The Semi-Visible Dark Photon

A. Abdullahi, MH, D. Massaro, S. Pascoli
to appear on arXiv soon.

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

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Perimeter Institute

Self-consistent sector of matter particles

The SM has very little room for new particles and forces at low scales.

$\mathscr{L}_{\rm SM}$

Dark Matter

Neutrino masses?

Anomalous measurements:
$(g-2)_\mu$? MiniBooNE? ...?

$\mathscr{L}_{\text{SM}}$

DARK SECTOR (DS)

Heavy neutrinos

$$\frac{M_N}{2}\overline{N^c}N$$

Neutrino masses?

Dark photons

$$G_{SM} \times U(1)_X$$

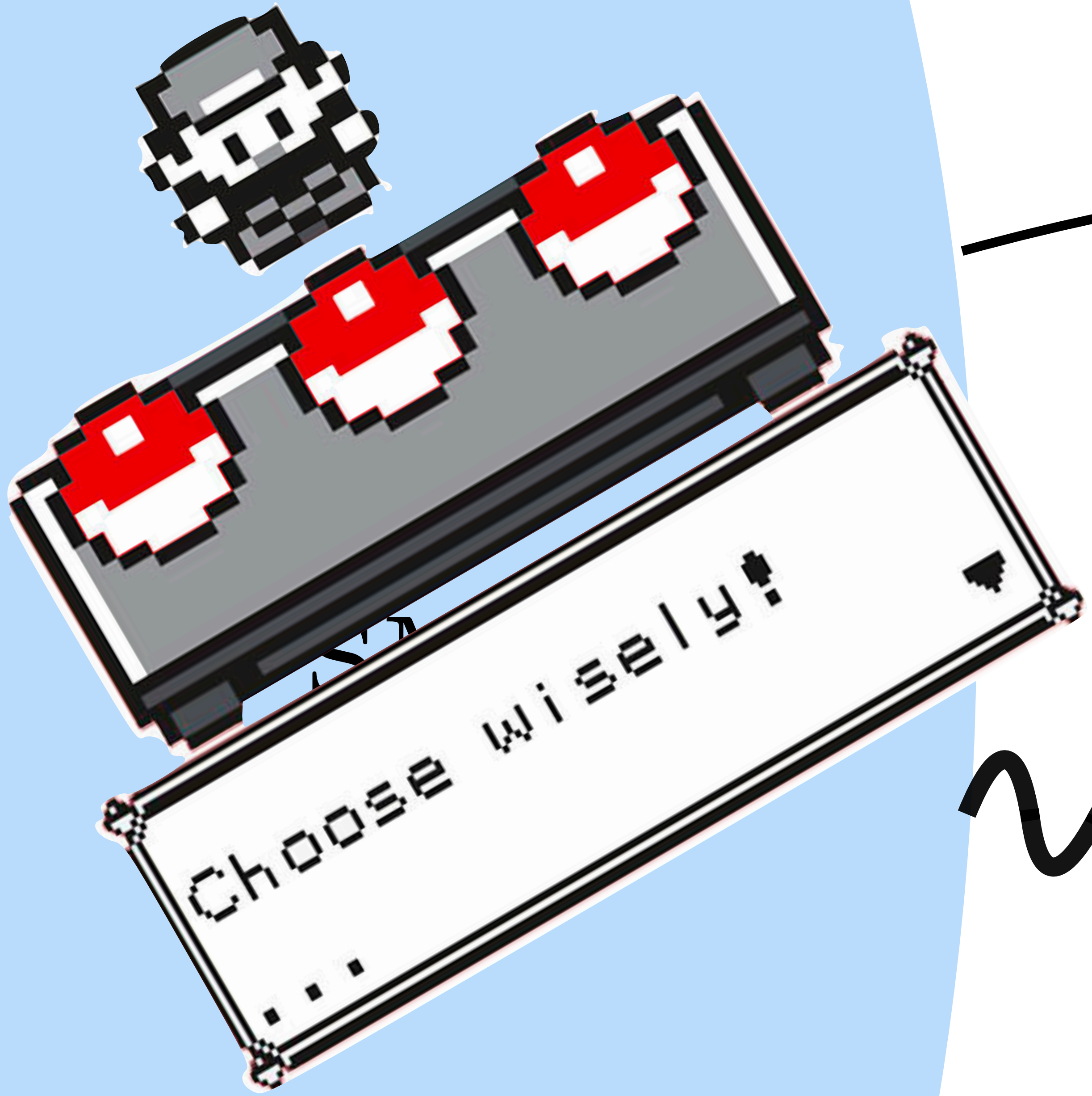
New fundamental forces?

Dark scalars

$$V(H, S)$$

Scalar degrees of freedom


Renormalizable Portals:
(SM SINGLET) X (DS SINGLET)
DARK SECTOR (DS)
$\mathscr{L}_{\mathrm{SM}}$
$\overline{L}\widetilde{H}N$
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
$V(H,S)$
Scalar degrees of freedom
Dim-5 axion "portal"
special, see other talks
$\frac{a}{\Lambda}G_{\mu\nu}\tilde{G}_{\mu\nu}$



Renormalizable Portals:
(SM SINGLET) X (DS SINGLET)

To Catch'em all

$\overline{L}\widetilde{H}N$

Neutrino portal

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

Vector portal

$S^\dagger S\,(H^\dagger H)$

Scalar portal

DARK SECTOR (DS)

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$\frac{M_N}{2}\overline{N^c}N$

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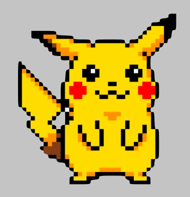
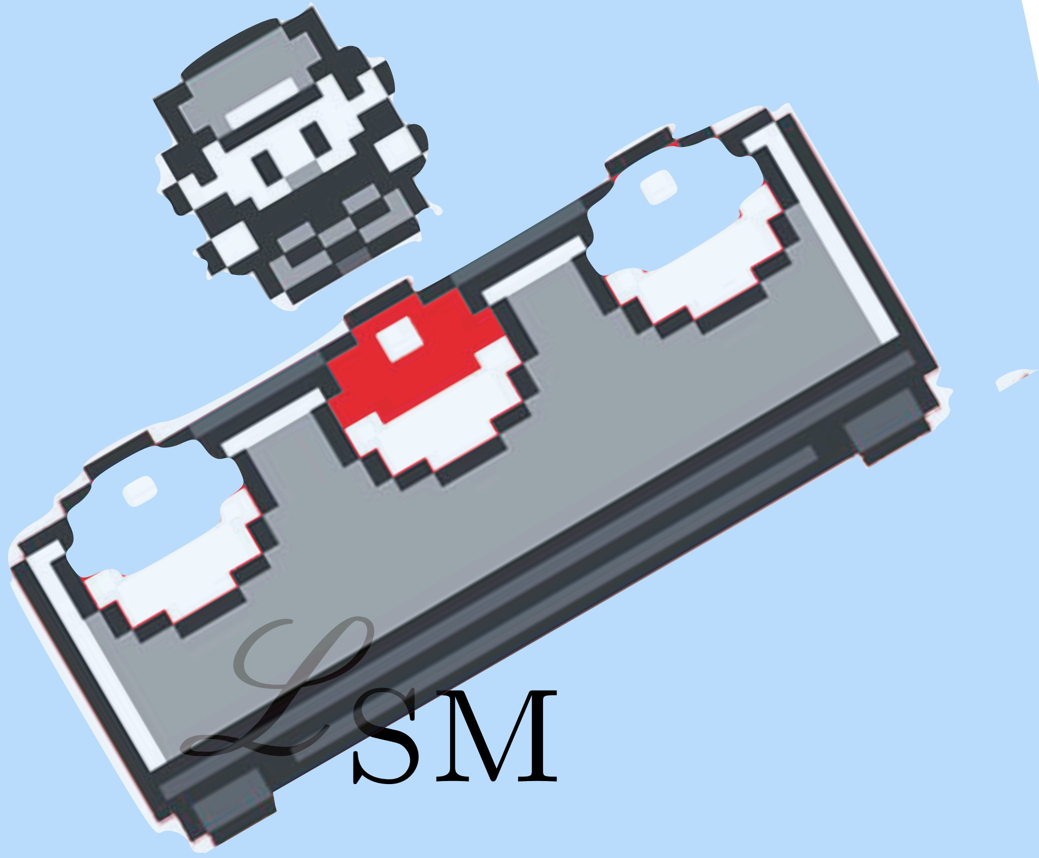
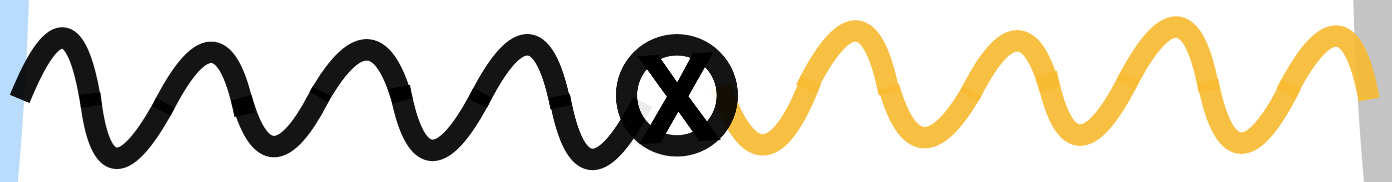




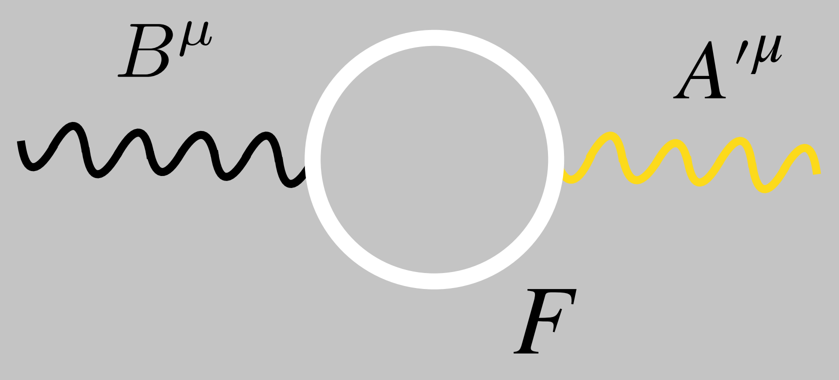
$B_{\mu\nu}X^{\mu\nu}$



Vector portal

Dark $\text{U}(1)_X$ symmetry

i) Kinetic mixing expected at some level



$$\varepsilon \sim \frac{g_X e}{16\pi^2} \log\left(\frac{\mu^2}{m_F^2}\right) \sim \mathcal{O}(10^{-3})$$

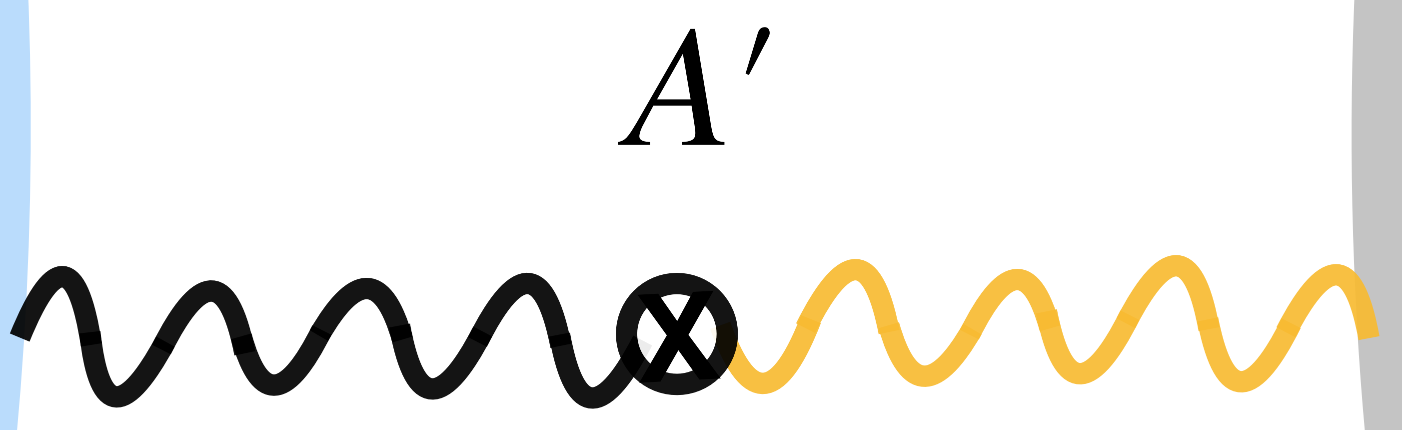
ii) May be broken spontaneously or Stückelberg(-ed) with mass $m_{Z'}$

iii) Anomalies: pick dark charges wisely (or you may get burned 🔥)

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

$$J^\mu_{\rm EM}$$

Couples to
electromagnetic
current



Dark $U(1)_X$ symmetry

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

Couples to some dark current.
It may contain:

$$J^\mu_X$$

1) dark matter

$$\psi$$

2) heavy neutral leptons

$$\overline{L}\tilde{H}\psi$$

Dark U(1)$_X$ symmetry

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

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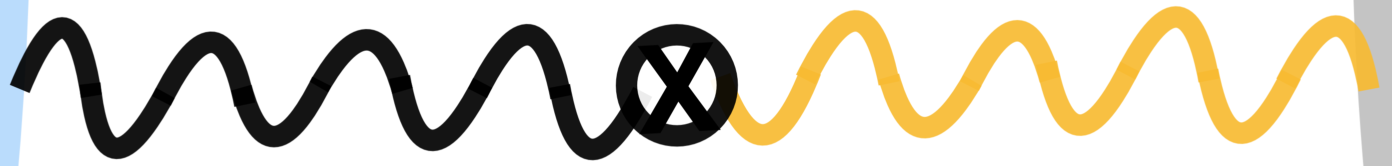
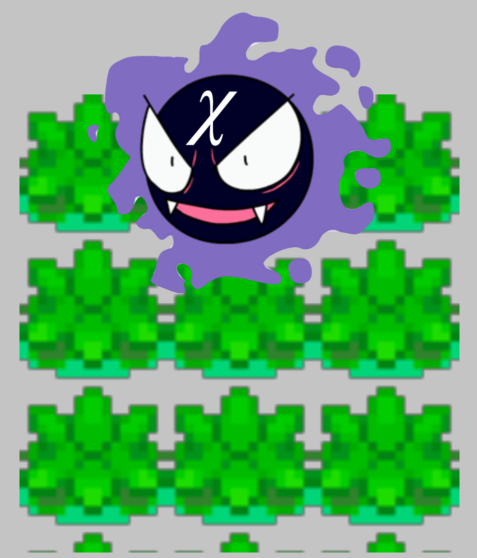
Couples to some dark current.
It may contain:

A'

J^μ_{EM}



J^μ_X



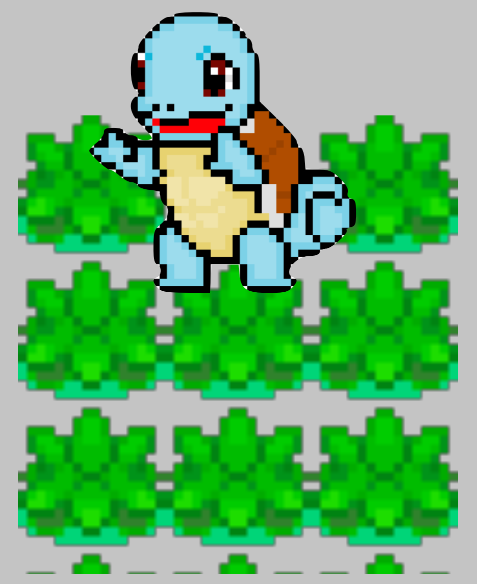
1) dark matter

ψ

Couples to electromagnetic current

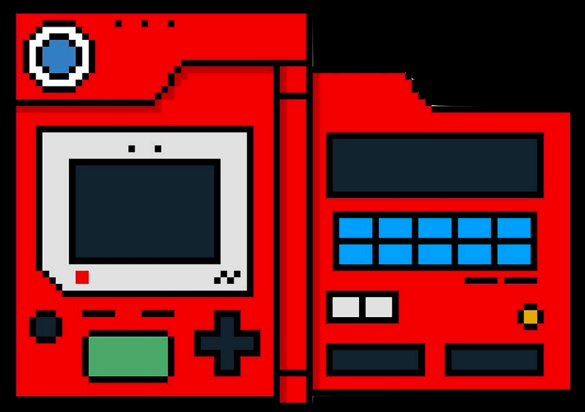
2) heavy neutral leptons

$\bar{L}\tilde{H}\psi$



Dark Photons as a portal to:

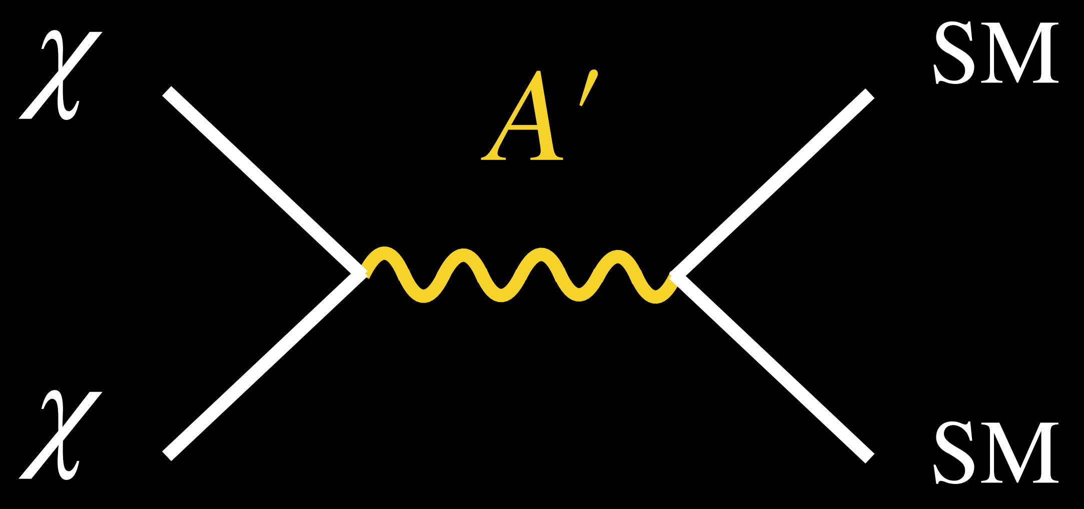
Models of Heavy Neutral Fermions (HNFs)

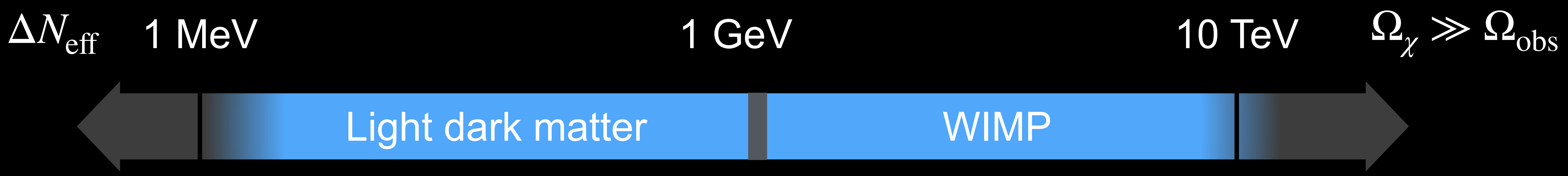


Light Dark Matter

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

Predictive and testable!





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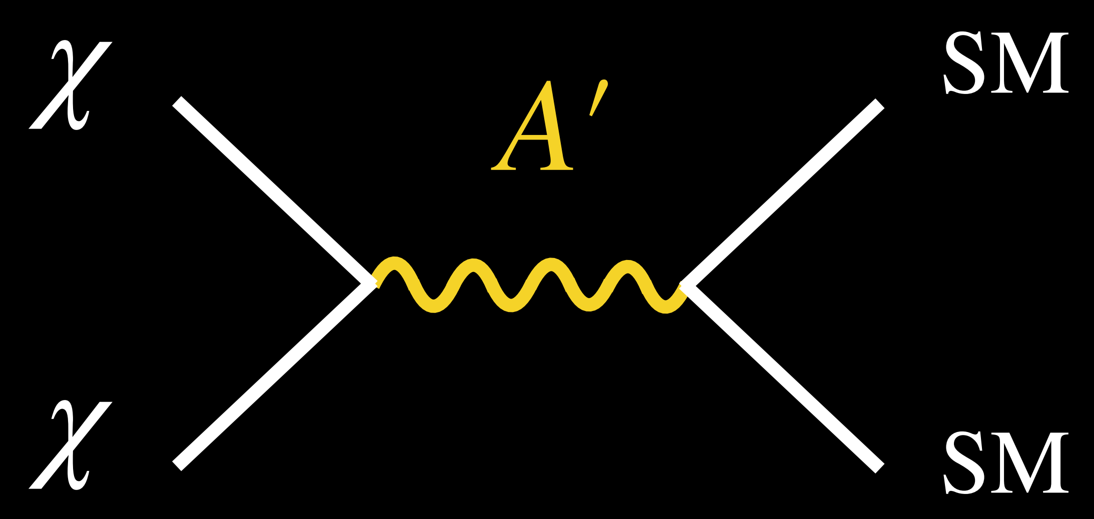
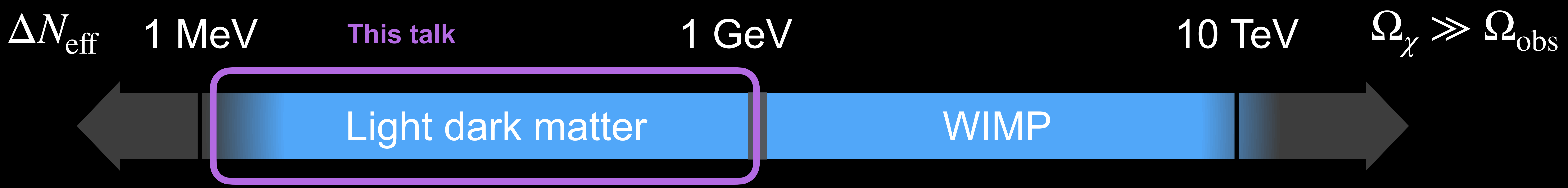


