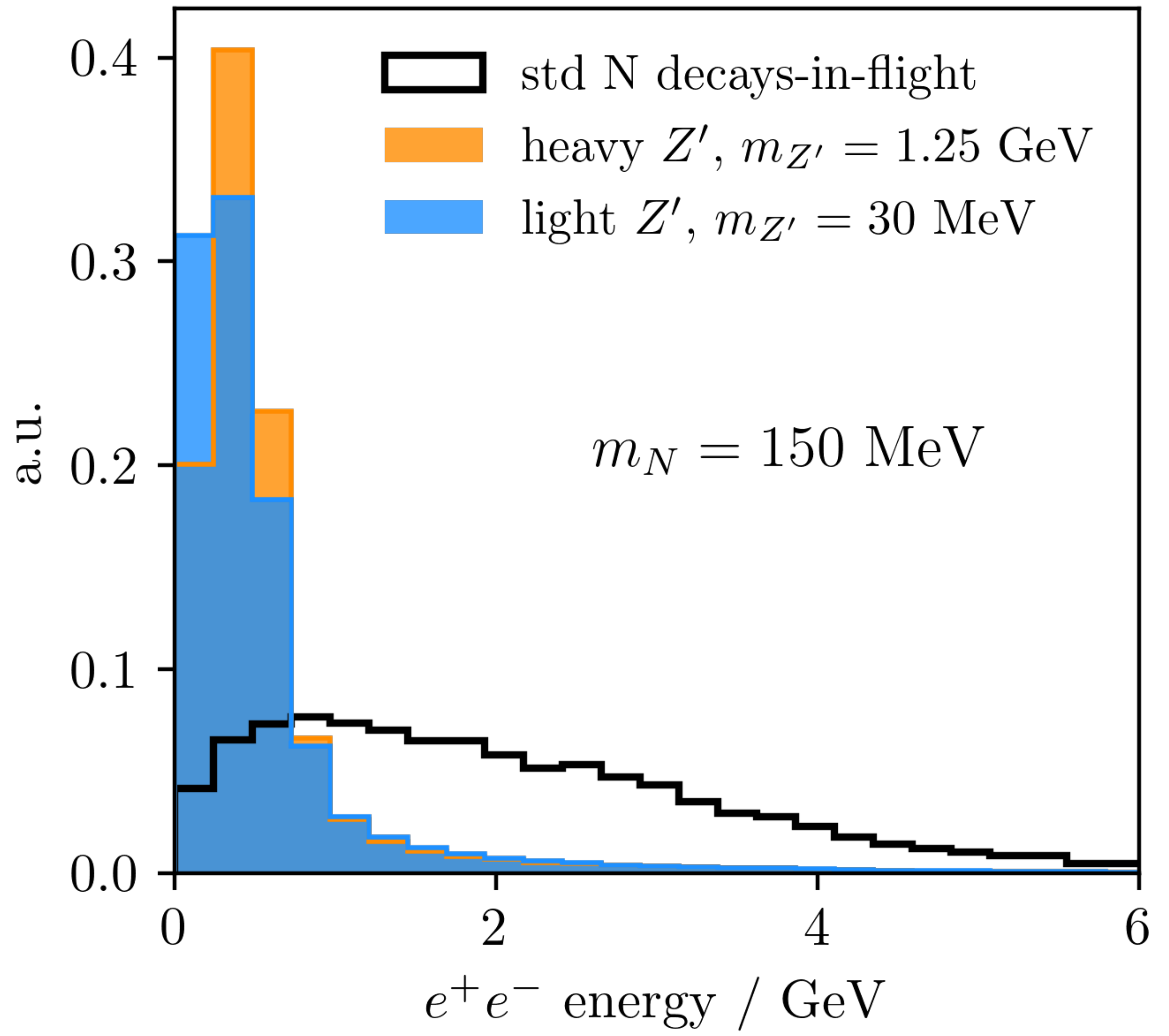
+ Gaseous Argon modules

+ Magnetic field to separate e^+e^-

No events were observed. Backgrounds were < 1.

Our signal:





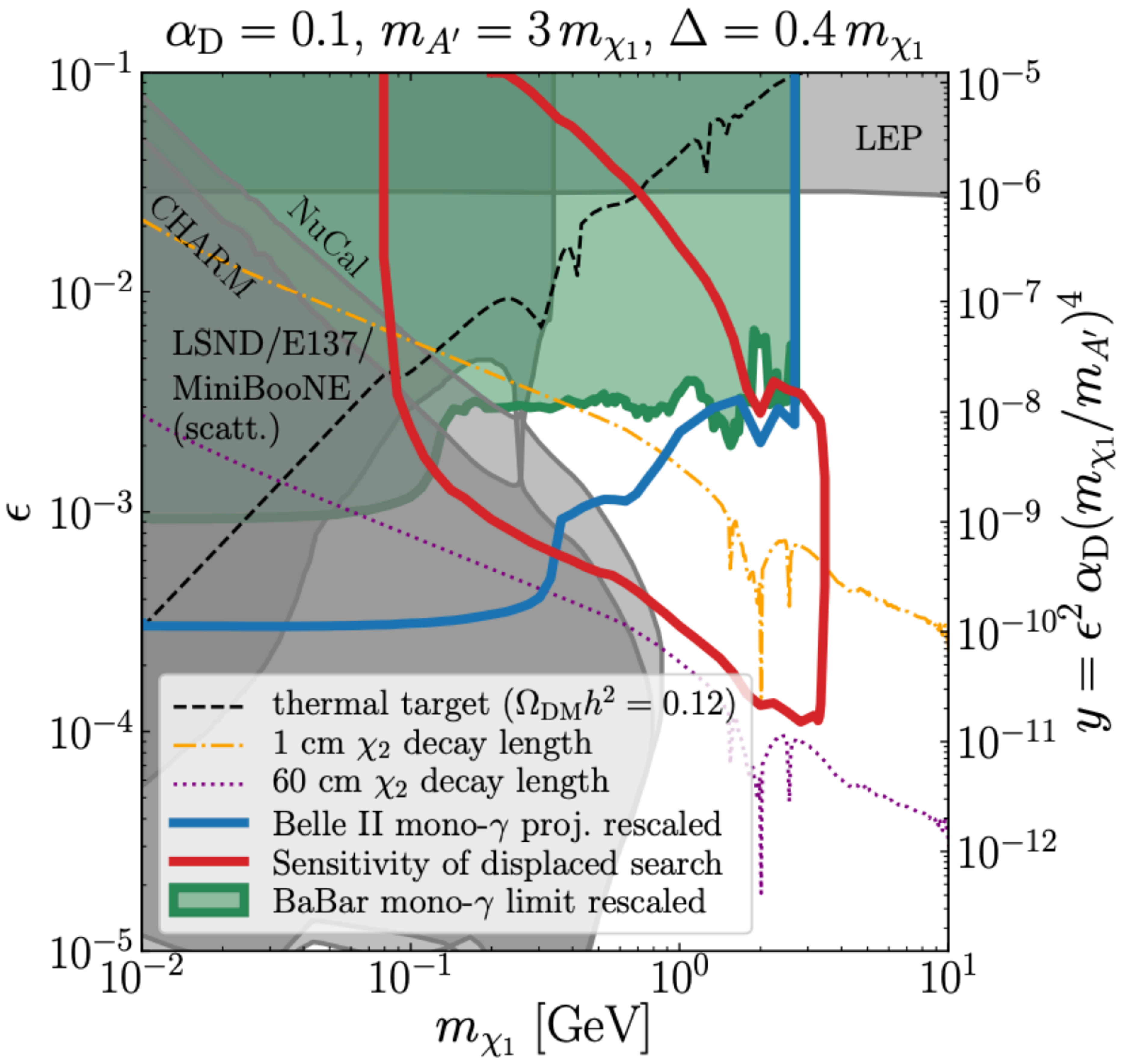
The search focused on the decay in flight of HNLs (solid black)

Our upscattering signal is different, mostly in energy (colors).

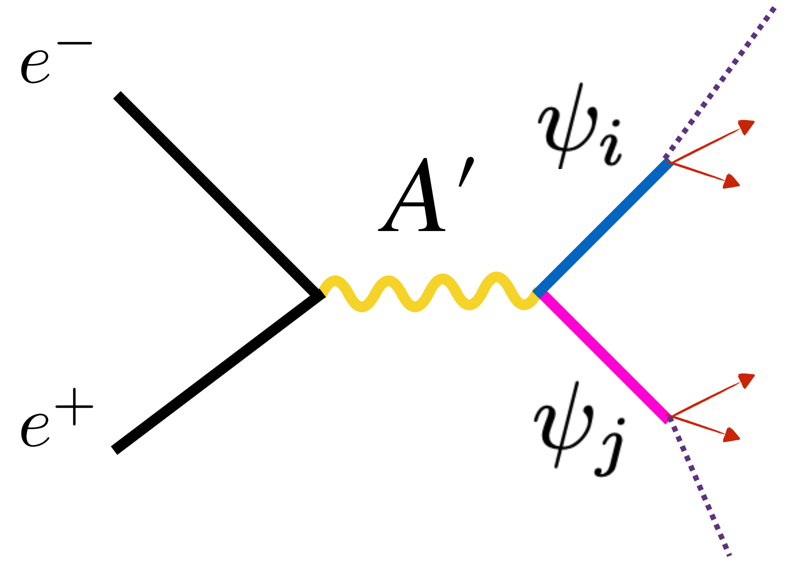
Fixed targets and neutrino experiments

Belle-II — displaced vertices

M. Duerr et al, arXiv:1911.03176



S-channel: lose the photon, but gain in rate.