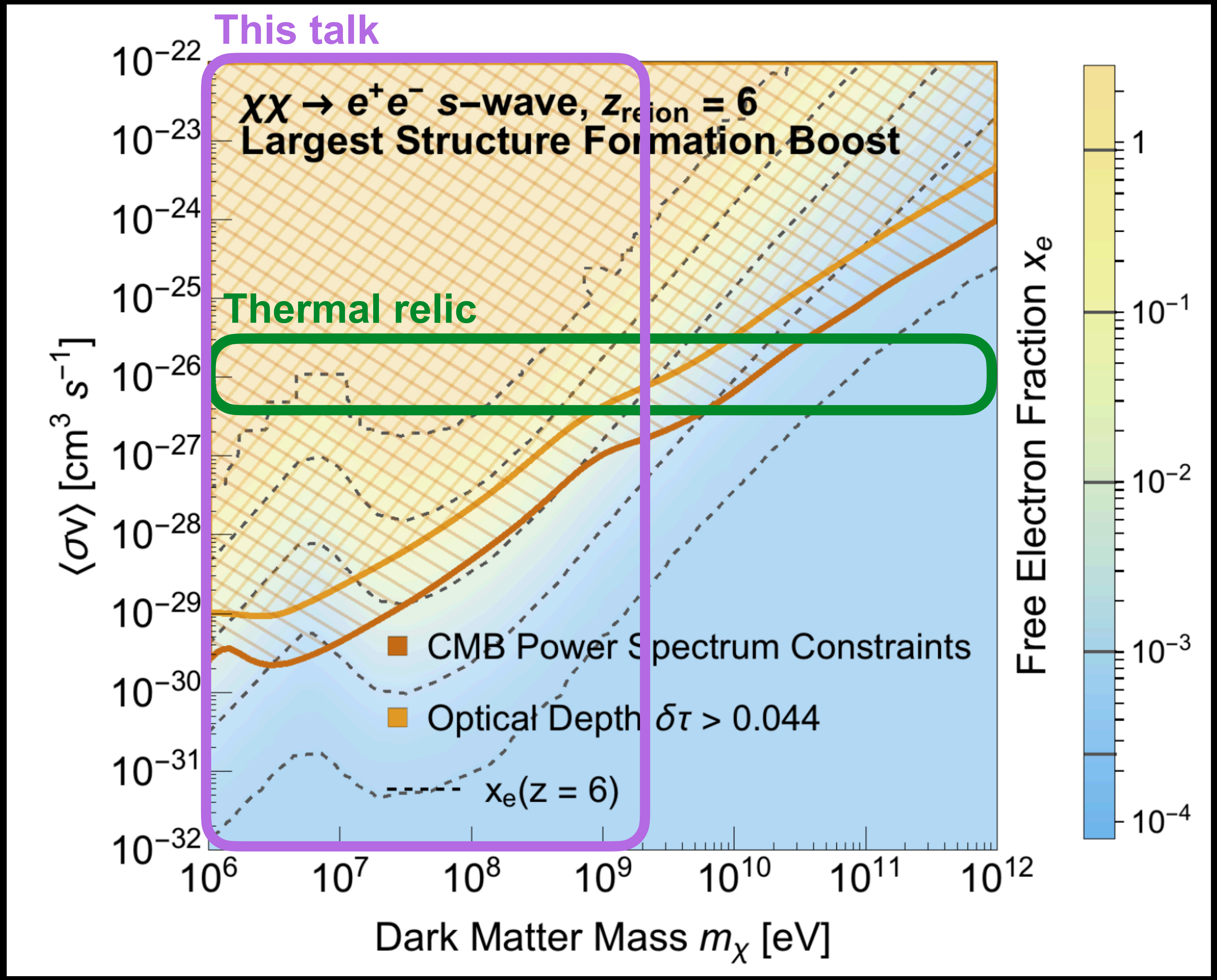


Light Dark Matter

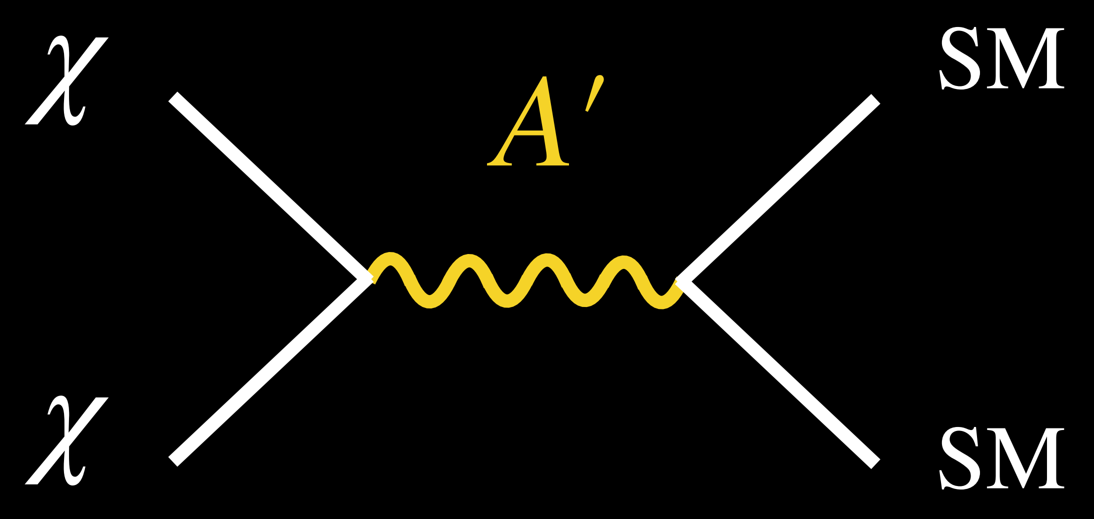
Freeze-out and CMB limits

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.



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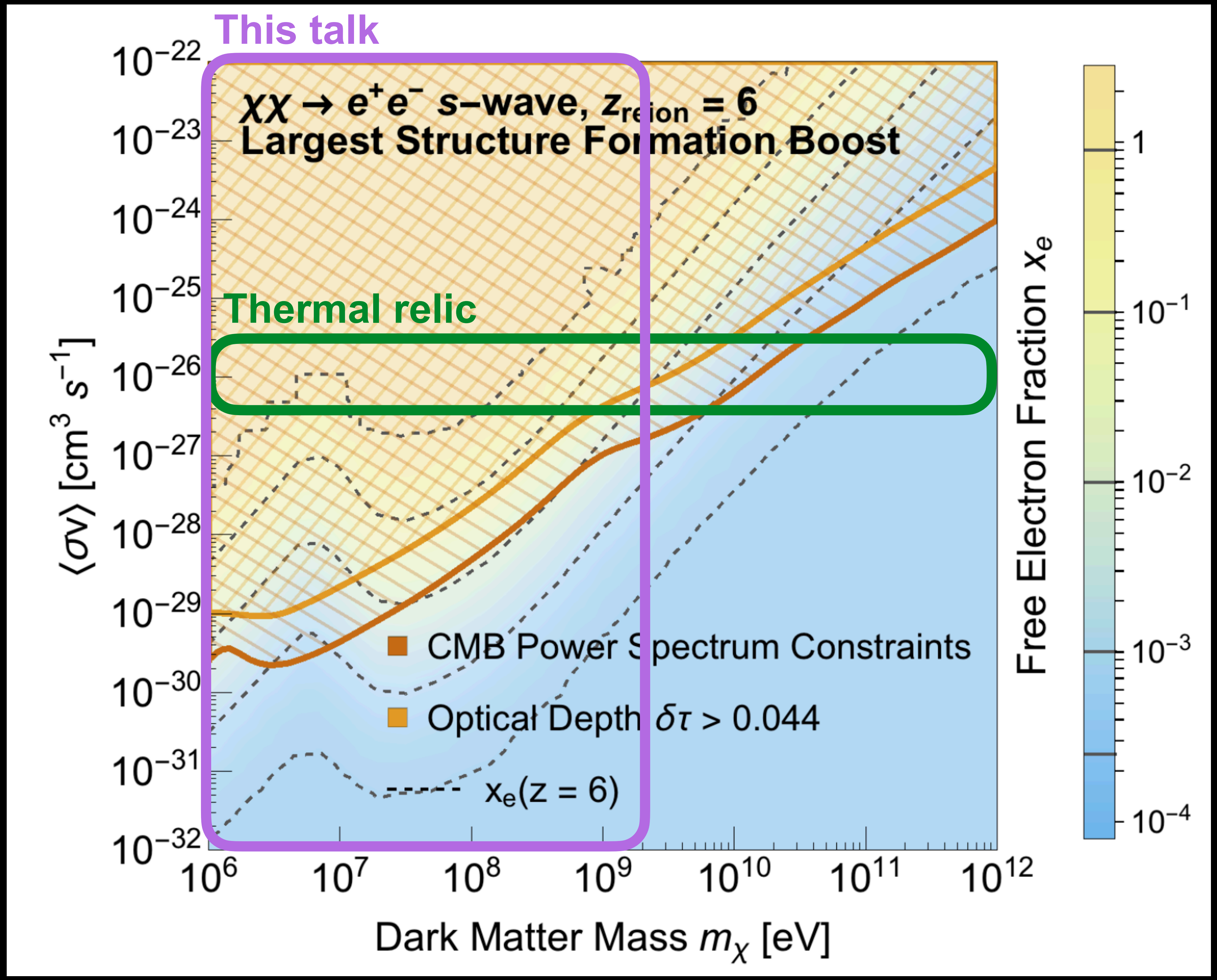


Solution 1) no charged states are produced,

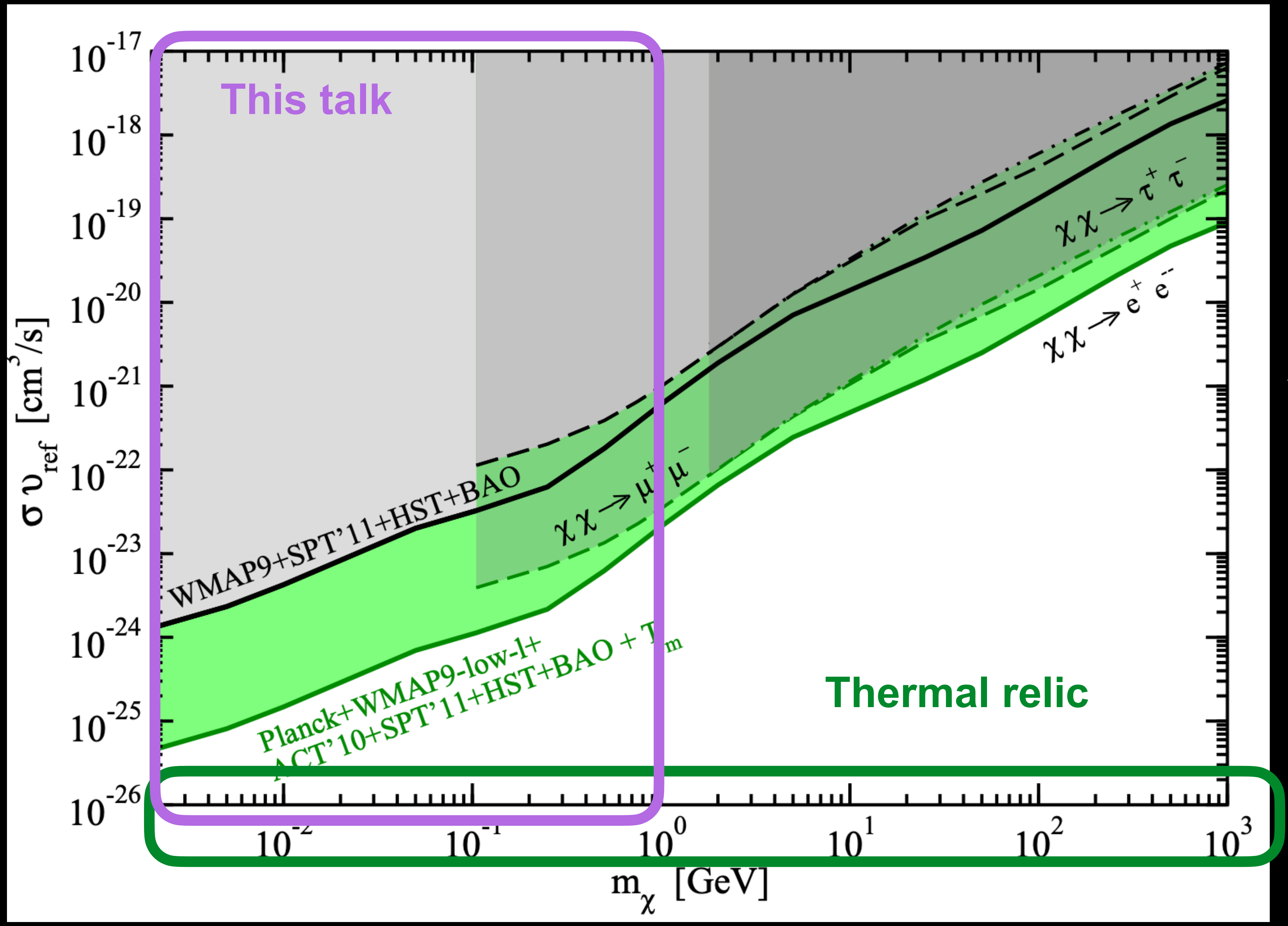
- "Neutrinophilic" dark matter
- Annihilations to dark states (secluded)

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,

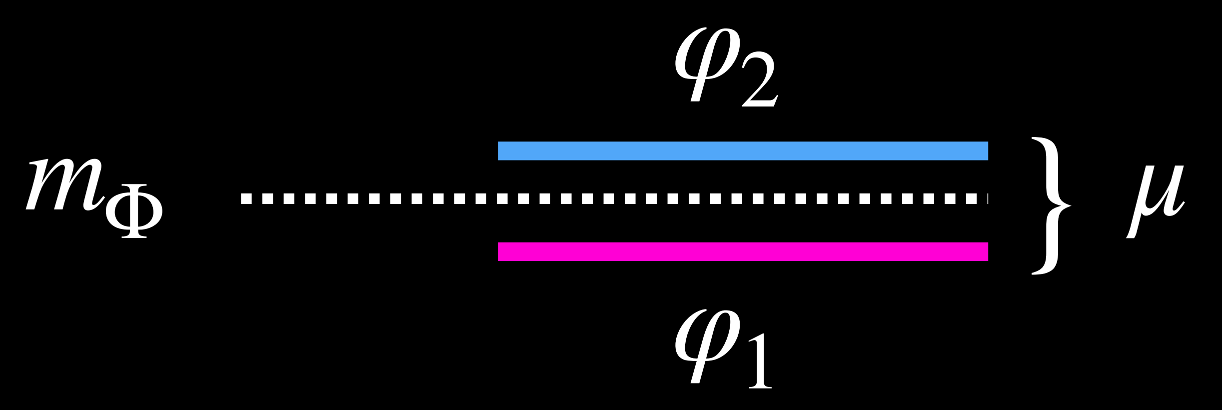
- p-wave annihilation, $\langle \sigma v \rangle \sim bv^2$
- Resonantly-enhanced annihilations
- Asymmetric dark matter
- Forbidden annihilation
- **Co-annihilation ("inelastic" Dark Matter)**

DM can only annihilate with heavier partner which eventually decays away ($\psi_2 \to \psi_1 + \ldots$)

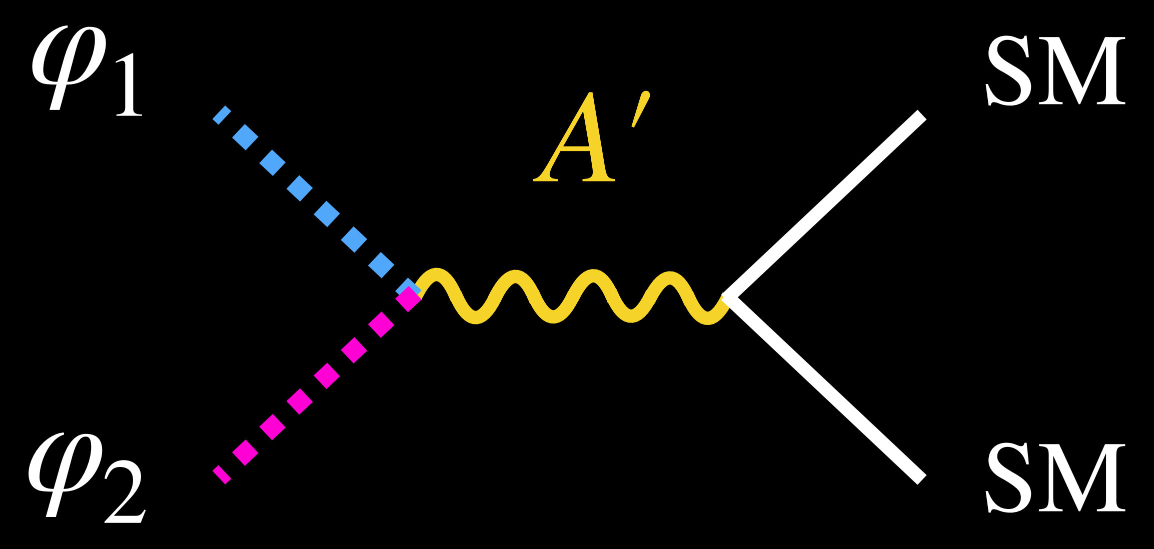
Light Dark Matter

Complex scalar

$U(1)_X$ charged complex scalar $\Phi \sim \varphi_1 + i\varphi_2$ with an induced small mass splitting. The term $\mu\Phi^2$ splits pair by breaking $U(1)_X$ by 2 units.



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



$$J_X^\mu = i(\Phi^* \partial^\mu \Phi - \Phi \partial^\mu \Phi^*) = (\varphi_2 \partial^\mu \varphi_1 - \varphi_1 \partial^\mu \varphi_2)$$

CP conservation ensures that no diagonal coupling appear.

Light Dark Matter

(Pseudo)Dirac Fermion

iDM

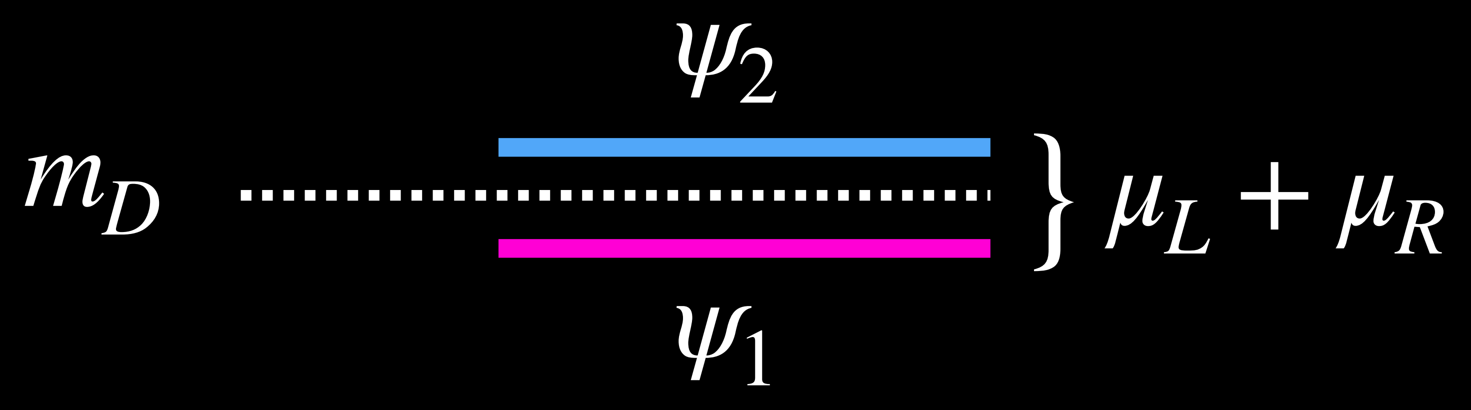
χ_L χ_R

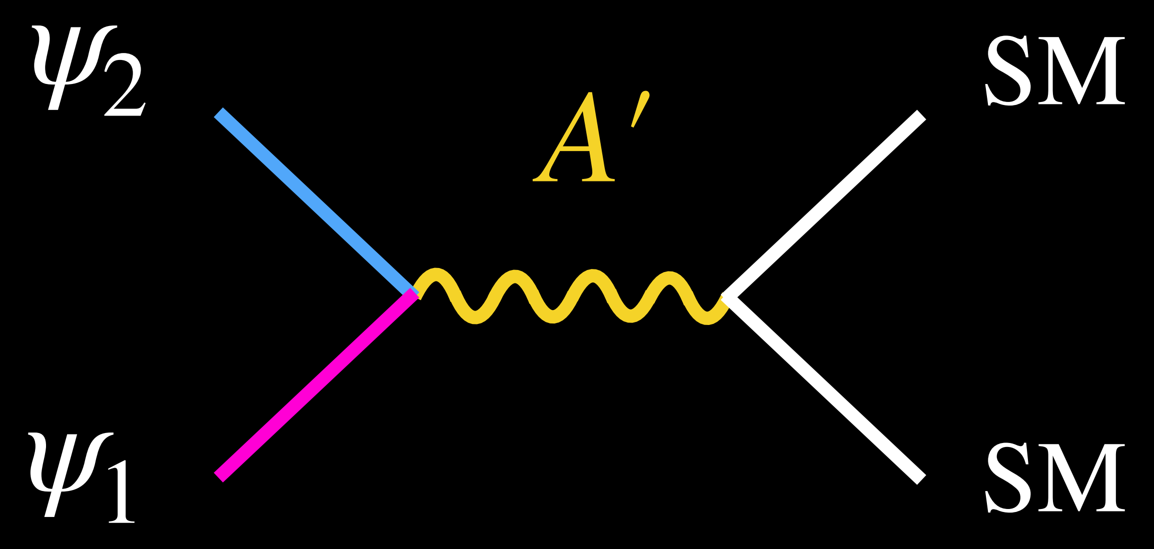
$U(1)_X$ charged fermion $\Psi = \psi_L + \psi_R$. In addition to the Dirac mass the dark fermion can be split by Majorana masses, again breaking the $U(1)_X$ by 2 units.

$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2}\begin{pmatrix}\overline{\chi_L} & \overline{\chi_R^c}\end{pmatrix}\begin{pmatrix}\mu_L & m_D \\ m_D & \mu_R\end{pmatrix}\begin{pmatrix}\chi_L^c \\ \chi_R\end{pmatrix}$$

$$J_X^\mu = \bar{\chi}\gamma^\mu\chi$$

If $\mu_L = \mu_R = 0$, χ is a Dirac particle, else, if $\mu \neq 0$, χ splits into two Majorana states, ψ_1 and ψ_2 with a mass splitting $\mu_L + \mu_R$.





Quasi-preserved C symmetry (exact if $\mu_L = \mu_R$) forbids off-diagonal couplings, even for large $\mu_L + \mu_R$

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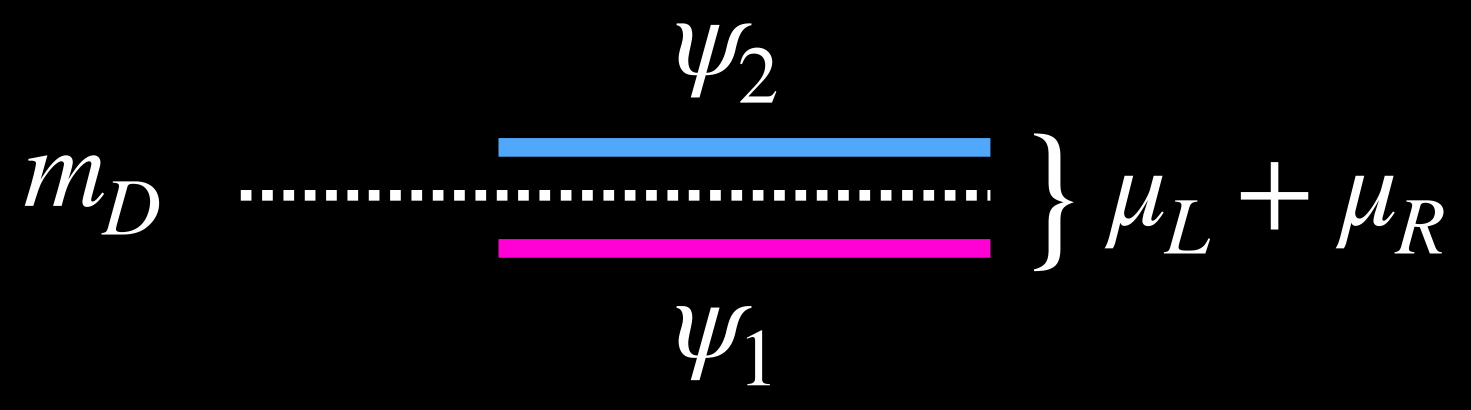
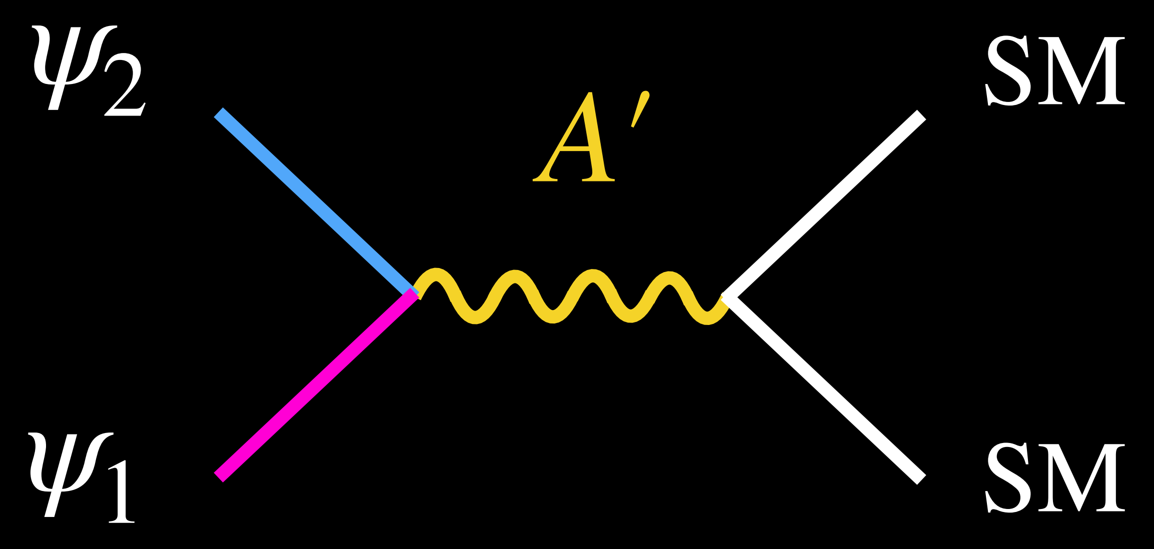
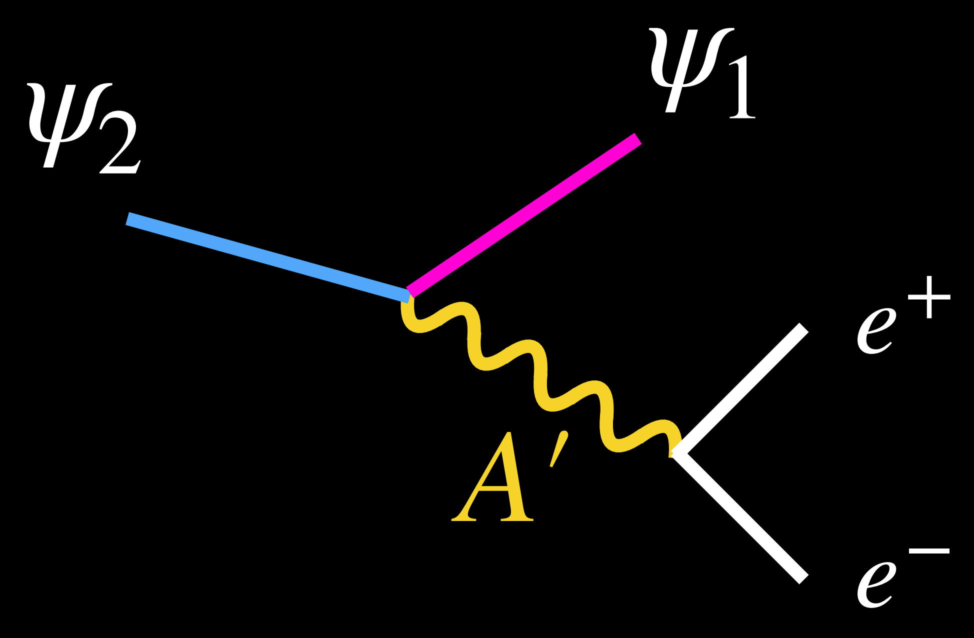


$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2} \begin{pmatrix} \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} \mu_L & m_D \\ m_D & \mu_R \end{pmatrix} \begin{pmatrix} \chi_L^c \\ \chi_R \end{pmatrix}$$

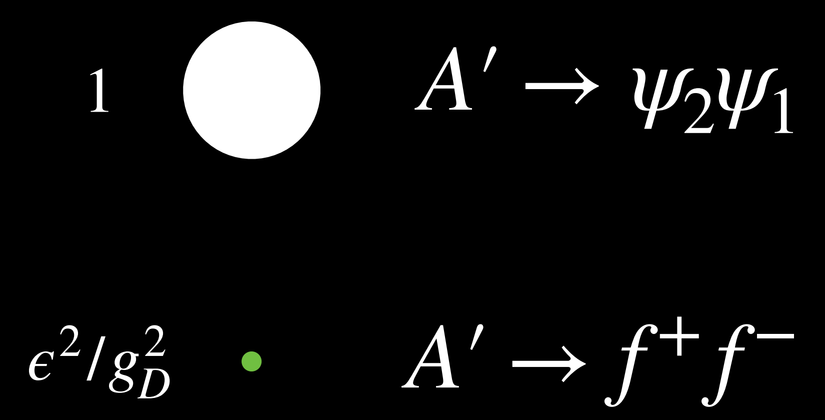


$$J_X^\mu = \bar{\chi}\gamma^\mu\chi = \overline{\psi_2}\gamma^\mu\psi_1$$

If $\mu_L = \mu_R = 0$, χ is a Dirac particle, else, if $\mu \neq 0$, χ splits into two Majorana states, ψ_1 and ψ_2 with a mass splitting $\mu_L + \mu_R$. If $\mu_L = \mu_R$, interaction is off-diagonal.



Dark photon decay branching ratios:



Quasi-preserved C symmetry (exact if $\mu_L = \mu_R$) forbids off-diagonal couplings, even for large $\mu_L + \mu_R$

Light Dark Matter

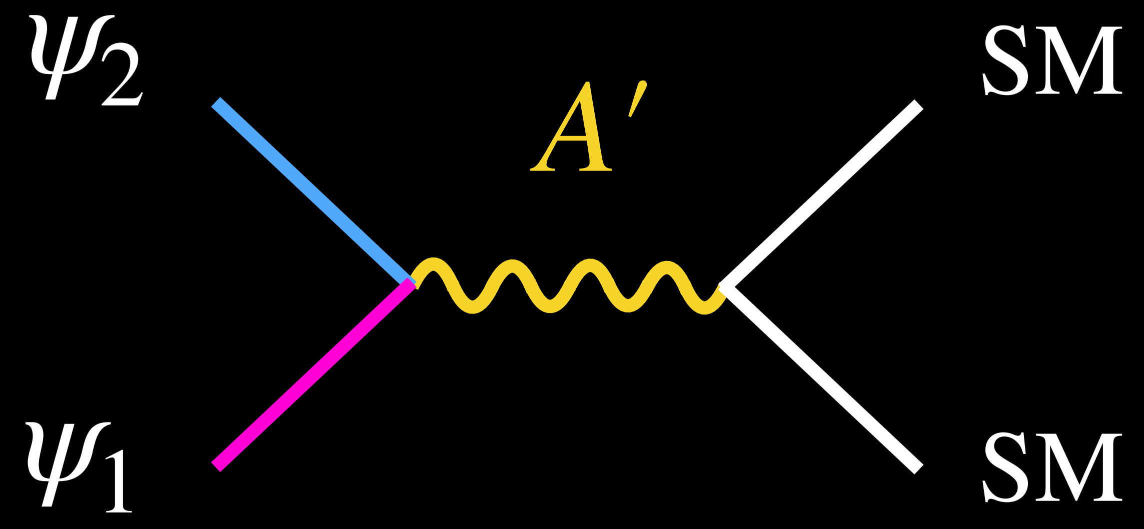
Dark "inverse seesaw"

η_L χ_L χ_R

$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral η_L. Dirac dark particle split by its mixing with Majorana, breaking $U(1)_X$ by 1 unit.

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

$$J_X^\mu = \bar{\chi}\gamma^\mu\chi = V_{ij}\overline{\psi}_i\gamma^\mu\psi_j$$



Dark photon decay branching ratios:

1 ● $A' \to \psi_3\psi_3,\ \psi_3\psi_2,\ \ldots$

ϵ^2/g_D^2 • $A' \to f^+f^-$

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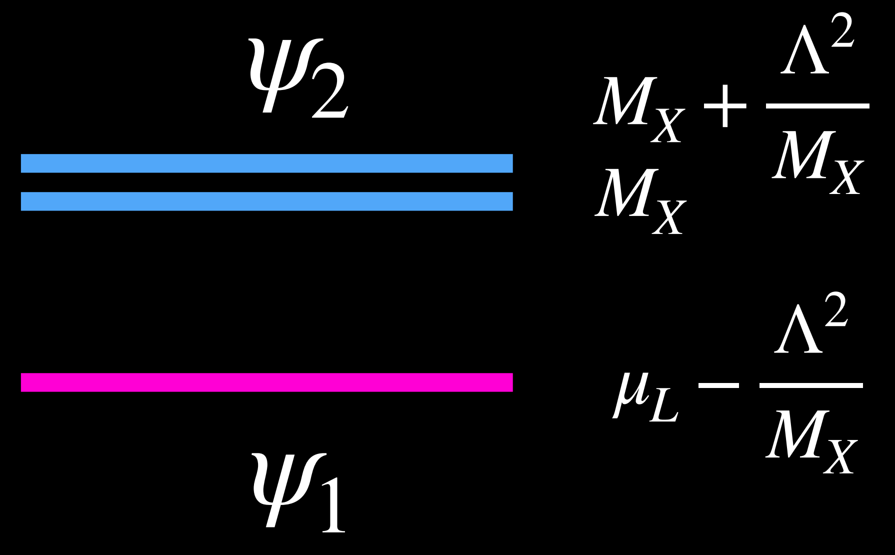
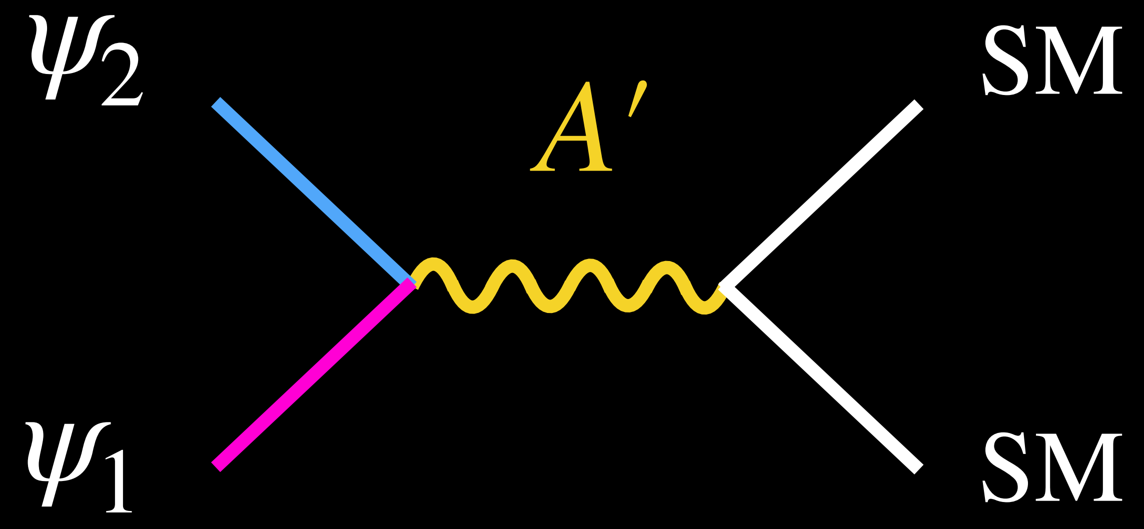
$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral η_L. Dirac dark particle split by its mixing with Majorana, breaking $U(1)_X$ by 1 unit.



$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2}\left(\overline{\eta_L} \;\; \overline{\chi_L} \;\; \overline{\chi_R^c}\right)\begin{pmatrix} \mu_L & \Lambda & \Lambda \\ \Lambda & 0 & M_X \\ \Lambda & M_X & 0 \end{pmatrix}\begin{pmatrix} \eta_L^c \\ \chi_L^c \\ \chi_R \end{pmatrix}$$

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



Where $\theta \sim m_1/m_2 \ll 1$. We treat the (pseudo)Dirac pair in ψ_2 as a single Dirac particle.

Dark photon decay branching ratios:

- 1 — $A' \to \psi_2\psi_2$
- θ^2 — $A' \to \psi_1\psi_2$
- θ^4 — $A' \to \psi_1\psi_1$
- ϵ^2/g_D^2 — $A' \to f^+f^-$

Light Dark Matter

A dark Dirac fermion seesaw

η_L η_R χ_L χ_R

$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral $\eta = \eta_L + \eta_R$.
No breaking of the $U(1)_X$.

$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2} \begin{pmatrix} \overline{\eta_L} & \overline{\eta_R^c} & \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} 0 & M_1 & 0 & M_L \\ M_1 & 0 & M_R & 0 \\ 0 & M_R & 0 & M_2 \\ M_L & 0 & M_2 & 0 \end{pmatrix} \begin{pmatrix} \eta_L^c \\ \eta_R \\ \chi_L^c \\ \chi_R \end{pmatrix}$$

$$J_X^\mu = \bar{\chi}\gamma^\mu \chi$$

Light Dark Matter

A dark Dirac fermion seesaw

i2DM

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

$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral $\eta = \eta_L + \eta_R$.
No breaking of the $U(1)_X$.

$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2} \begin{pmatrix} \overline{\eta_L} & \overline{\chi_L} \end{pmatrix} \begin{pmatrix} M_1 & M \\ M & M_2 \end{pmatrix} \begin{pmatrix} \eta_R \\ \chi_R \end{pmatrix}$$

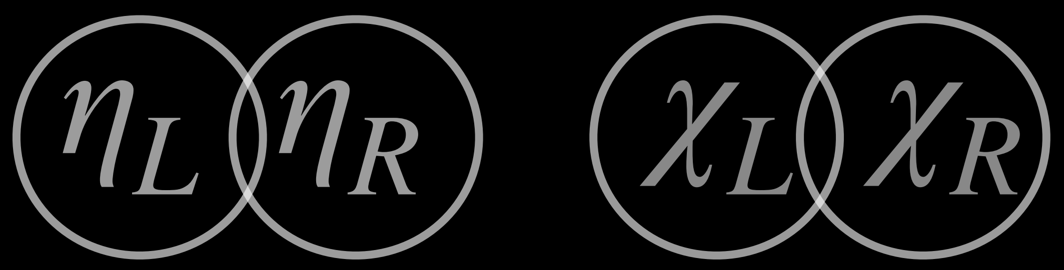
$$J_X^\mu = \bar{\chi} \gamma^\mu \chi$$

A. Filomonova et al, arXiv:2201.08409

Light Dark Matter

A dark Dirac fermion seesaw

i2DM



$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$ and a neutral $\eta = \eta_L + \eta_R$.
No breaking of the $U(1)_X$.

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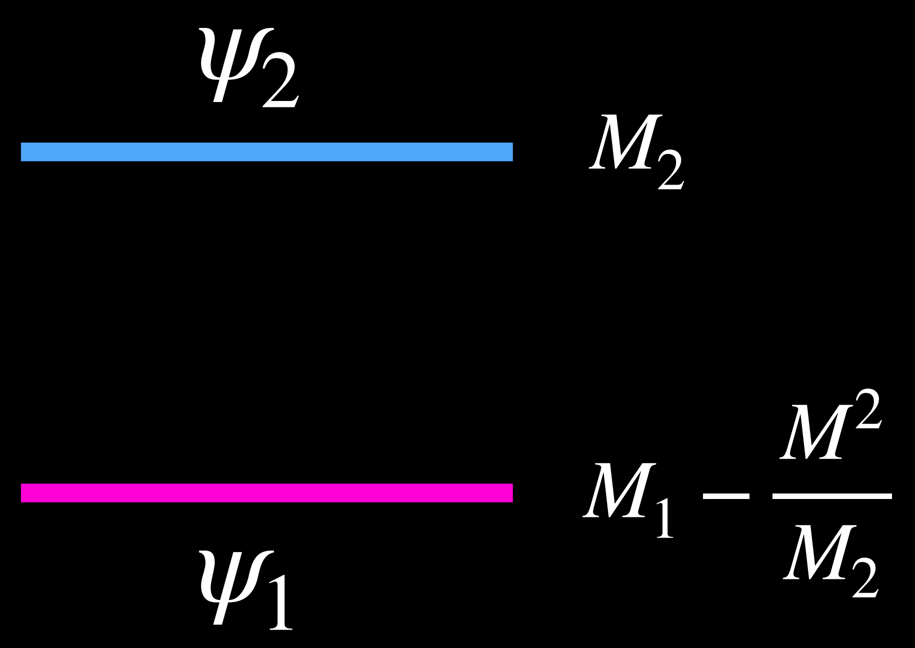
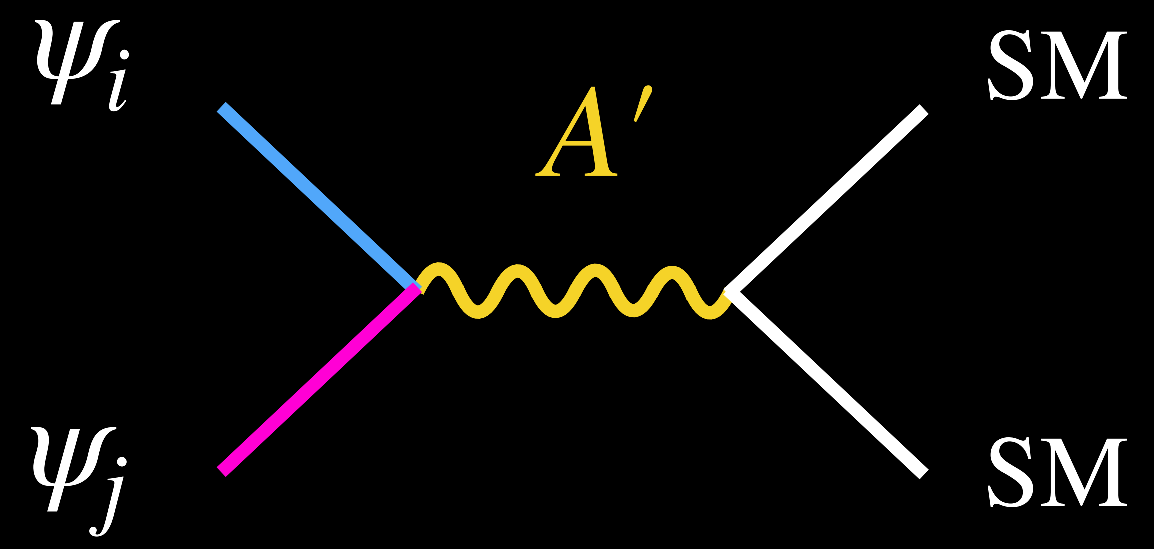


$$J_X^\mu = \bar{\chi}\gamma^\mu\chi = \left(\theta^2\overline{\psi_1}\gamma^\mu\psi_1 + \theta\overline{\psi_2}\gamma^\mu\psi_1 + \overline{\psi_2}\psi_2\right)$$

Where $\theta \sim m_1/m_2$, and no Majorana masses allowed. We have 2 Dirac particles.