$\frac{\alpha_D}{\alpha}$ of the ISR rate.

Different kinematics,
larger pT for the fermions.

S-channel production not included,
sensitivity can be much better.


NA64 proj. (S2)
BP1a (iDM)
$m_{A'} = 4.00 \times 10^{-1}$ GeV
$\varepsilon = 6.00 \times 10^{-3}$
$P_{\rm inv} = 9.76 \times 10^{-1}$
semi-visible A'
invisible A'
all events
Fraction of events
$E_{e^+} + E_{e^-}$ / GeV
$(E_{e^+} - E_{e^-})/(E_{e^+} + E_{e^-})$
$\theta_{e^\pm}$ / deg
ψ_1
ψ_2
ψ_3
1.0
$\mathcal{B}(A' \to \psi_i \psi_j)$
m_{ee} / GeV
E_{e^+} / GeV
E_{e^-} / GeV
$(E_{e^+} + E_{e^-})$ / GeV
$\Delta\theta_{e^+e^-}$ / deg
Fraction of events

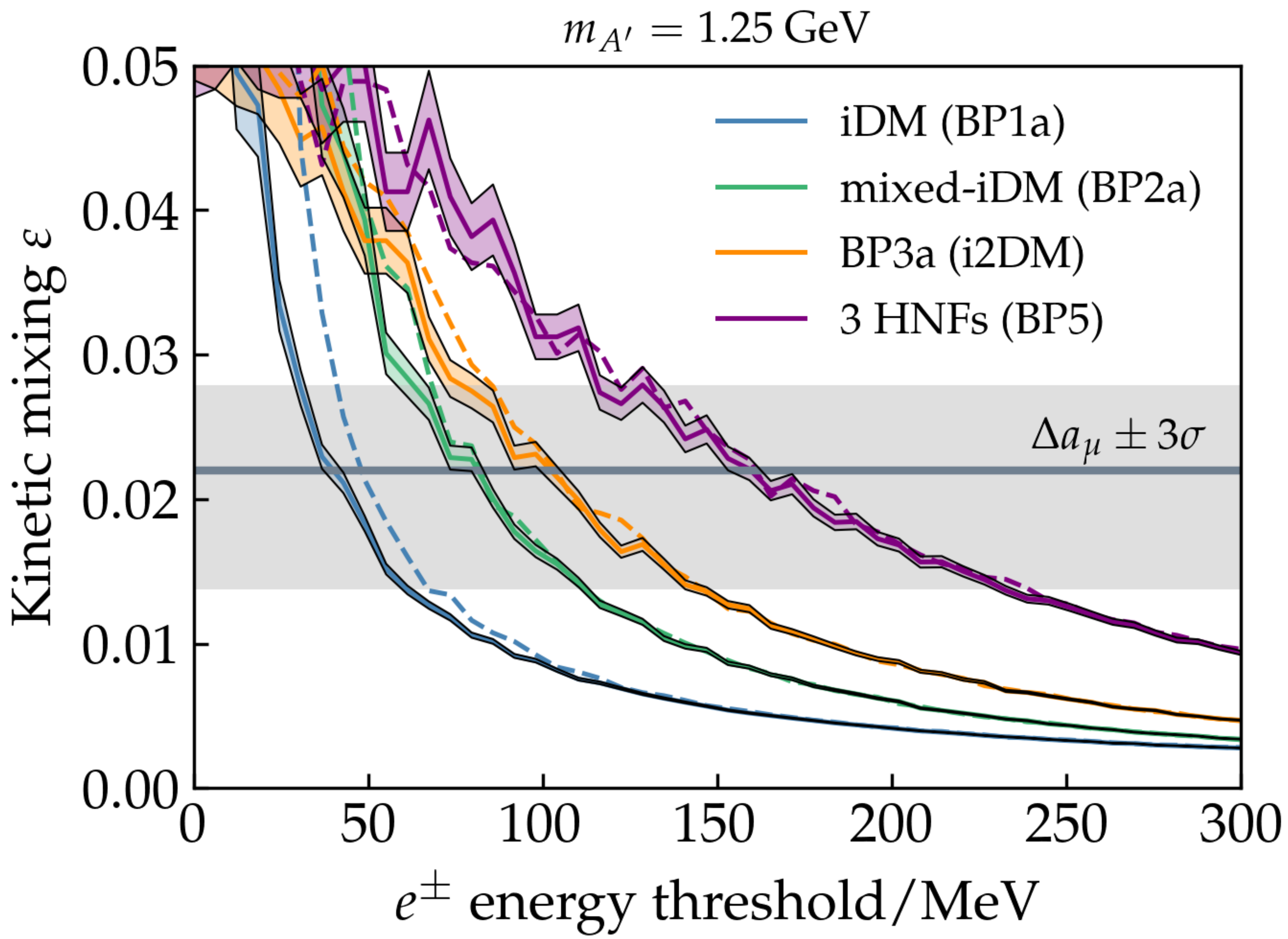
NA64 proj. (S2)
BP2a (mixed-iDM)
$m_{A'} = 1.00$ GeV
$\varepsilon = 1.50 \times 10^{-2}$
$P_{\rm inv} = 1.83 \times 10^{-1}$
semi-visible A'
invisible A'
all events
Fraction of events
$E_{e^+} + E_{e^-}$ / GeV
$(E_{e^+} - E_{e^-})/(E_{e^+} + E_{e^-})$
$\theta_{e^\pm}$ / deg
ψ_1
ψ_2
ψ_3
4.0 $\times 10^{-2}$
9.6 $\times 10^{-1}$
$\mathcal{B}(A' \to \psi_i \psi_j)$
m_{ee} / GeV
E_{e^+} / GeV
E_{e^-} / GeV
$(E_{e^+} + E_{e^-})$ / GeV
$\Delta\theta_{e^+e^-}$ / deg
Fraction of events