Dark photon decay branching ratios:

1	$A' \to \psi_2\psi_2$
θ^2	$A' \to \psi_1\psi_2$
θ^4	$A' \to \psi_1\psi_1$
ϵ^2/g_D^2	$A' \to f^+f^-$



A. Filomonova et al, arXiv:2201.08409

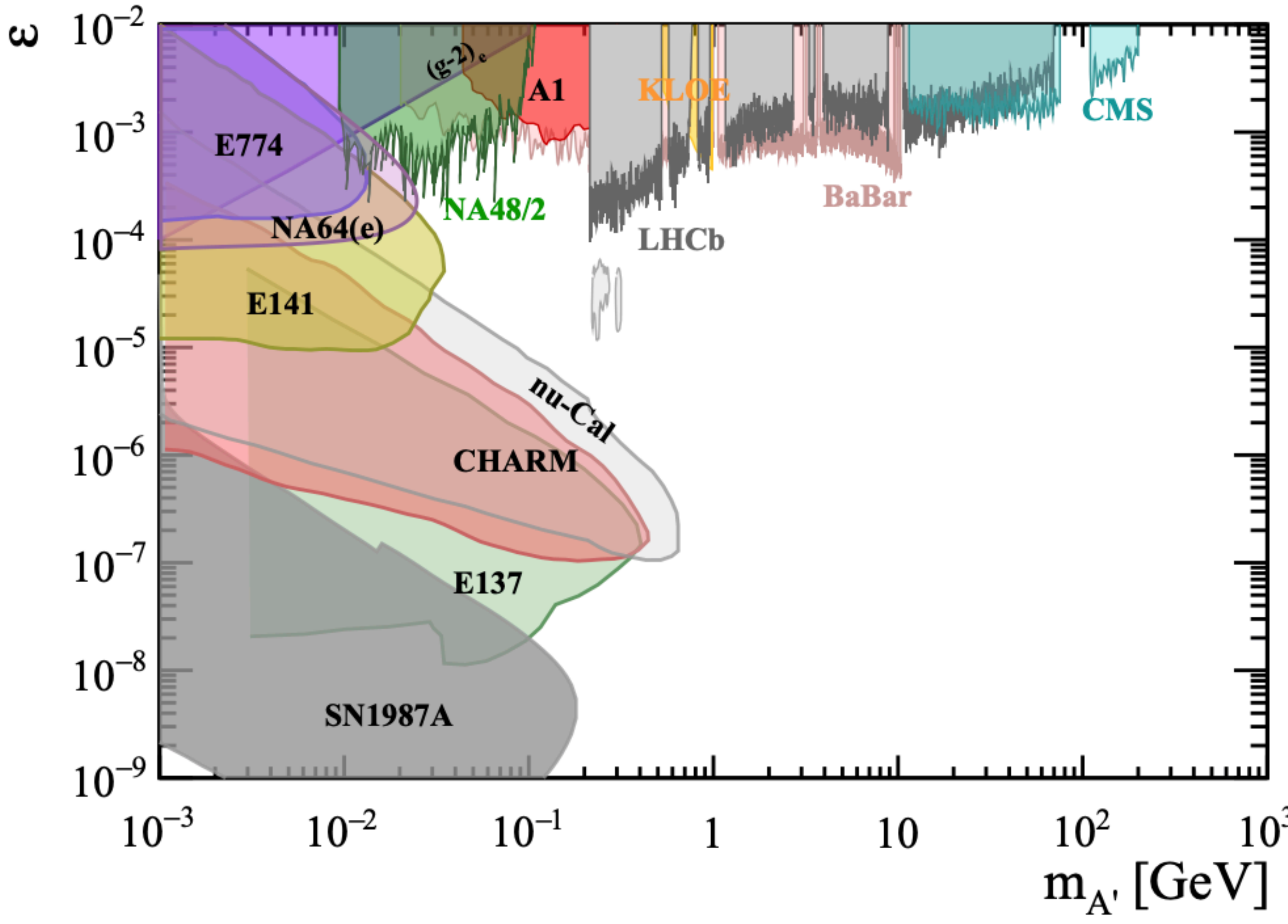
Dark Photons and Heavy Neutral Fermions

Phenomenology

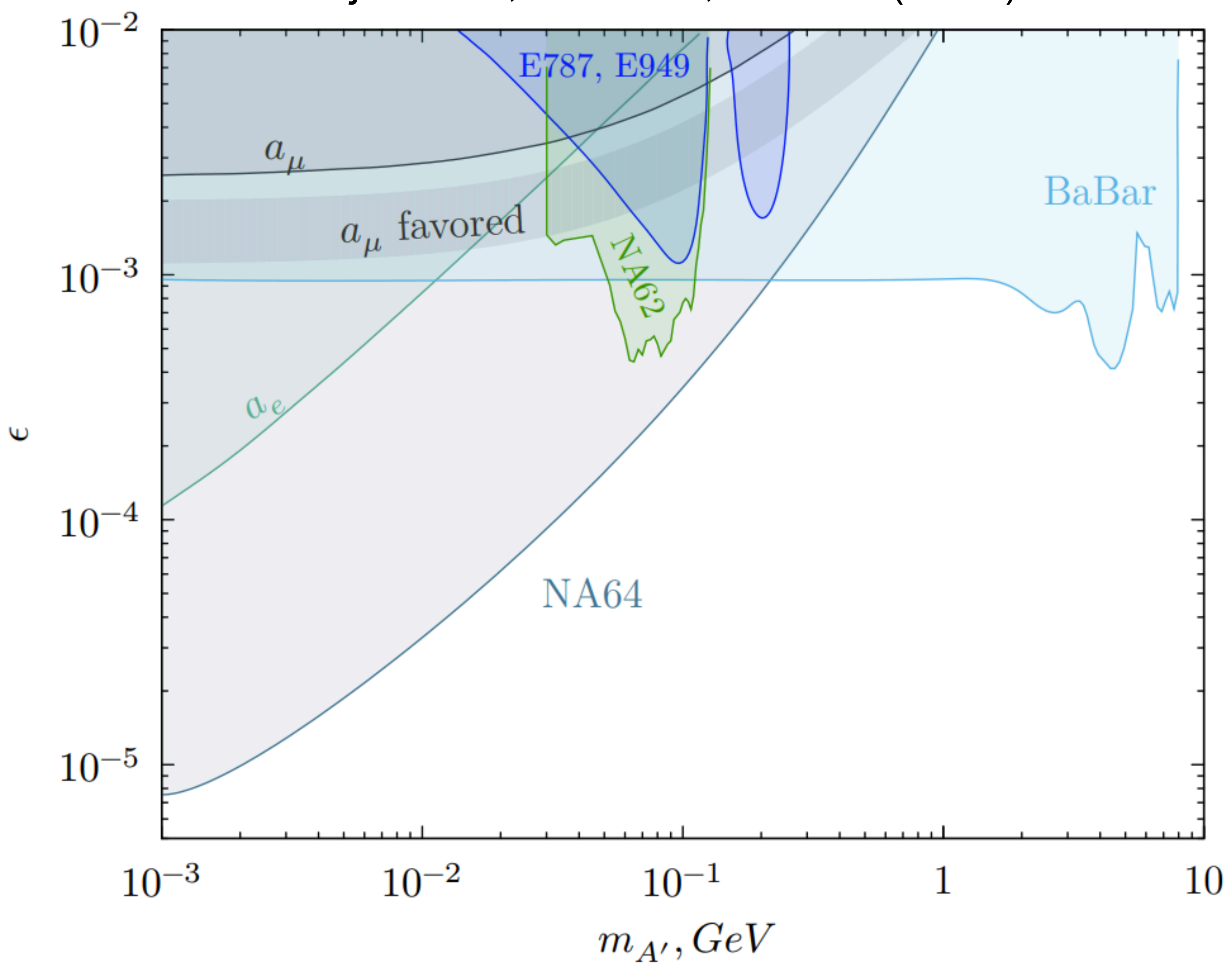
Dark Photons

Visible and Invisible dark photon explanations of $(g-2)_\mu$ are ruled out

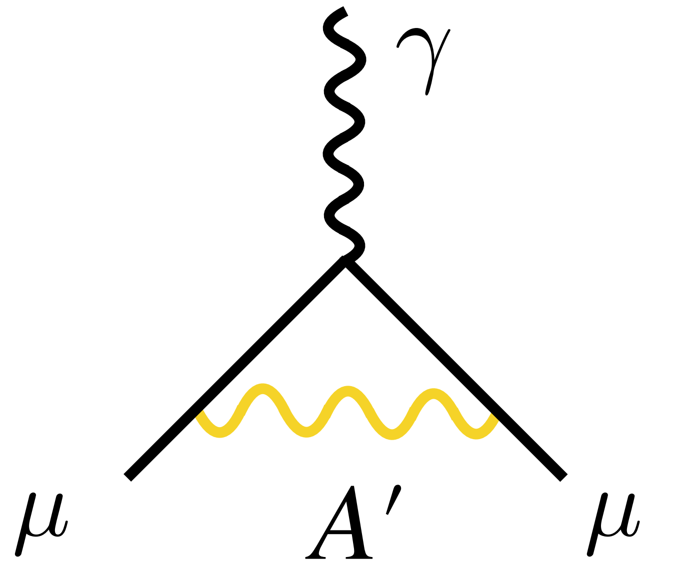
M. Fabbrichesi et al,
SpringerBriefs in Physics 2020, 2005.01515



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



Hypothetical vector bosons contribute positively:



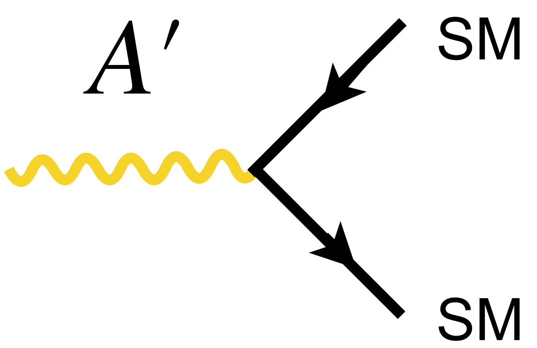
$$\Delta a_\mu^{A'} \sim \frac{\varepsilon^2 \alpha}{3\pi} \frac{m_\mu^2}{m_{A'}}$$

for

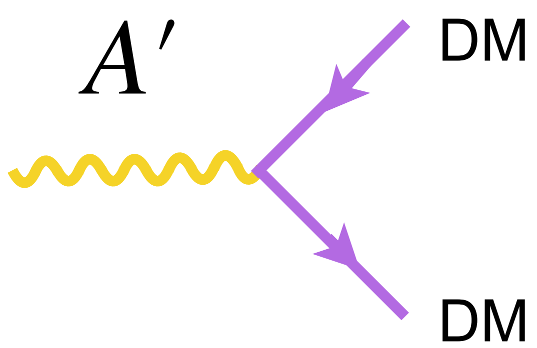
$$m_\mu \ll m_{A'}$$

Pospelov, PRD80:095002,2009

Visible:

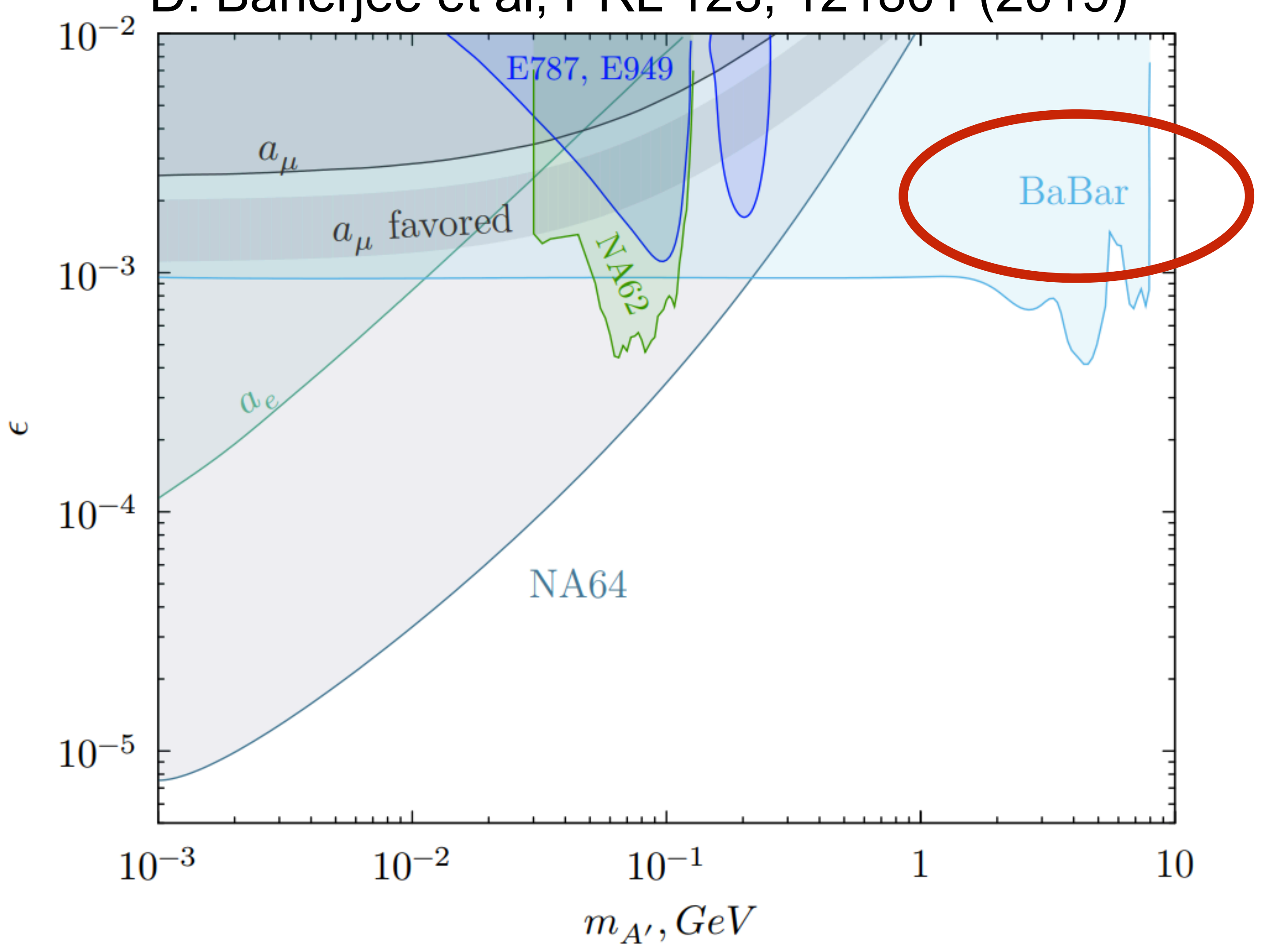


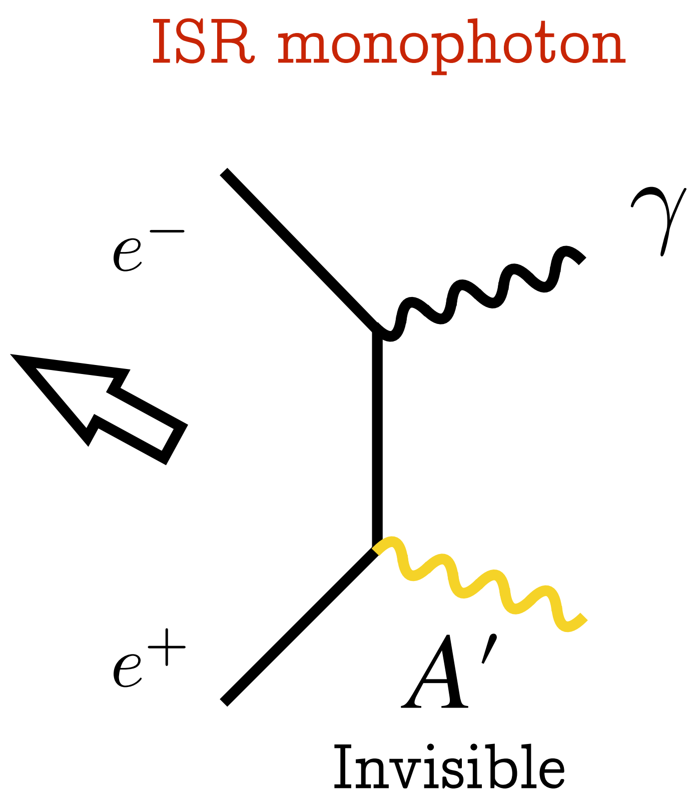
Invisible:

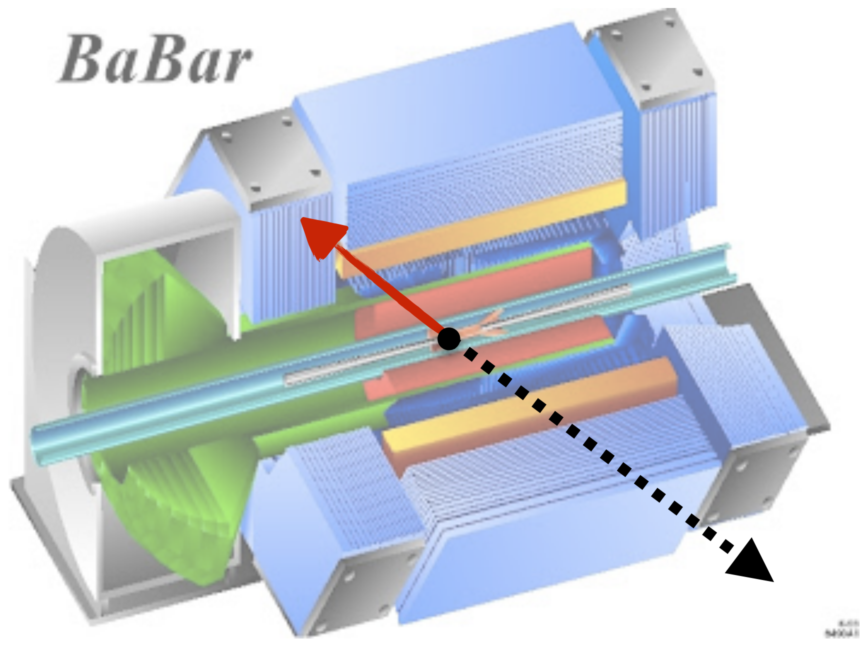


Dark Photons at BaBar

Initial state radiation searches (monophotons)







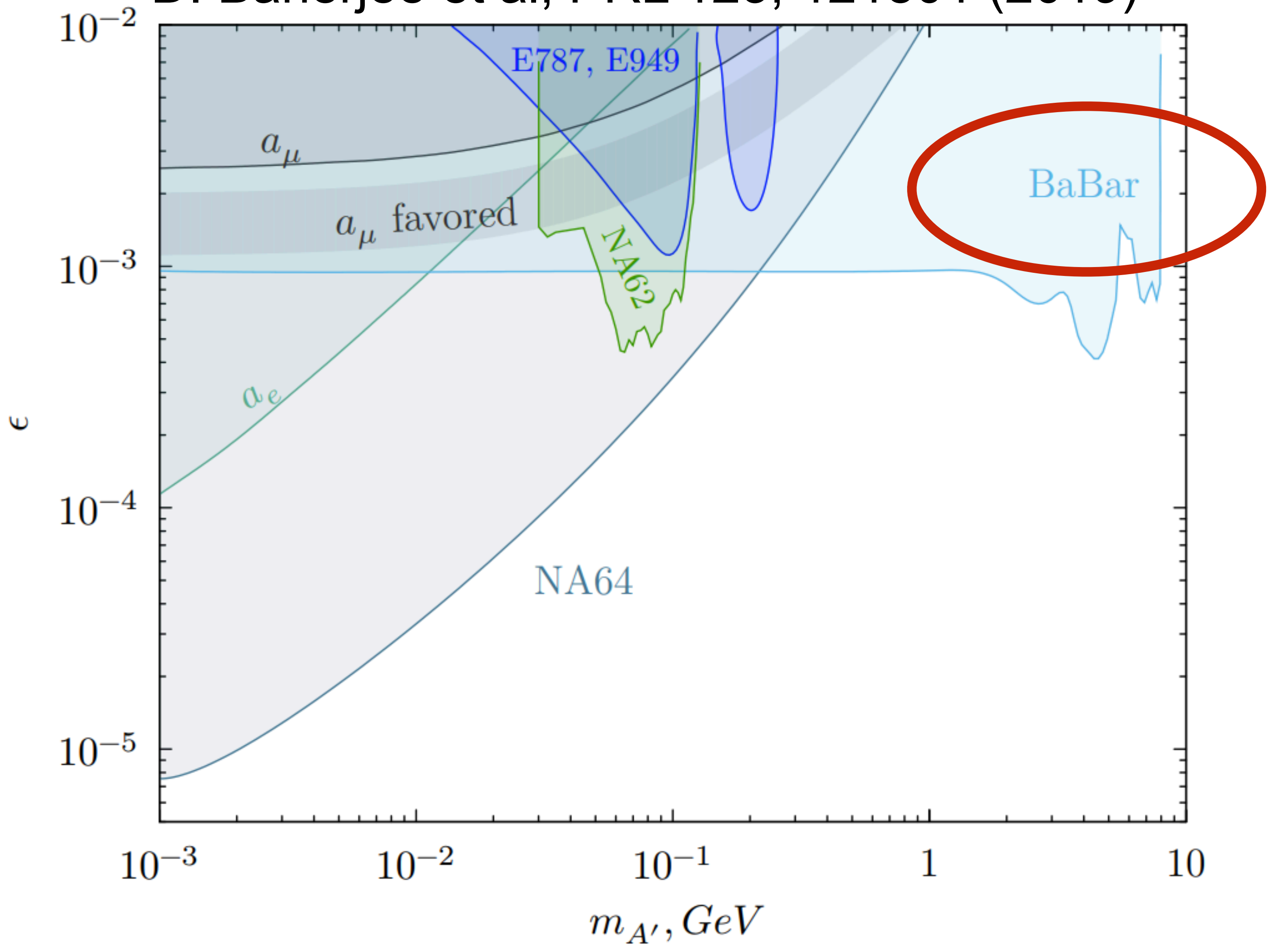
A single photon recoiling against an invisible massive particle. Dark photon mass reconstructed as:

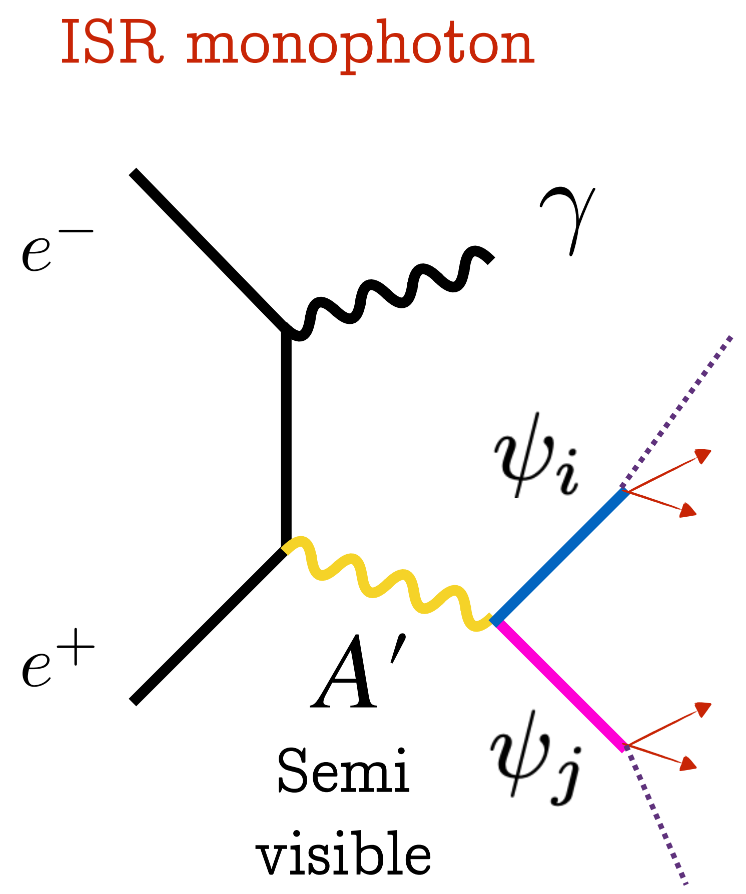
$$M_X^2 = s - 2E_\gamma^{\rm CM}\sqrt{s}$$

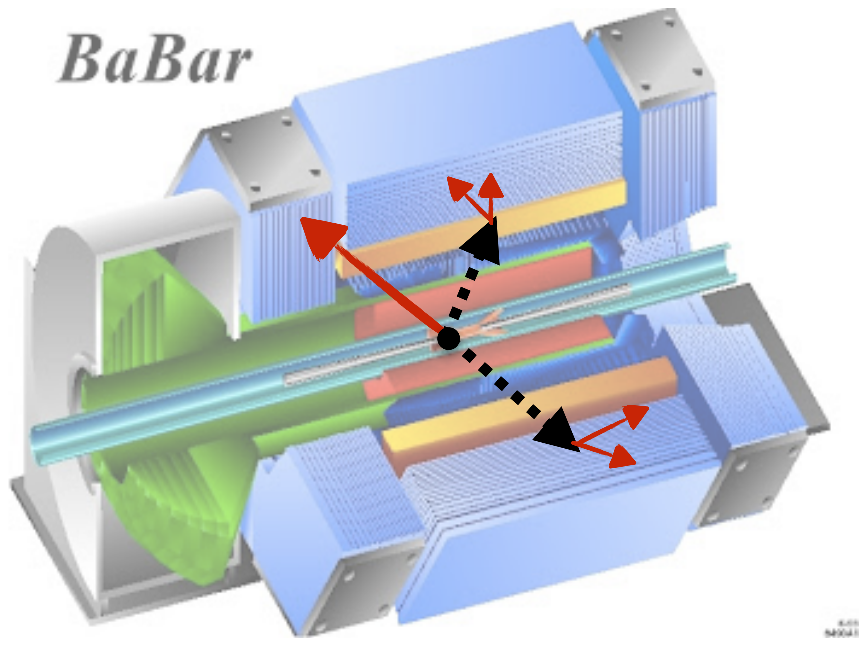
Dark Photons at BaBar

Initial state radiation searches (monophotons)

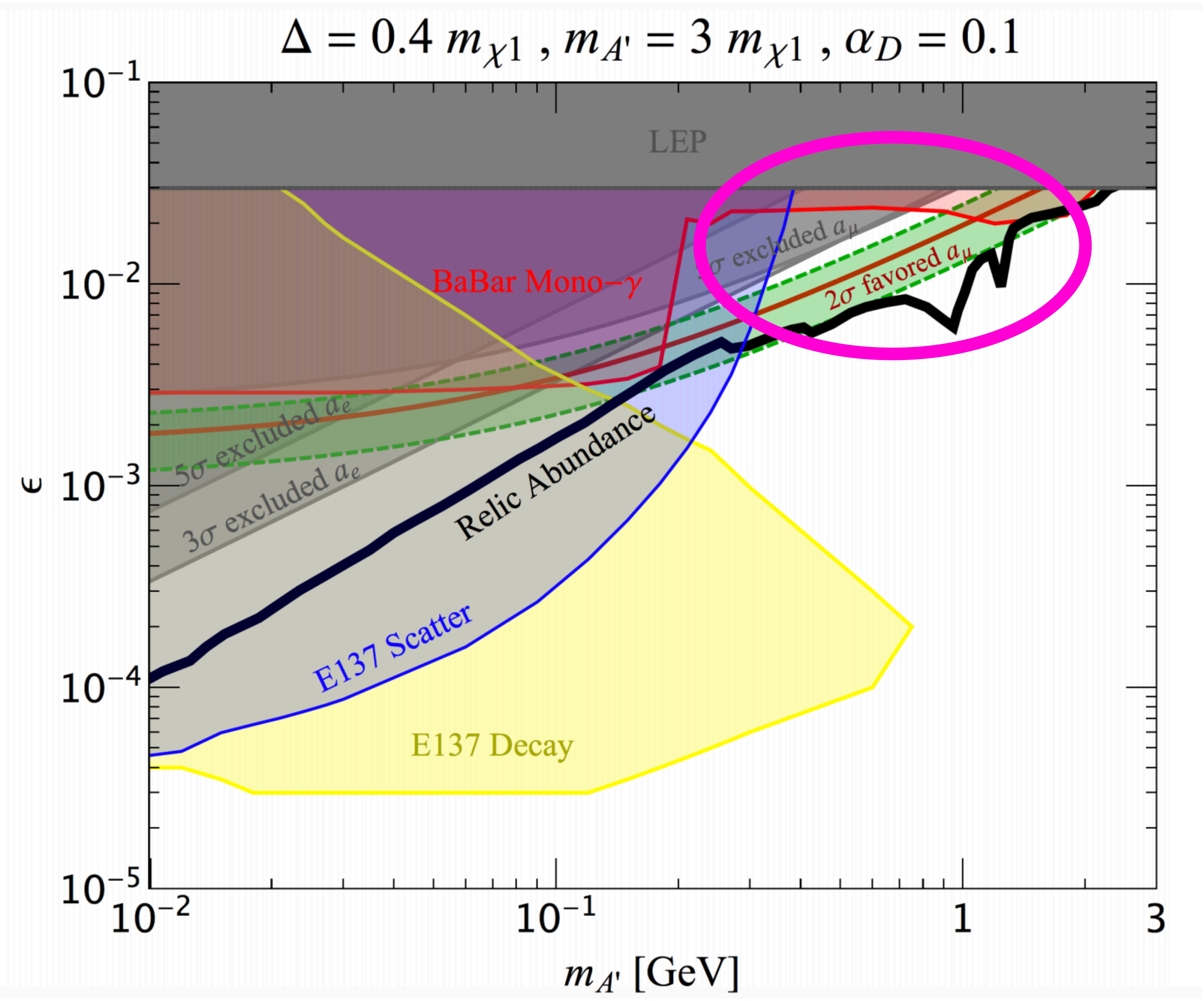
D. Banerjee et al, PRL 123, 121801 (2019)







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



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

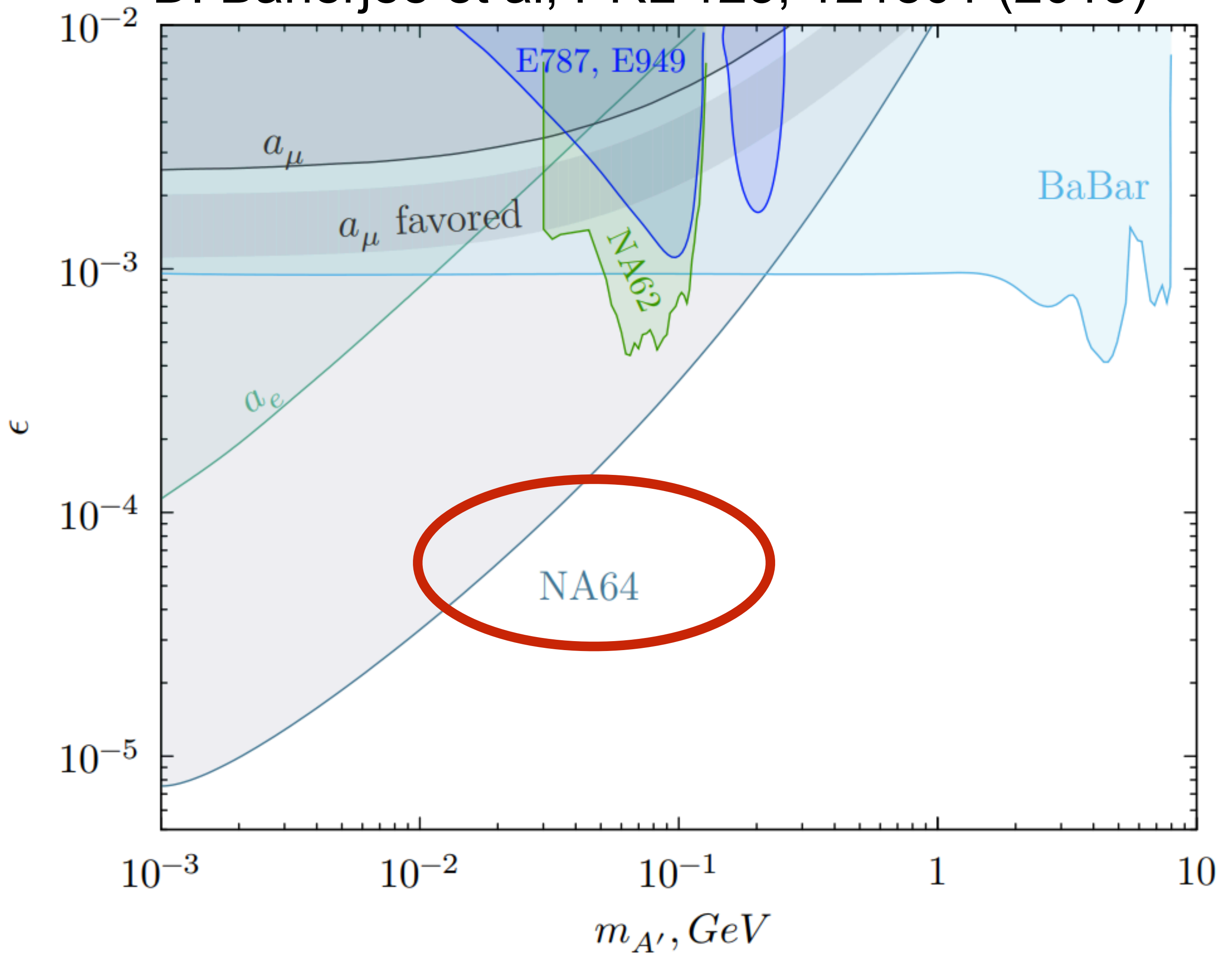
For example, taking $\varepsilon = 2.1 \times 10^{-2}$, $m_{A'} = 1.25\,\text{GeV}$ we need $P_{\text{missing}\,A'} < 2.2 \times 10^{-3}$

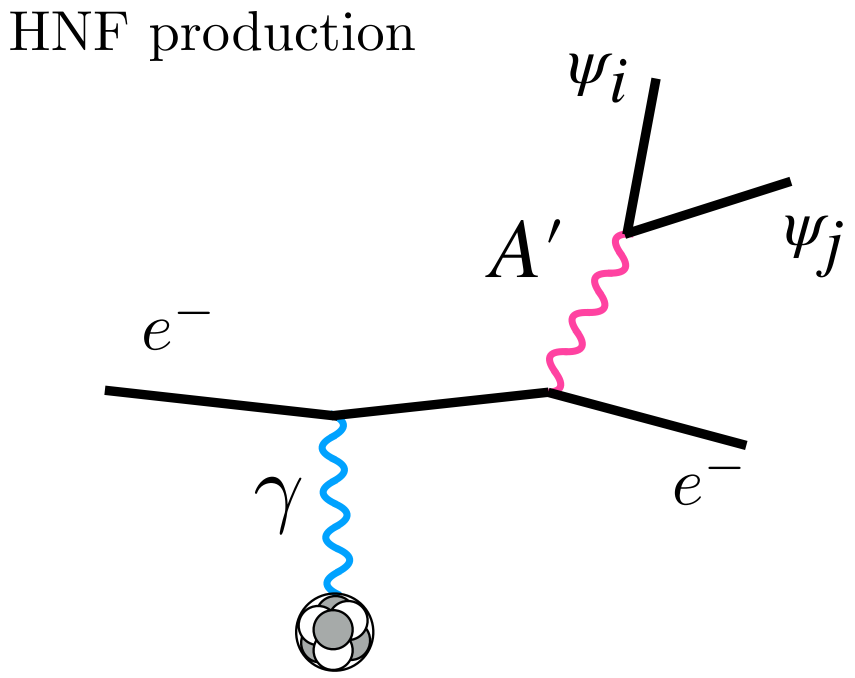
New $(g-2)_\mu$ region of interest around dark photon masses of 0.3 to 3 GeV.

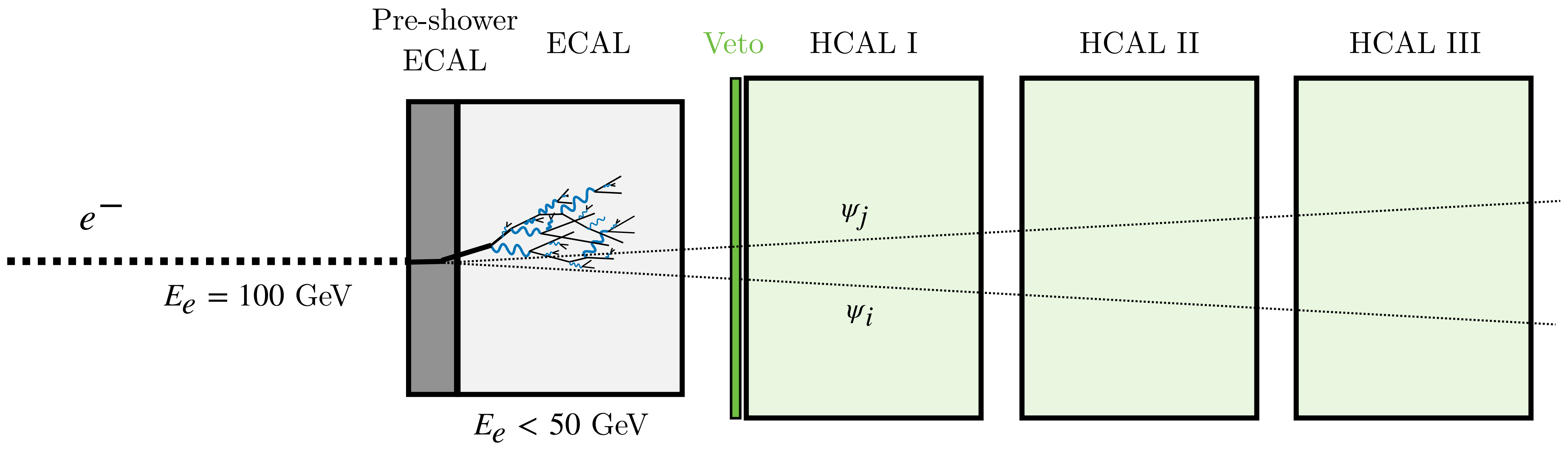
Searches for invisible dark photons at NA64

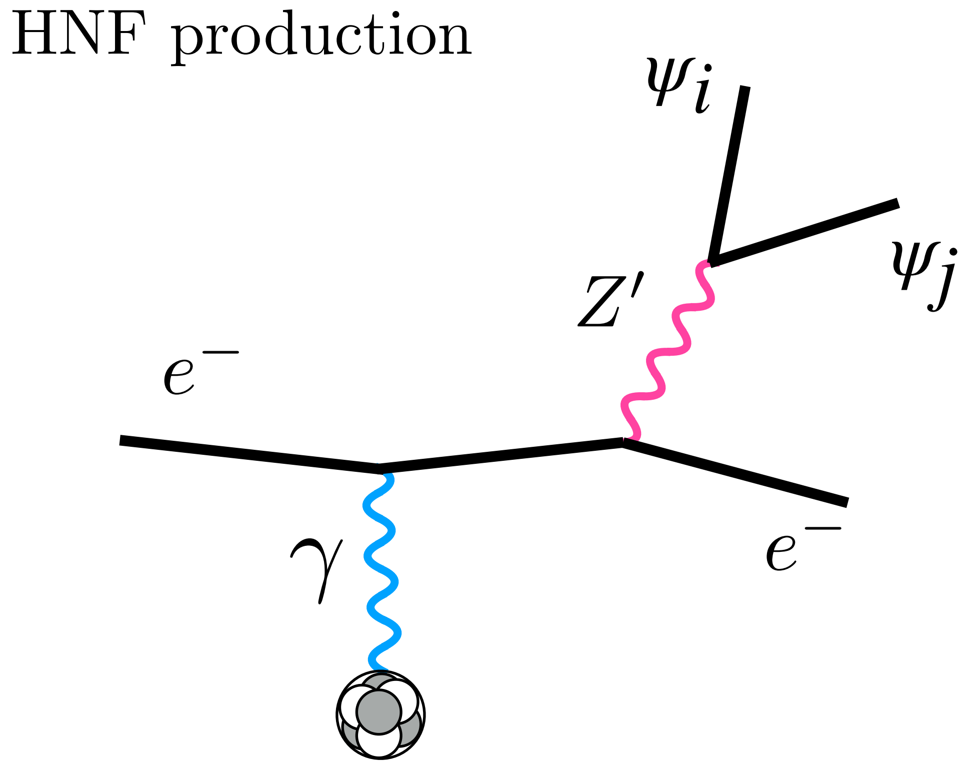
Electrons on target

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







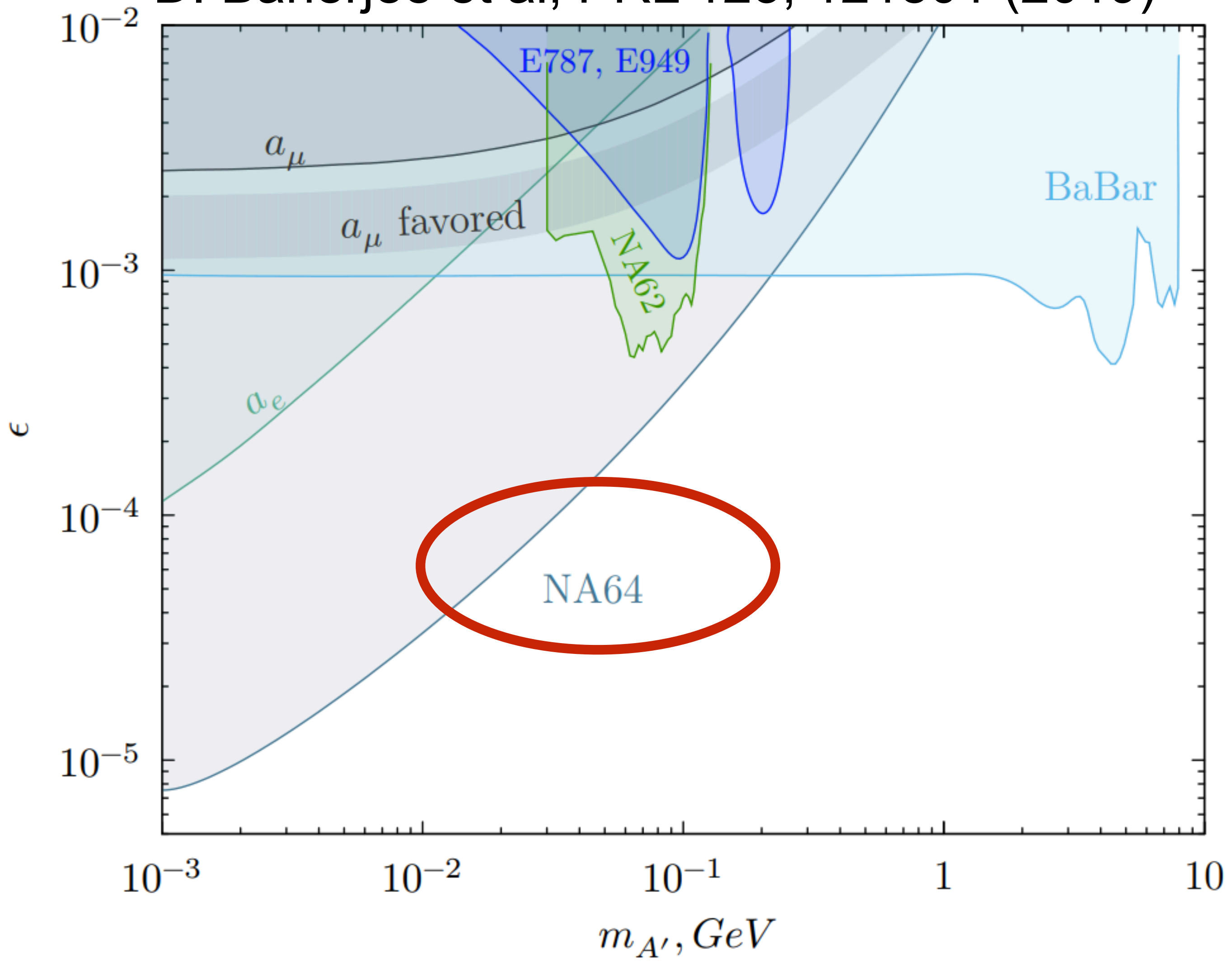


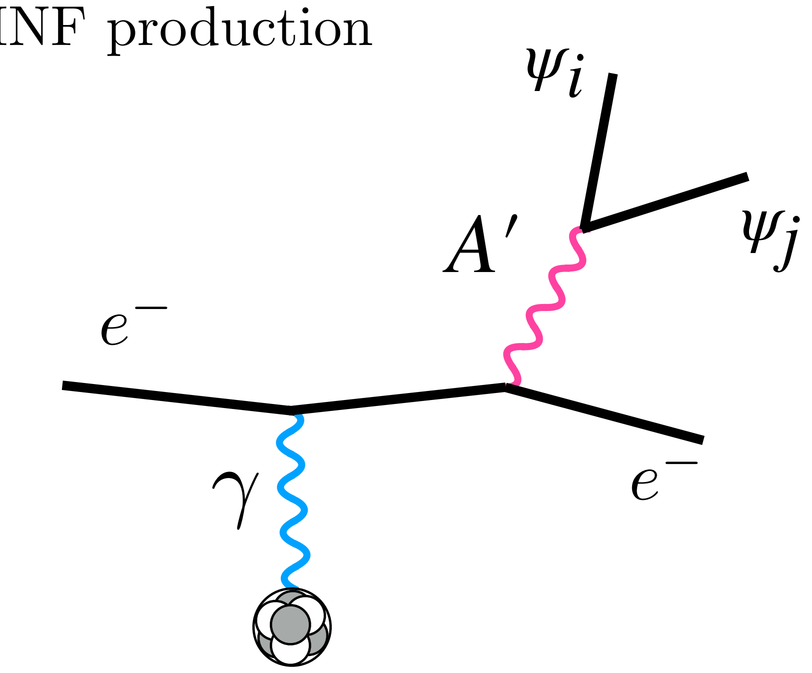
Fixed-target searches for invisible A' also very sensitive.