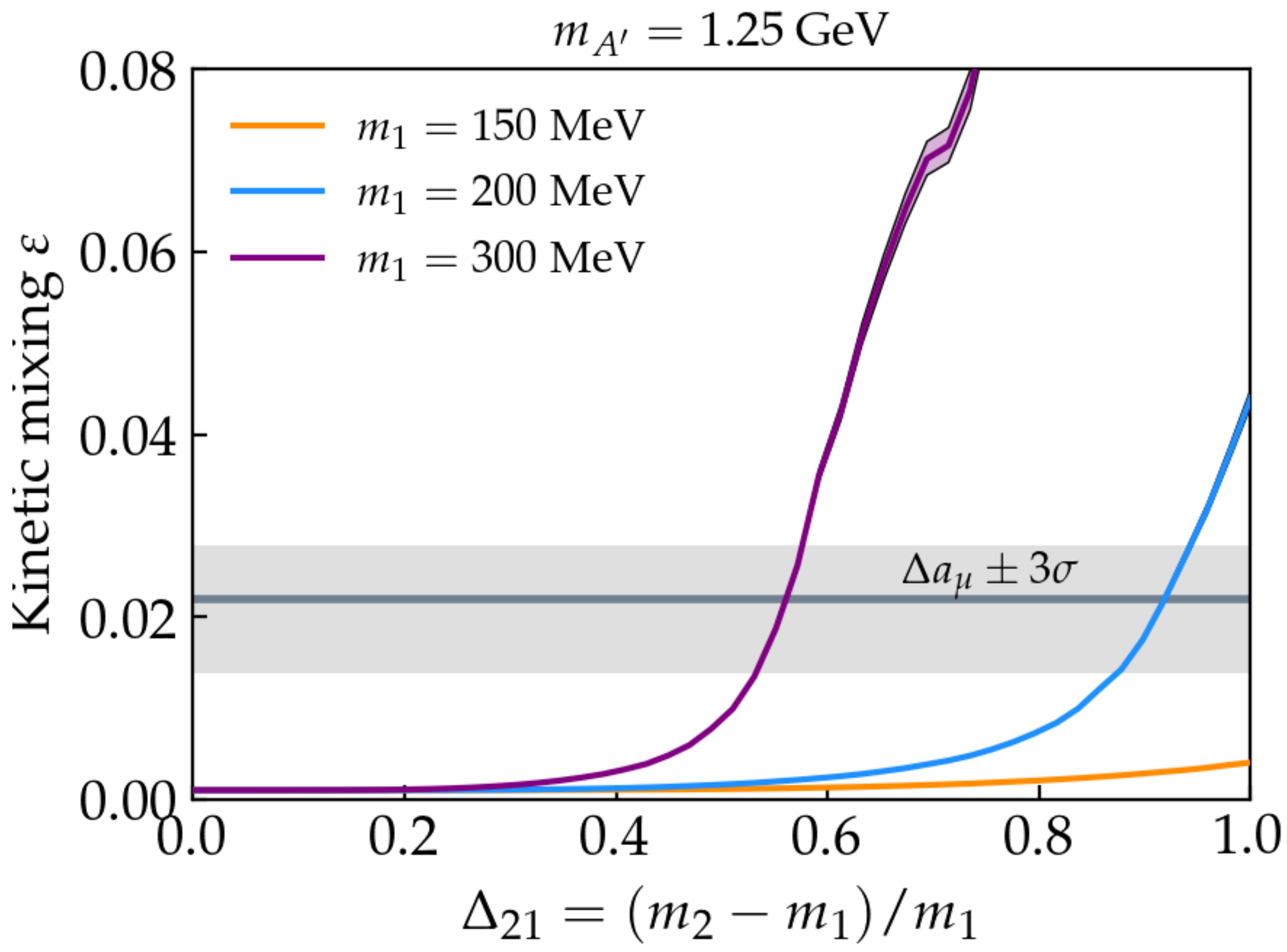
NA64 proj. (S2)
BP3b (i2DM)
$m_{A'} = 1.00$ GeV
$\varepsilon = 2.00 \times 10^{-2}$
$P_{\text{inv}} = 4.98 \times 10^{-1}$
semi-visible A'
invisible A'
all events
Fraction of events
$E_{e^+} + E_{e^-}$ / GeV
$(E_{e^+} - E_{e^-})/(E_{e^+} + E_{e^-})$
$\theta_{e^\pm}$ / deg
ψ_1
ψ_2
ψ_3
3.6 $\times 10^{-4}$
2.9 $\times 10^{-2}$
9.7 $\times 10^{-1}$
$\mathcal{B}(A' \to \psi_i \psi_j)$
m_{ee} / GeV
E_{e^+} / GeV
E_{e^-} / GeV
$(E_{e^+} + E_{e^-})$ / GeV
$\Delta\theta_{e^+e^-}$ / deg
Fraction of events

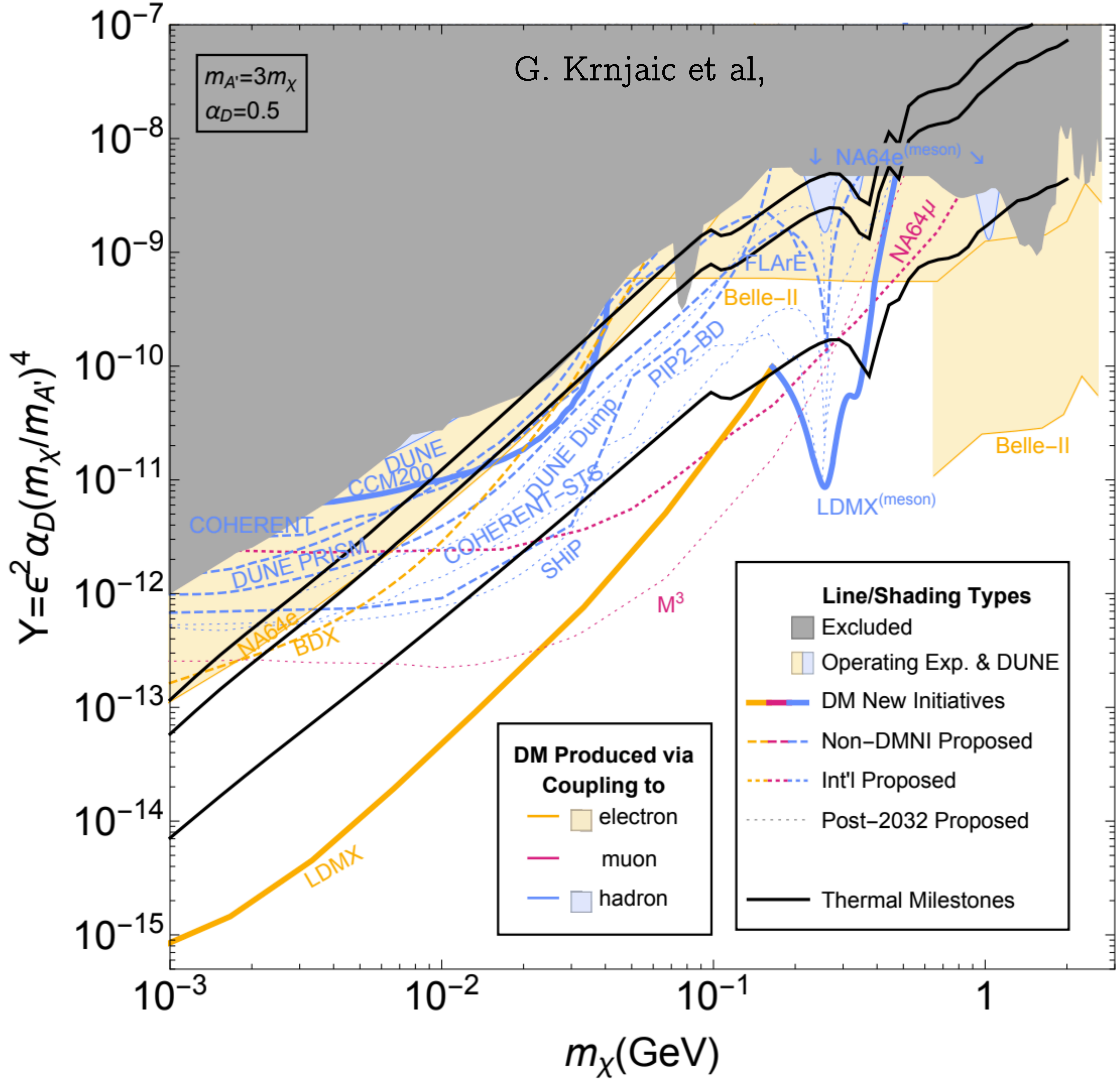
Signal characteristics

Dependence of the results on simulation assumptions