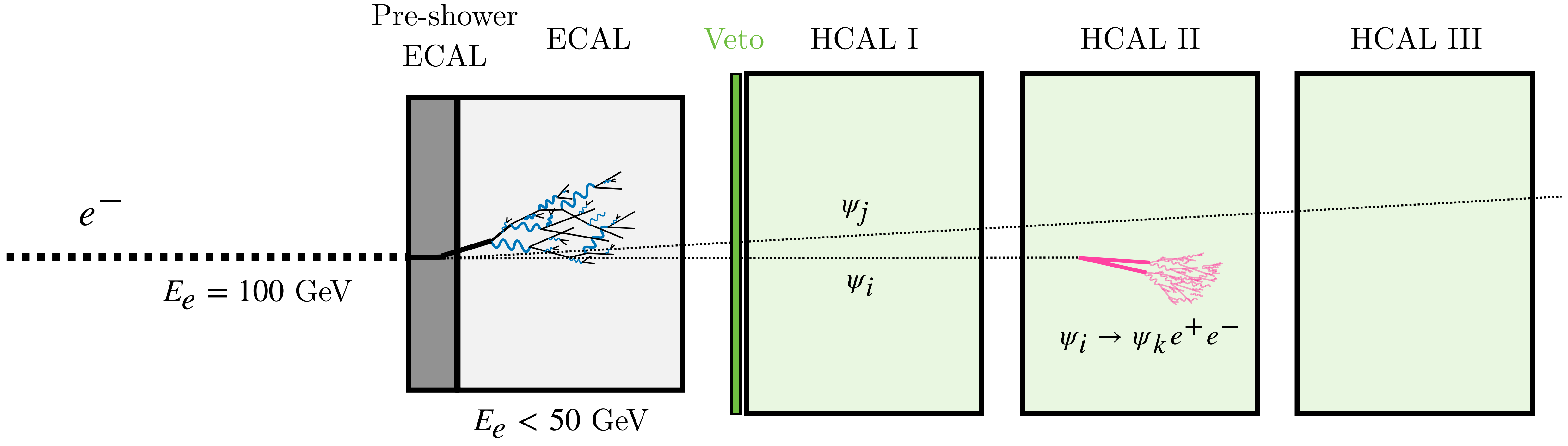
Searches for invisible dark photons at NA64

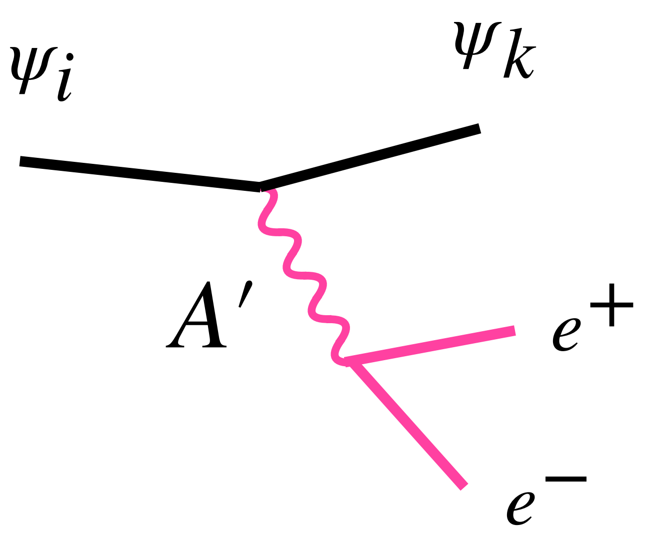
Electrons on target

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

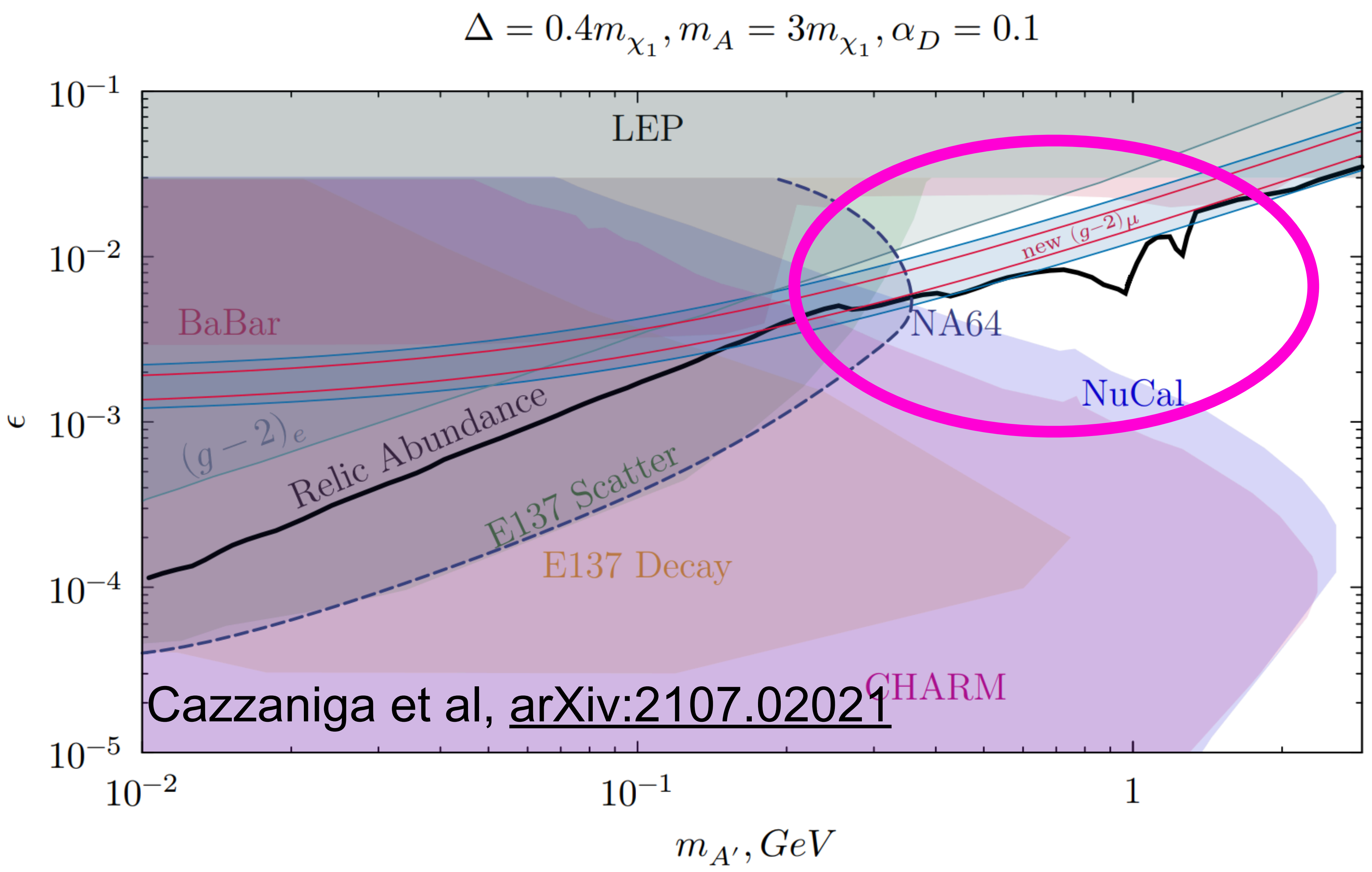








Fixed-target searches for semi-invisible A' with displaced decay. Getting close to the (g-2) region.

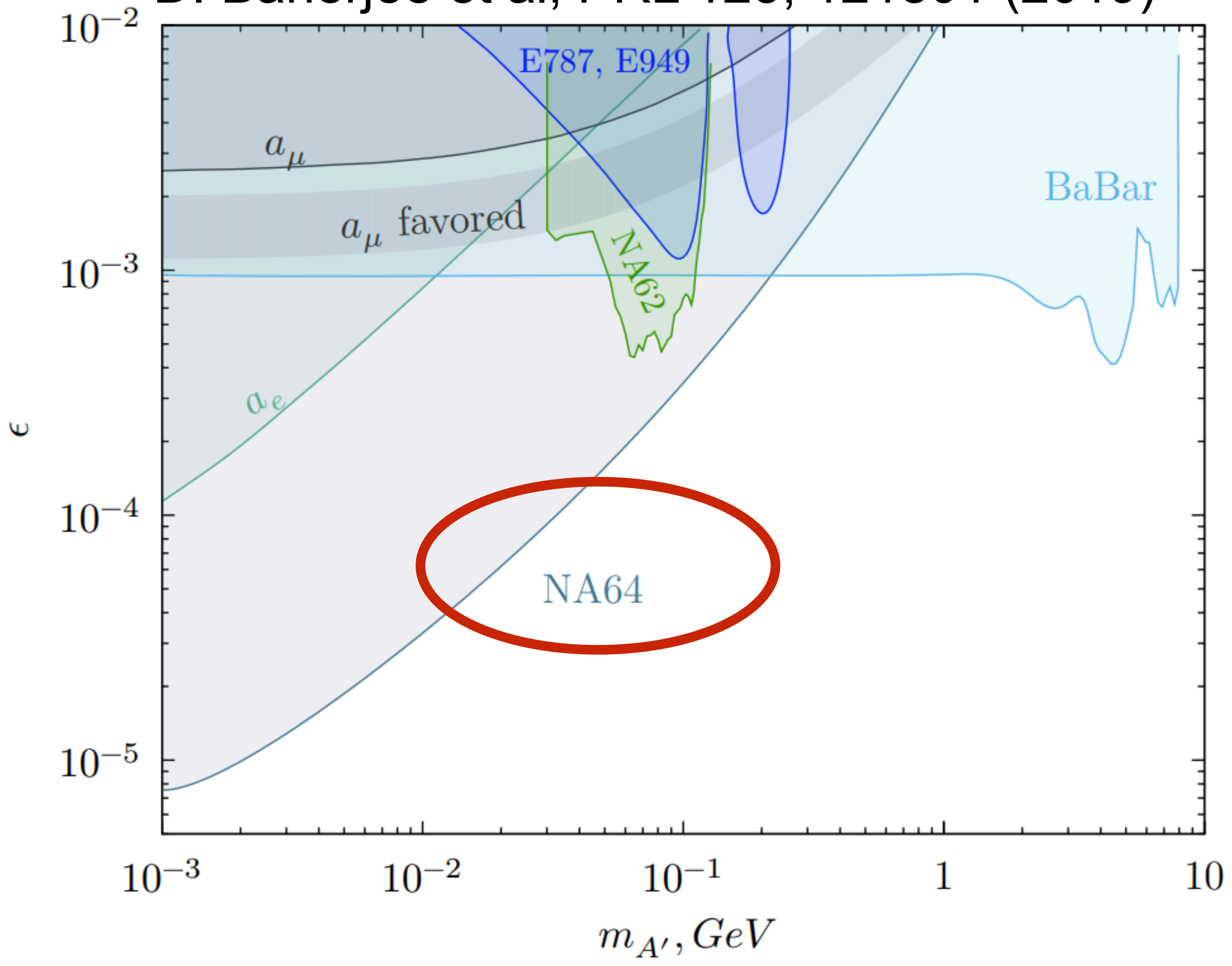


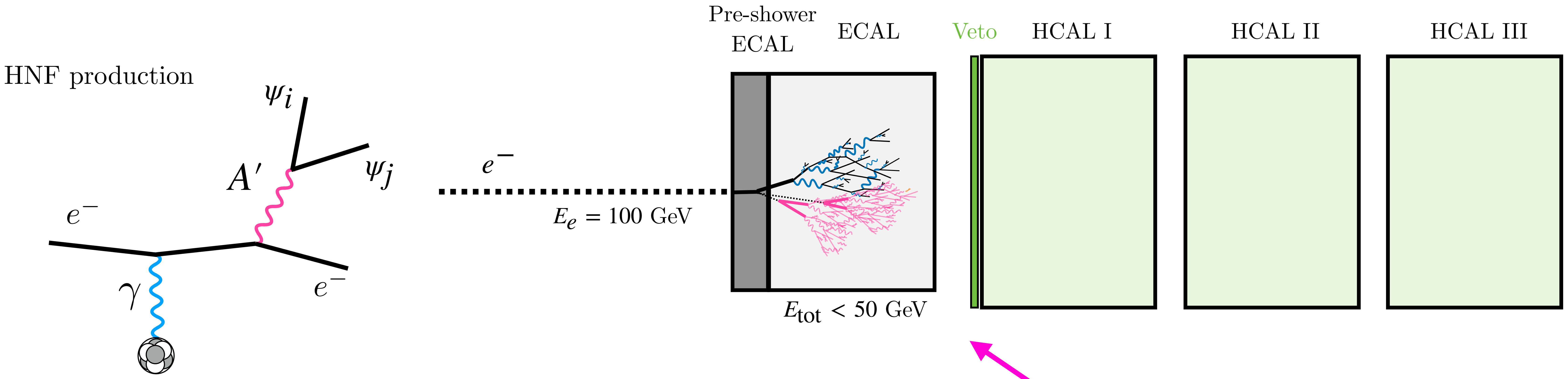
Cazzaniga et al, arXiv:2107.02021

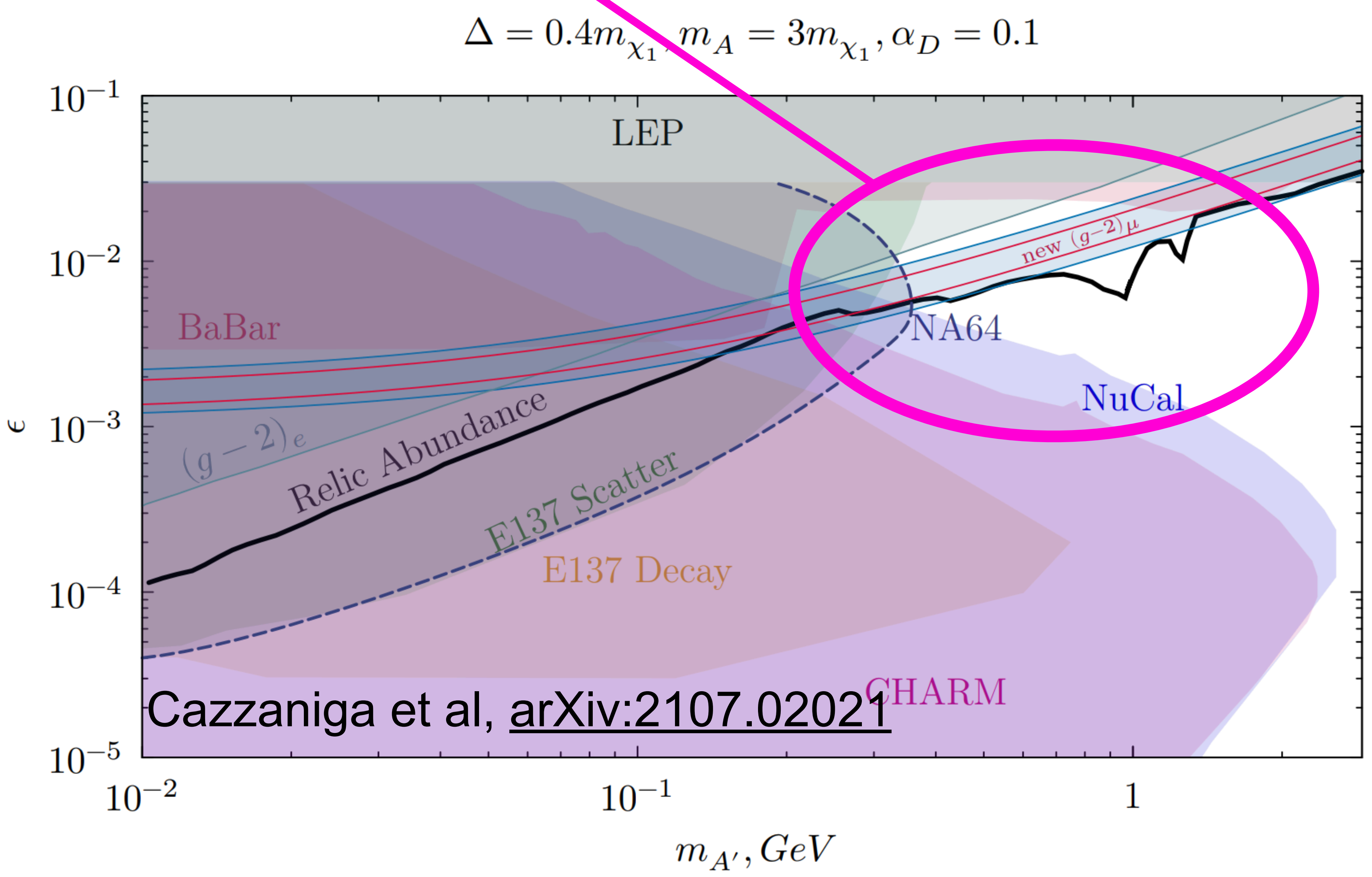
Searches for invisible dark photons at NA64

Electrons on target

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







Cazzaniga et al, arXiv:2107.02021

Currently, the g-2 region is where prompt decays happen.

We estimate the sensitivity of a search where the HNF decay happens inside the detector.

Currently being performed by the collaboration!

Results

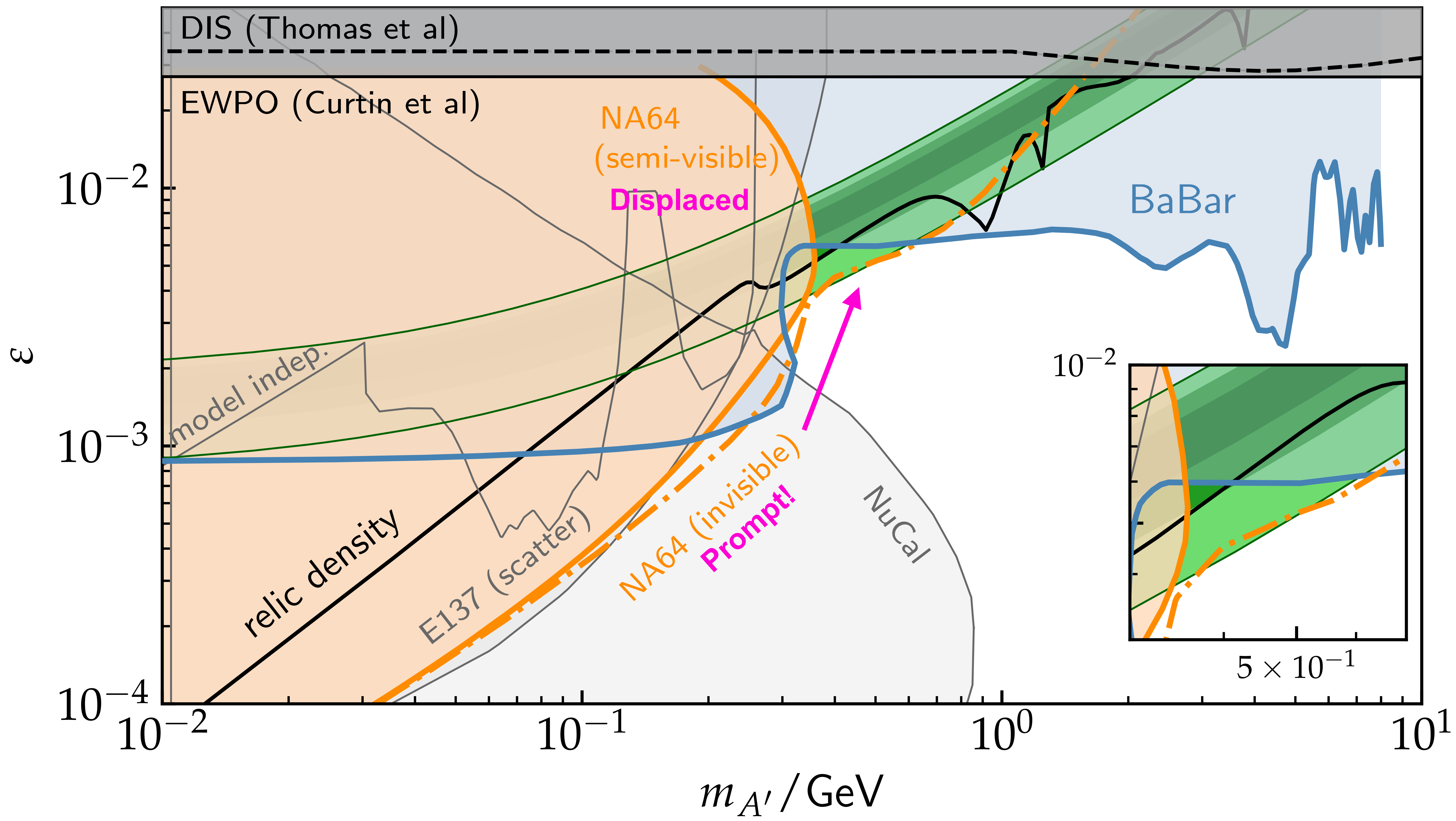
Revisiting BaBar and NA64 limits on A' and HNFs

Results of our BaBar and NA64 simulations

(Pseudo)Dirac Fermion

χ_L χ_R

iDM: $\Delta_{21} = 0.5, \quad m_1/m_{A'} = 0.33, \quad \alpha_D = 0.5$



Very small parameter space that can explain (g-2)$_\mu$

Only a single "semi-visible" decay from the dark photon is can be easily missed at BaBar when soft*.

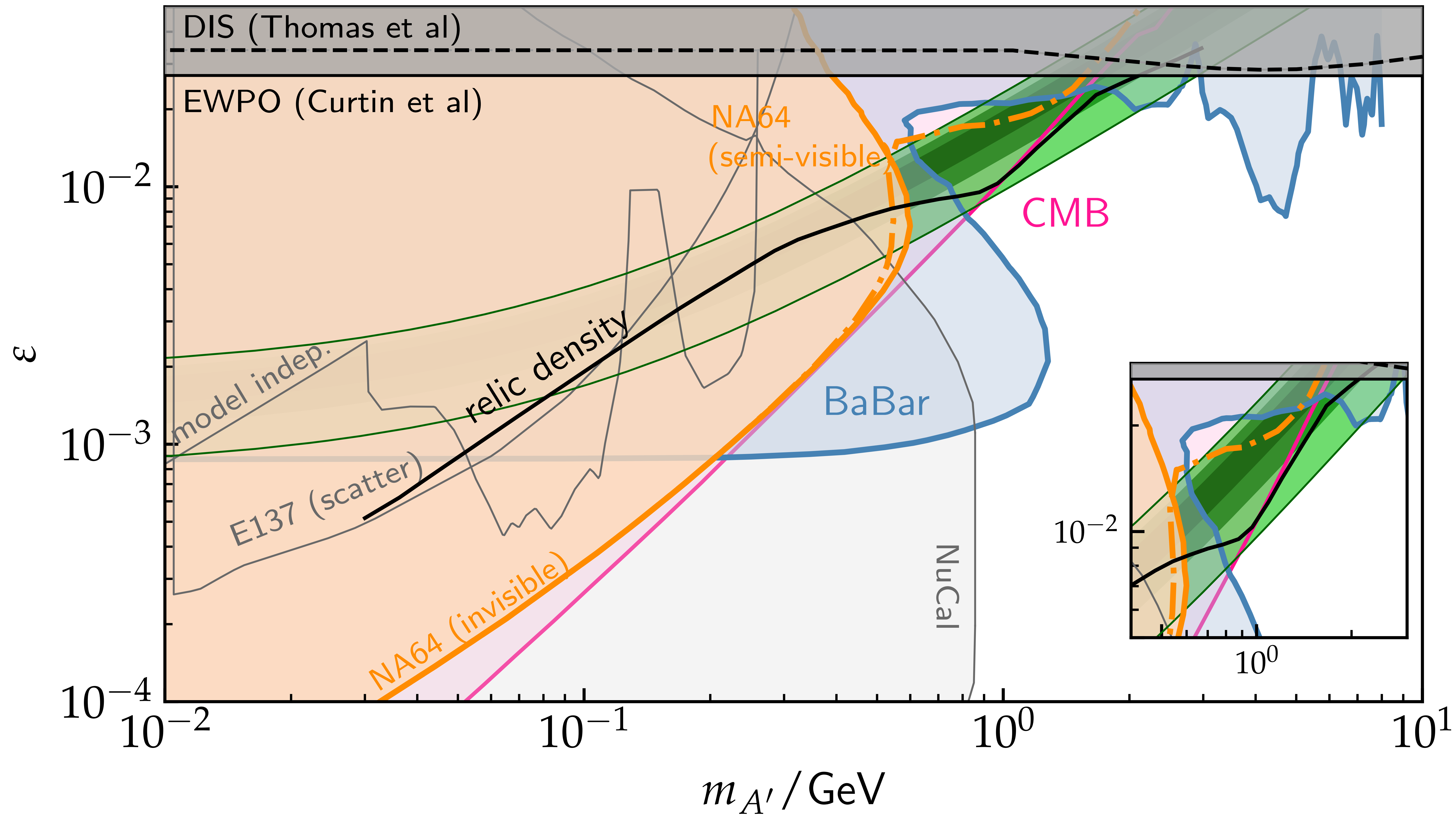
*Updated G. Mohlabeng (2019) with new energy thresholds and angular cuts. BaBar selection assumes E_e > 100 MeV for all tracks and less pessimistic assumptions than M. Duerr et al, arXiv:1911.03176.

Results of our BaBar and NA64 simulations

A dark Dirac fermion seesaw

$\eta_L\,\eta_R \quad \chi_L\,\chi_R$

i2DM: $\Delta_{21} = 0.4, \quad m_1/m_{A'} = 0.33, \quad \alpha_D = 0.5, \quad \theta = 4.5^\circ$



Very small parameter space that **can explain** (g-2)$_\mu$

However, ψ_1 cannot be DM as otherwise it would be excluded by CMB.

ψ_1 can still be a heavy neutrino that decays $\psi_1 \to \nu e^+ e^-$.

Relic density from A. Filomonova et al, arXiv:2201.08409

Results of our BaBar and NA64 simulations

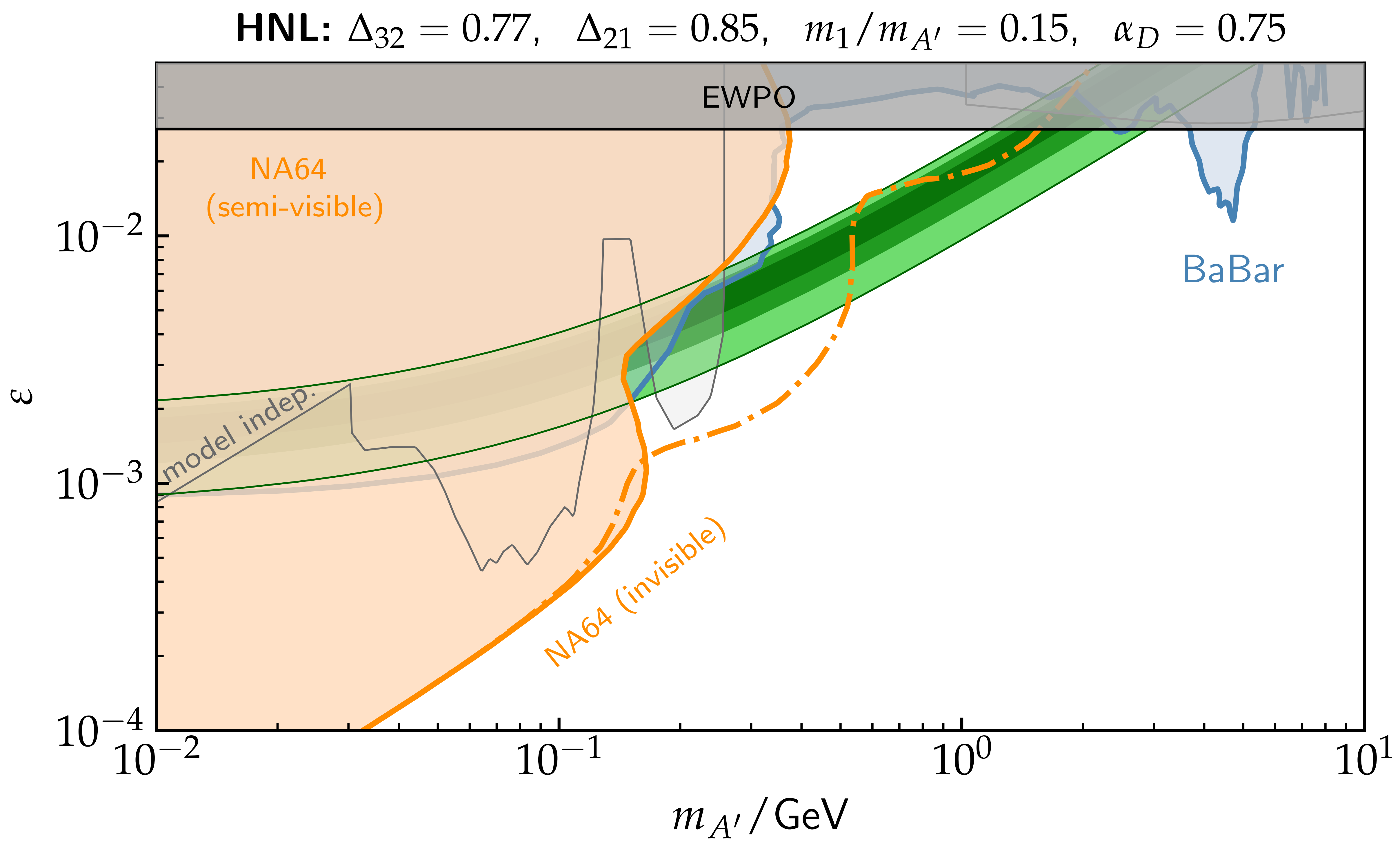
A dark Dirac fermion seesaw

η_L χ_L χ_R

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

(if HNF = HNL)

But ψ_i have to mix with neutrinos as otherwise we overproduce dark matter.



Results of our BaBar and NA64 simulations

A dark Dirac fermion seesaw

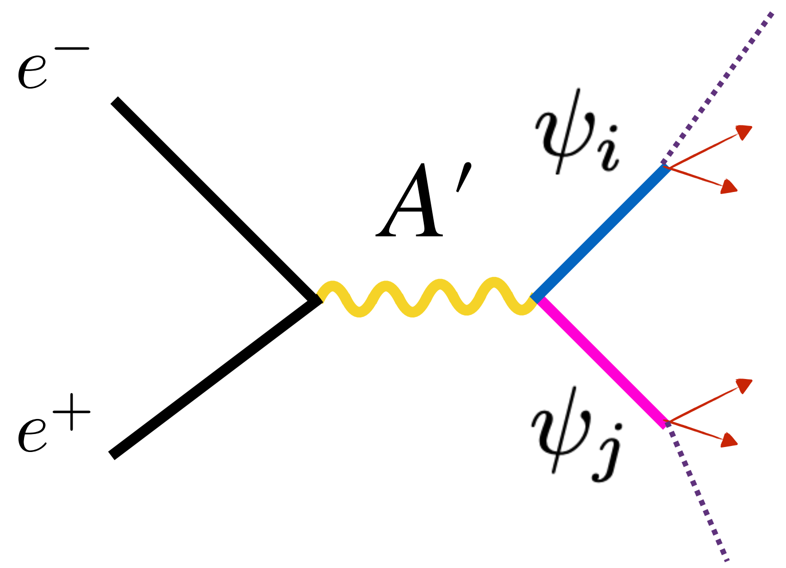
η_L χ_L χ_R

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

(if HNF = HNL)

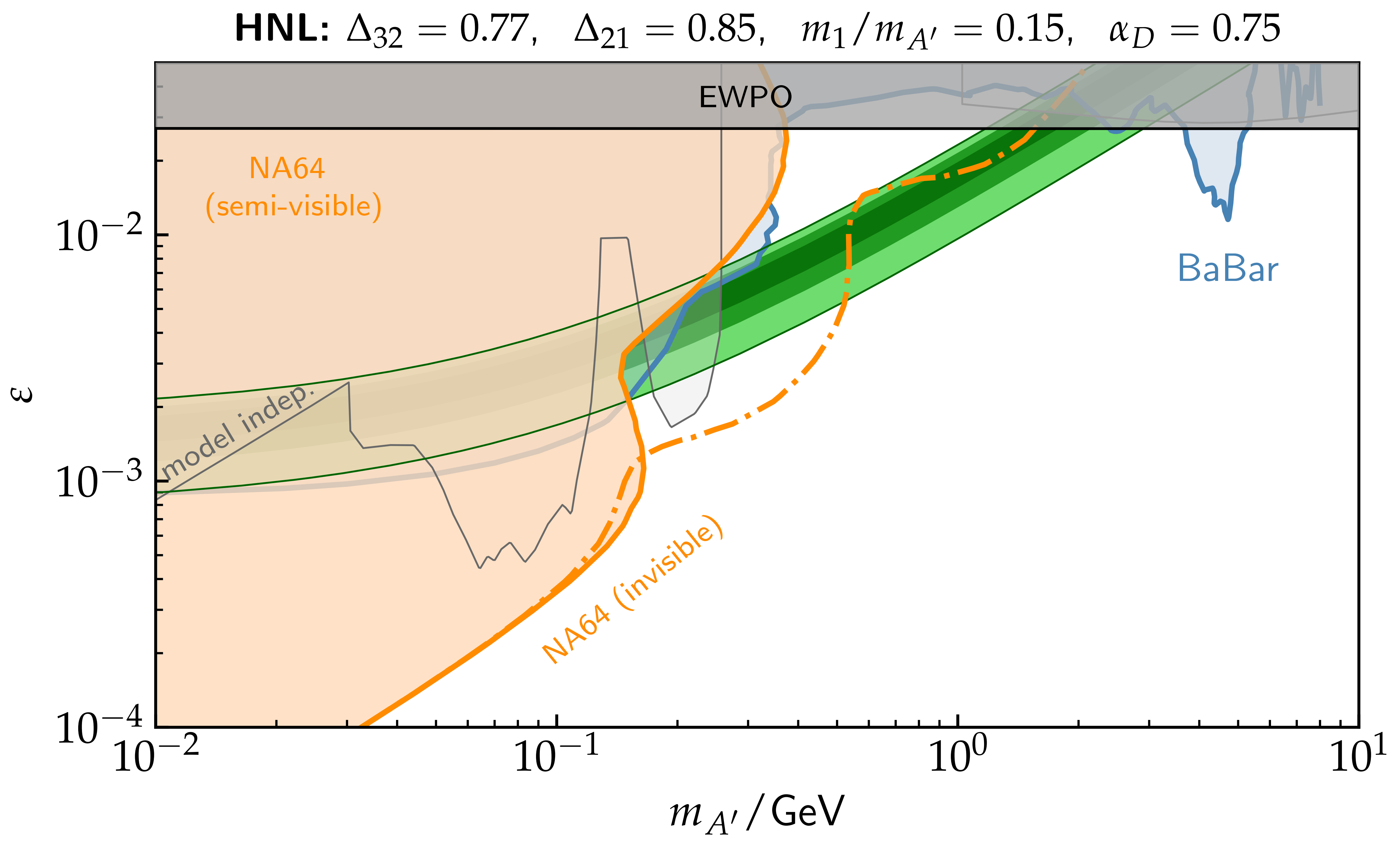
But ψ_i have to mix with neutrinos as otherwise we overproduce dark matter.

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



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

Different kinematics, larger pT for the fermions.



Explanation is **possible**, but only for large dark couplings:

i) Landau pole not too far from GeV scale...

ii) S-channel production can dominate

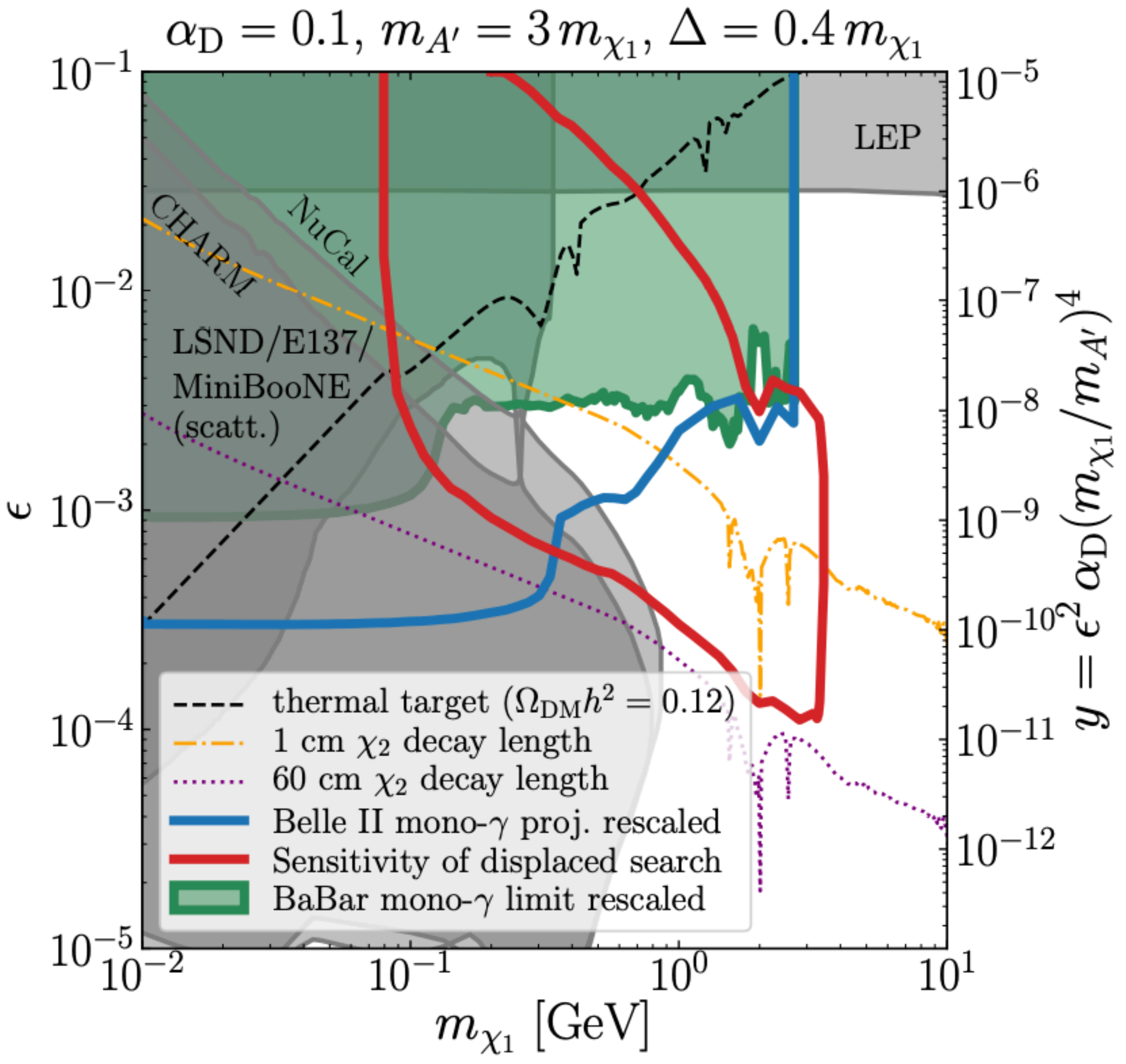
We choose benchmark points in A. Abdullahi, MH, S. Pascoli, 2020, where anomalies in neutrino experiments, including the MiniBooNE excess, can be explained.

Future prospects

Fixed targets and neutrino experiments

Belle-II — displaced vertices

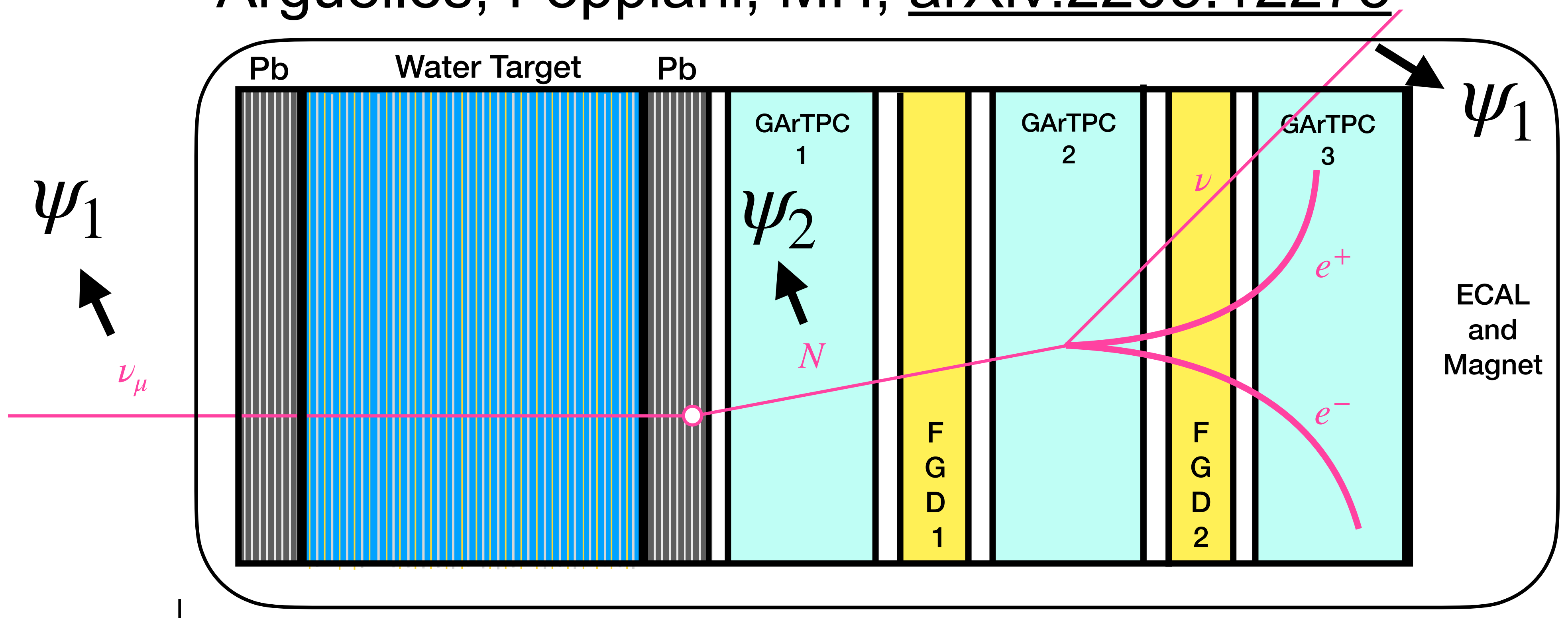
M. Duerr et al, arXiv:1911.03176



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

Neutrino experiments

Argüelles, Foppiani, MH, arXiv:2205.12273



Current T2K data: zero-background, zero-event limit that constrains decay-like signatures and upscattering enhanced by upstream lead. Signature in GAr-TPCs.

Short-baseline program can also look for similar signatures in LAr-TPCs. B. Batell et al, arXiv:2106.04584

Conclusions

A semi-visible dark photon with $m_{Z'} \sim 1$ GeV and $\varepsilon \sim 10^{-2}$ is easy to look for, but so far, limits are rather weak.

Interesting solution to the (g-2)μ puzzle and can also have connections to the anomalies in the neutrino short-baseline program.

A plan for the future to extend our coverage of these models:

1. Searches for A' in CERN's NA64 program allowing for prompt decay signature.
2. Make use of $\psi_1 \to \psi_2 \to \psi_1 e^+ e^-$ upscattering signatures at neutrino experiments.
3. Searches for monophotons and displaced vertices at Belle-II.
4. Eventually, LDMX could dig much deeper into parameter space.

Conclusions

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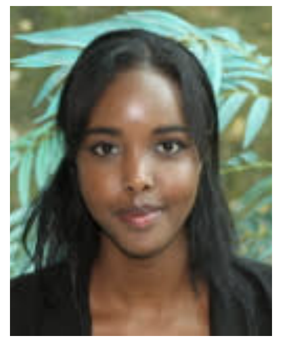
4.Eventually, LDMX could dig much deeper into parameter space.

Thank you

Happy hunting!