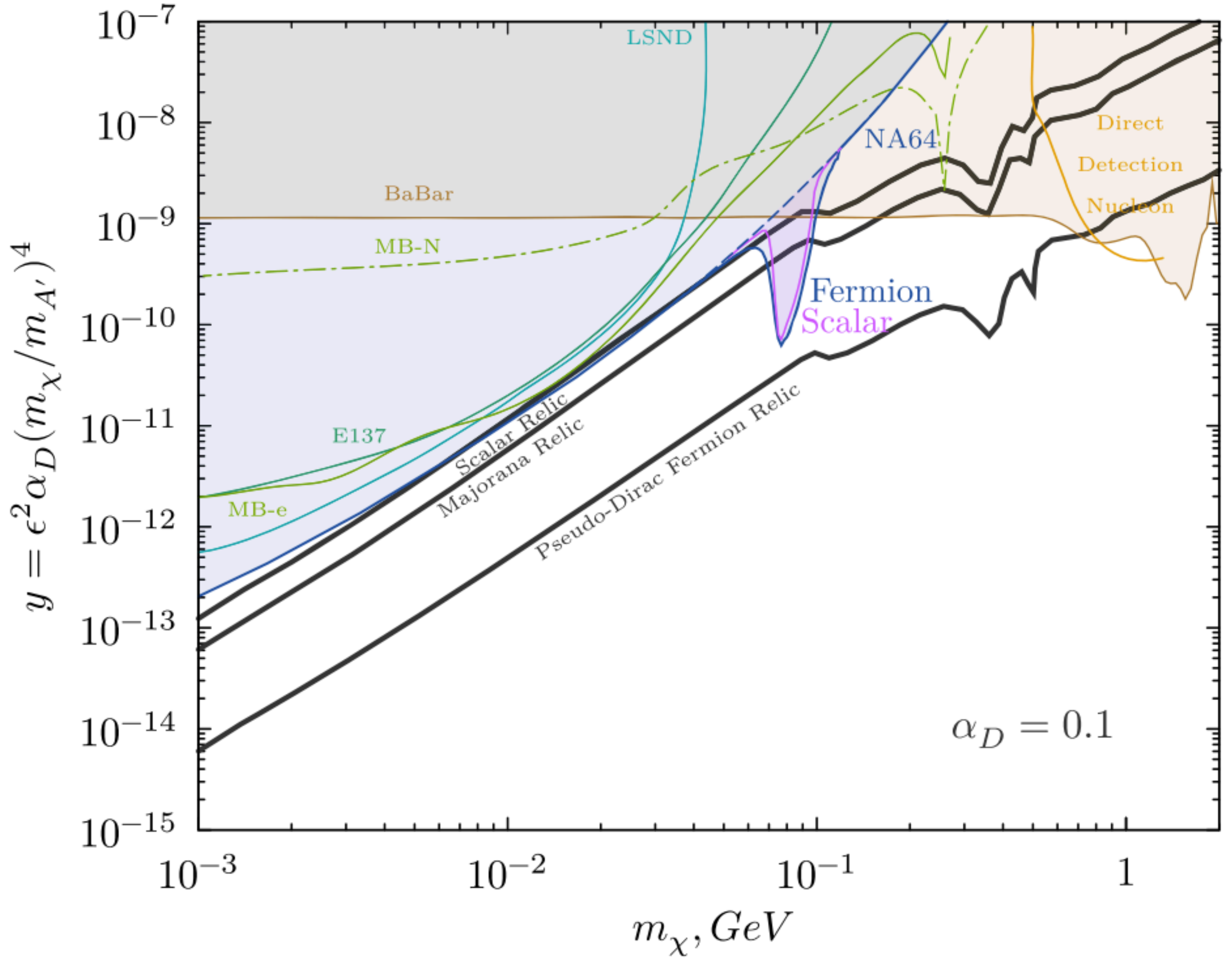
At BaBar, **energy thresholds** are the dominant source of “invisible” dark photon events:





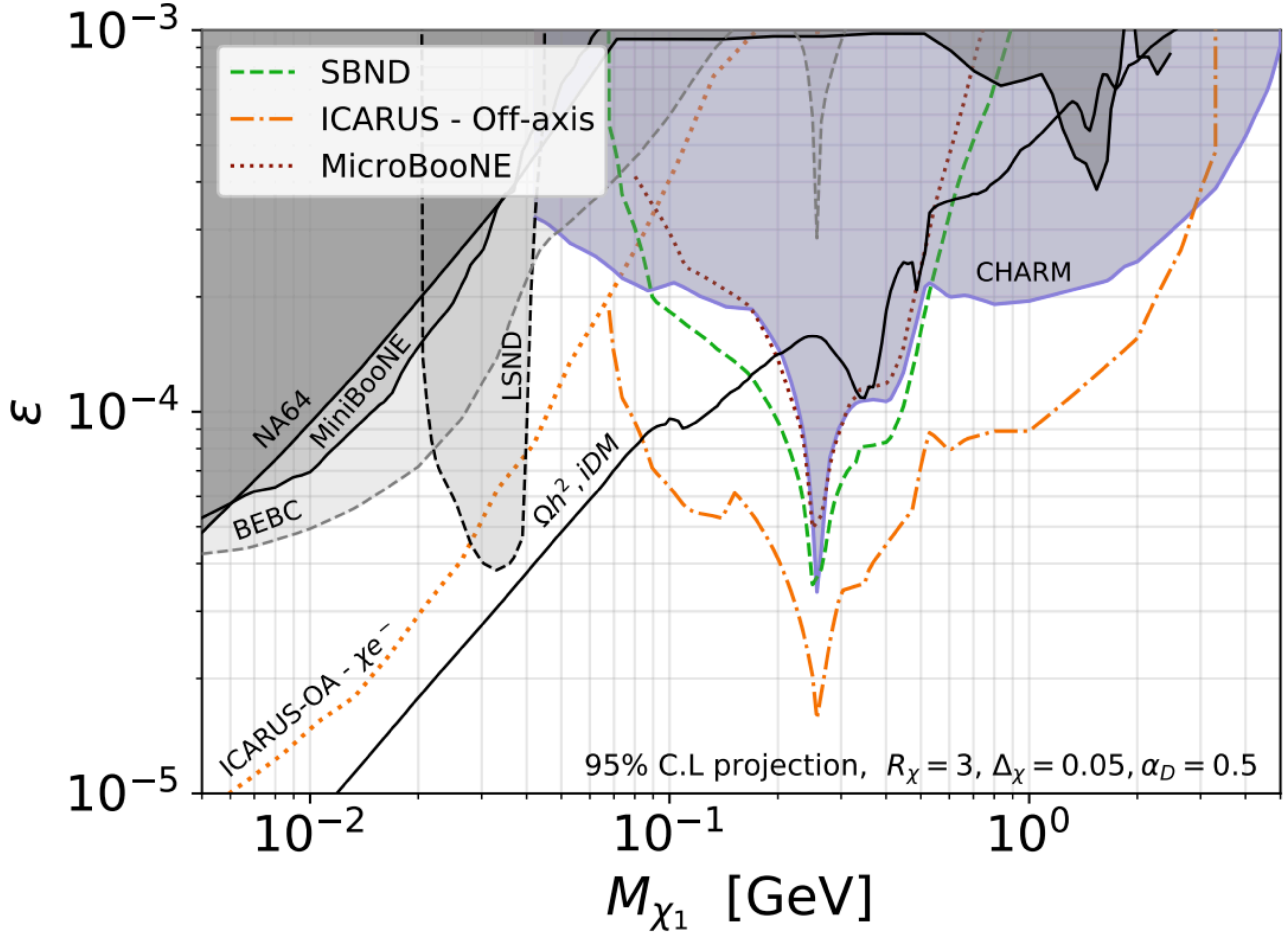


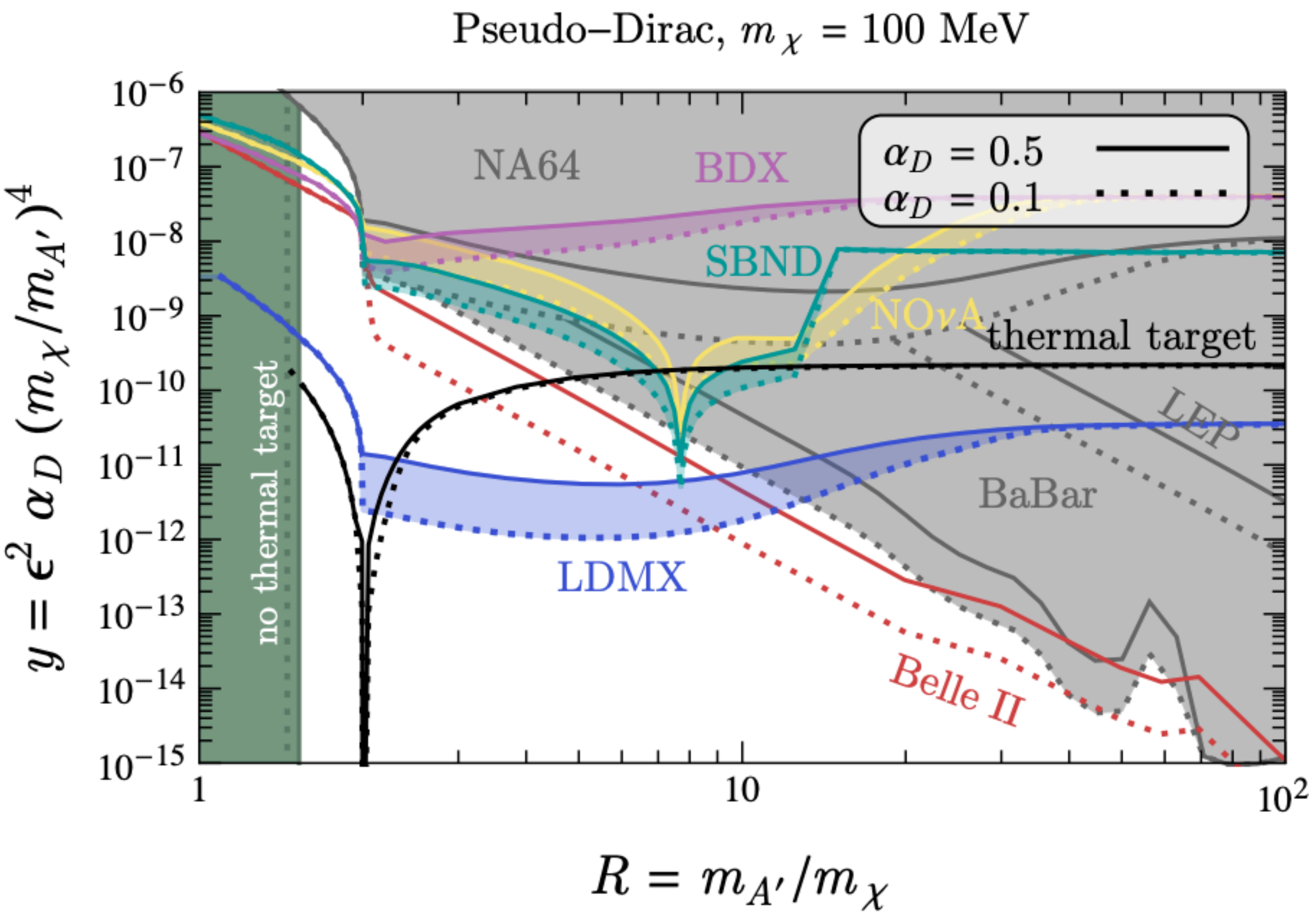
NA64 including resonant production.



iDM at the Short-Baseline program at FNAL.

B. Batell et al, arXiv:2106.04584





Pseudo–Dirac, m_χ = 100 MeV
α_D = 0.5
α_D = 0.1
NA64
BDX
SBND
NOνA
thermal target
LEP
BaBar
LDMX
Belle II
no thermal target
$y = \epsilon^2 \alpha_D (m_\chi/m_{A'})^4$
$R = m_{A'}/m_\chi$