Collaborators:



Asli Abdullahi
Fermilab

Daniele Massaro
Uni of Bologna

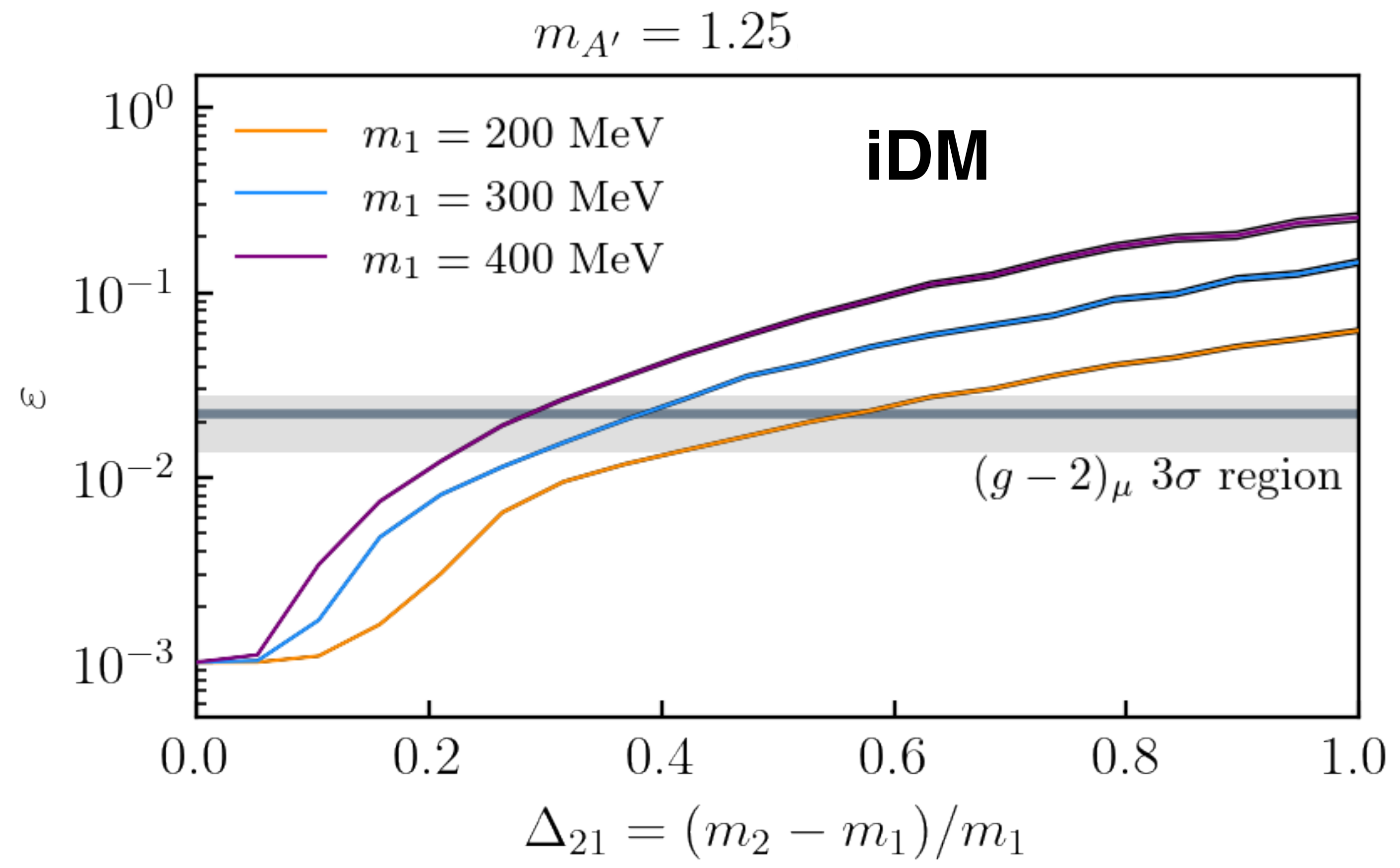
Silvia Pascoli
Uni of Bologna

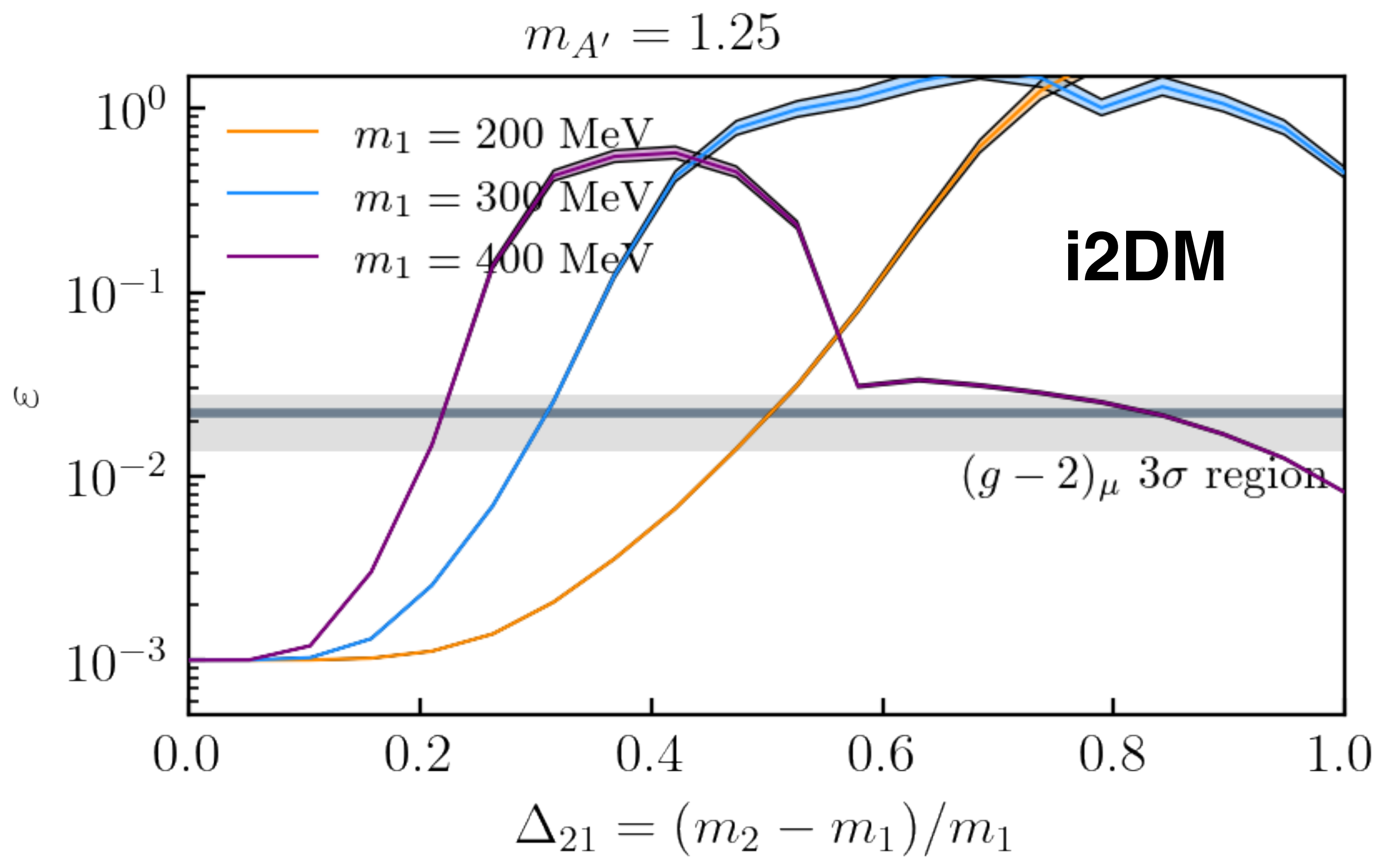
Back-up slides

Signal characteristics

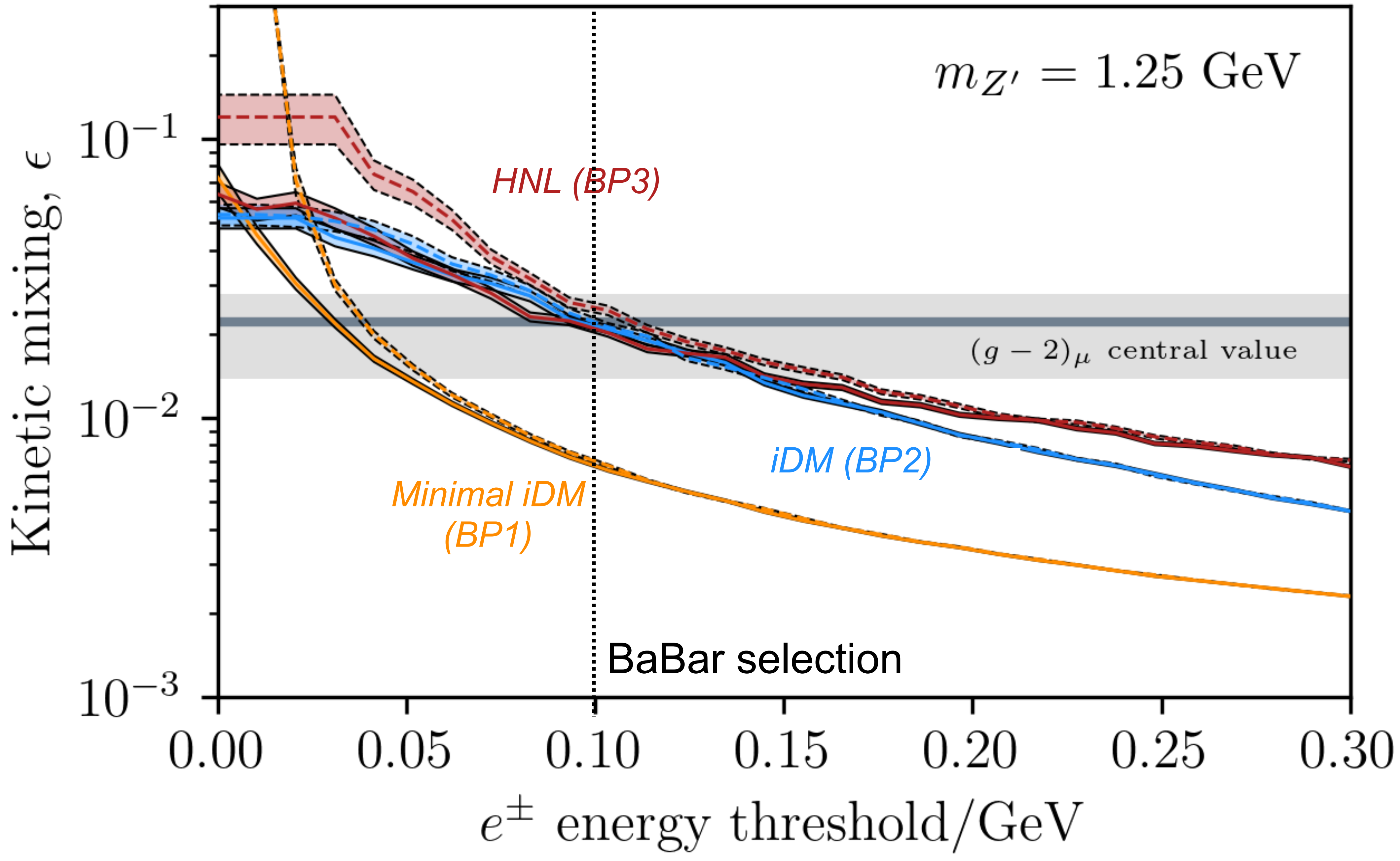
Dependence of the results on simulation assumptions

Smaller **mass splittings** gives very soft electrons, which are often missed.





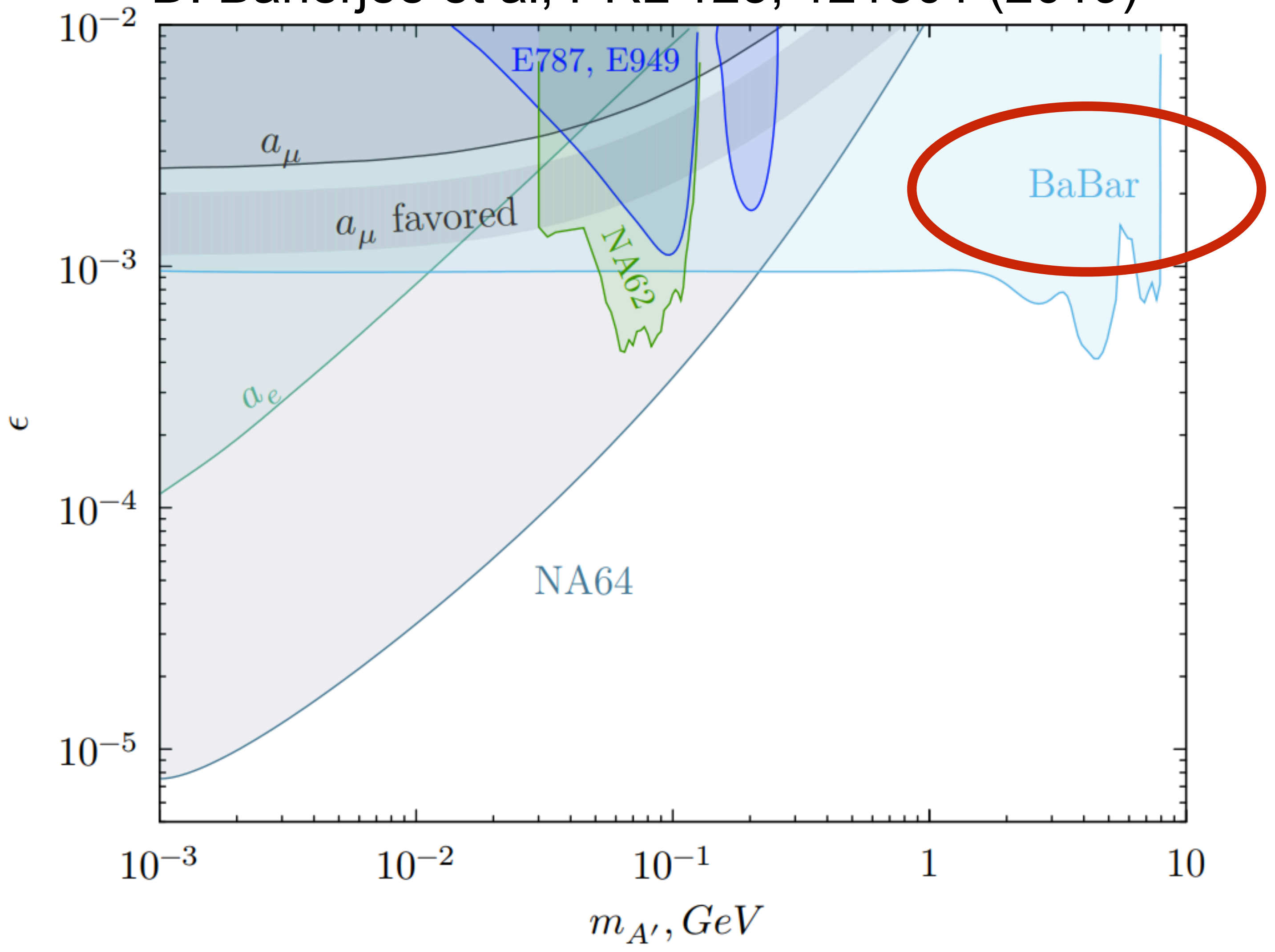
At BaBar, **energy thresholds** are the dominant source of "invisible" dark photon events:



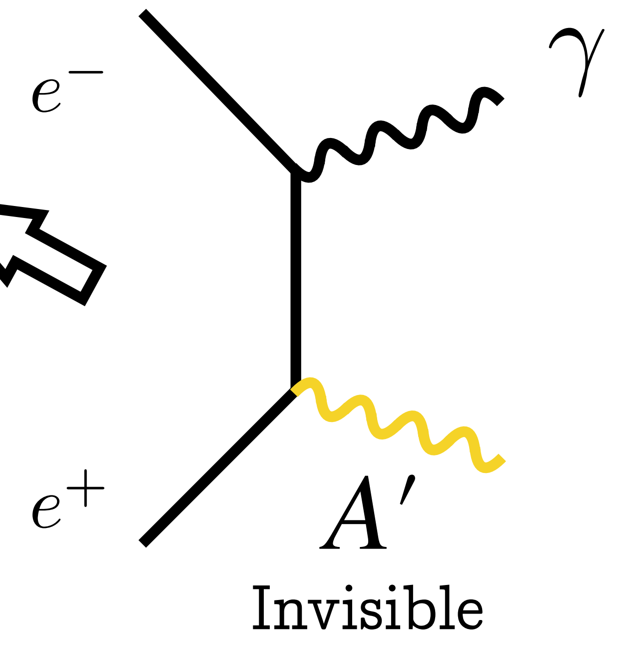
Dark Photons at BaBar

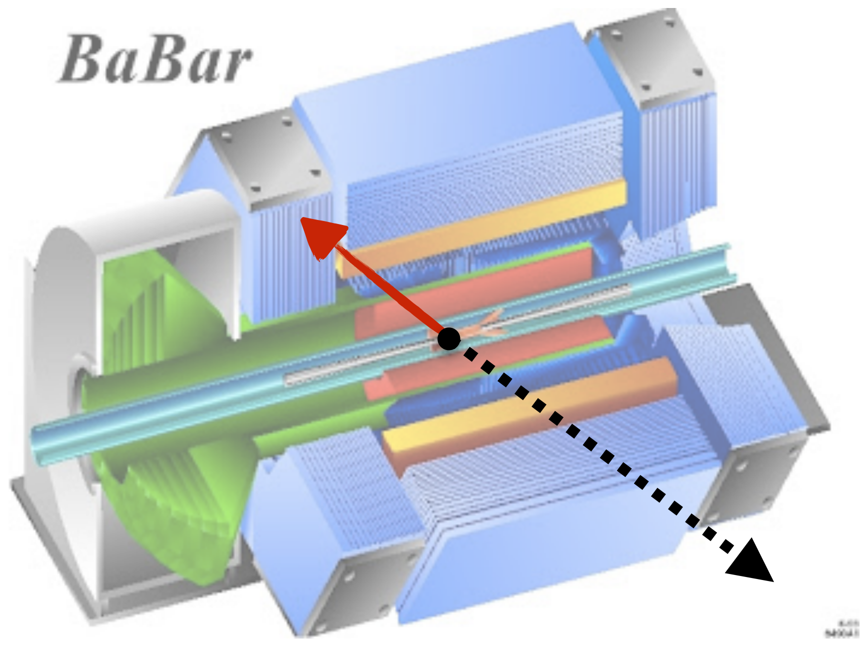
Photon recoiling against missing energy

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

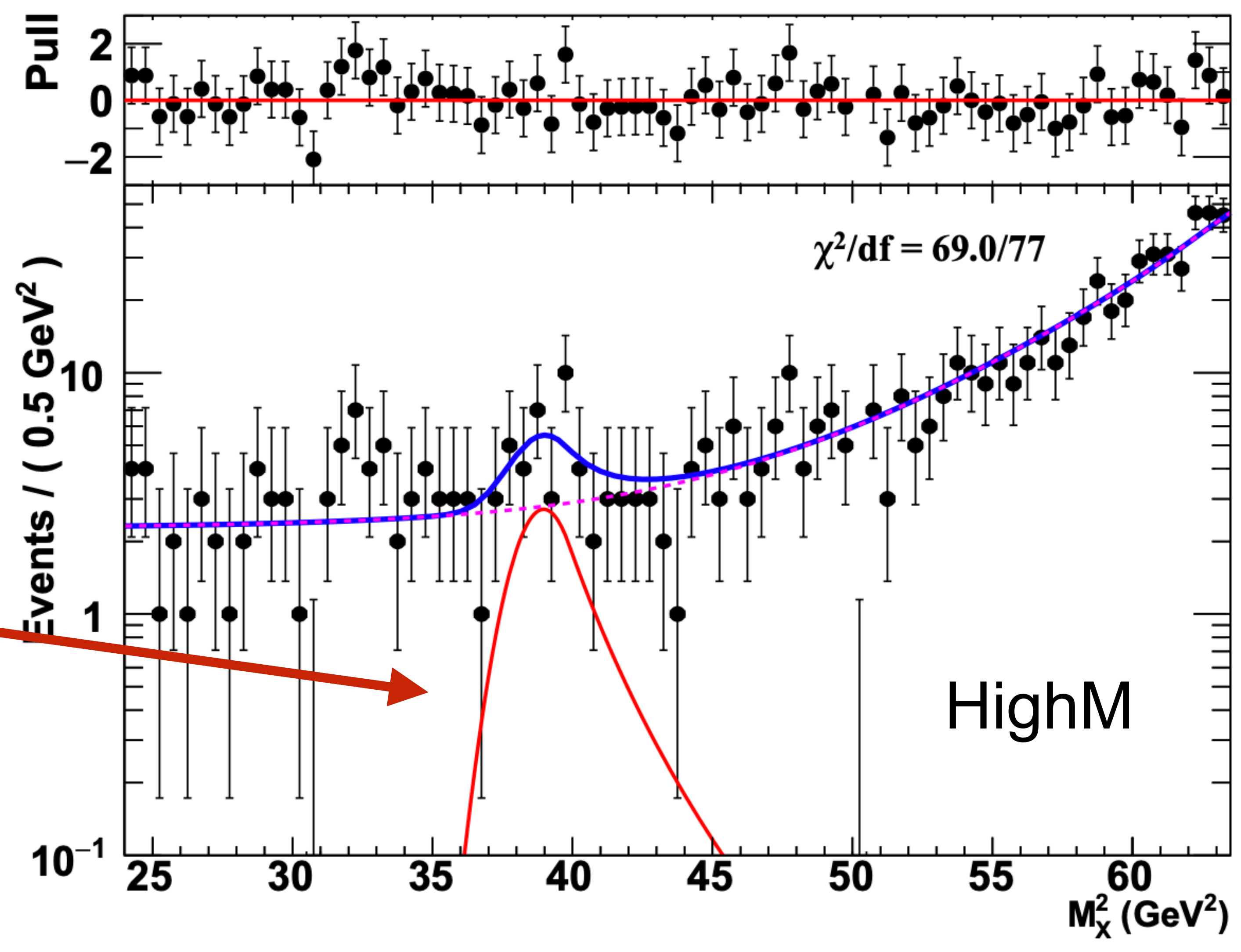


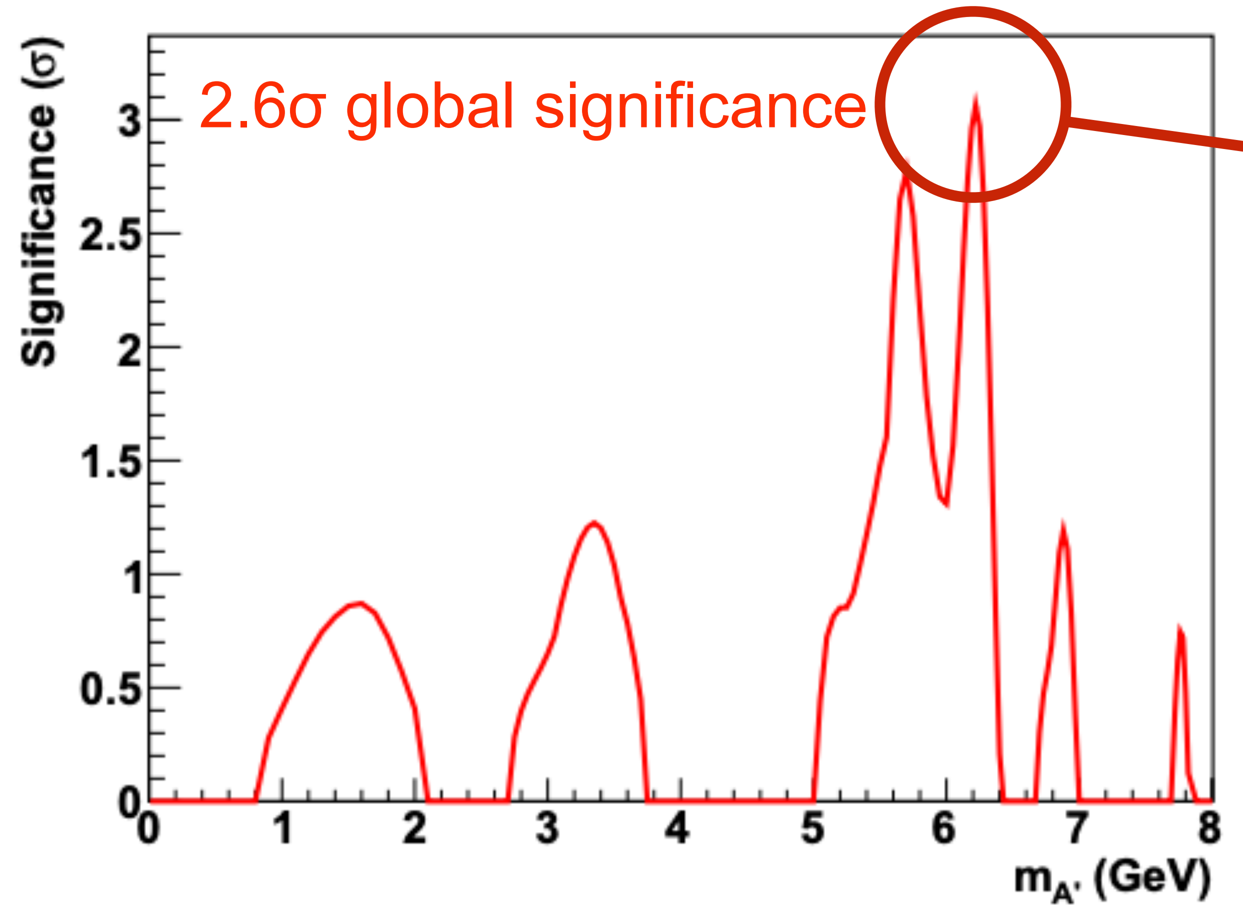
ISR monophoton





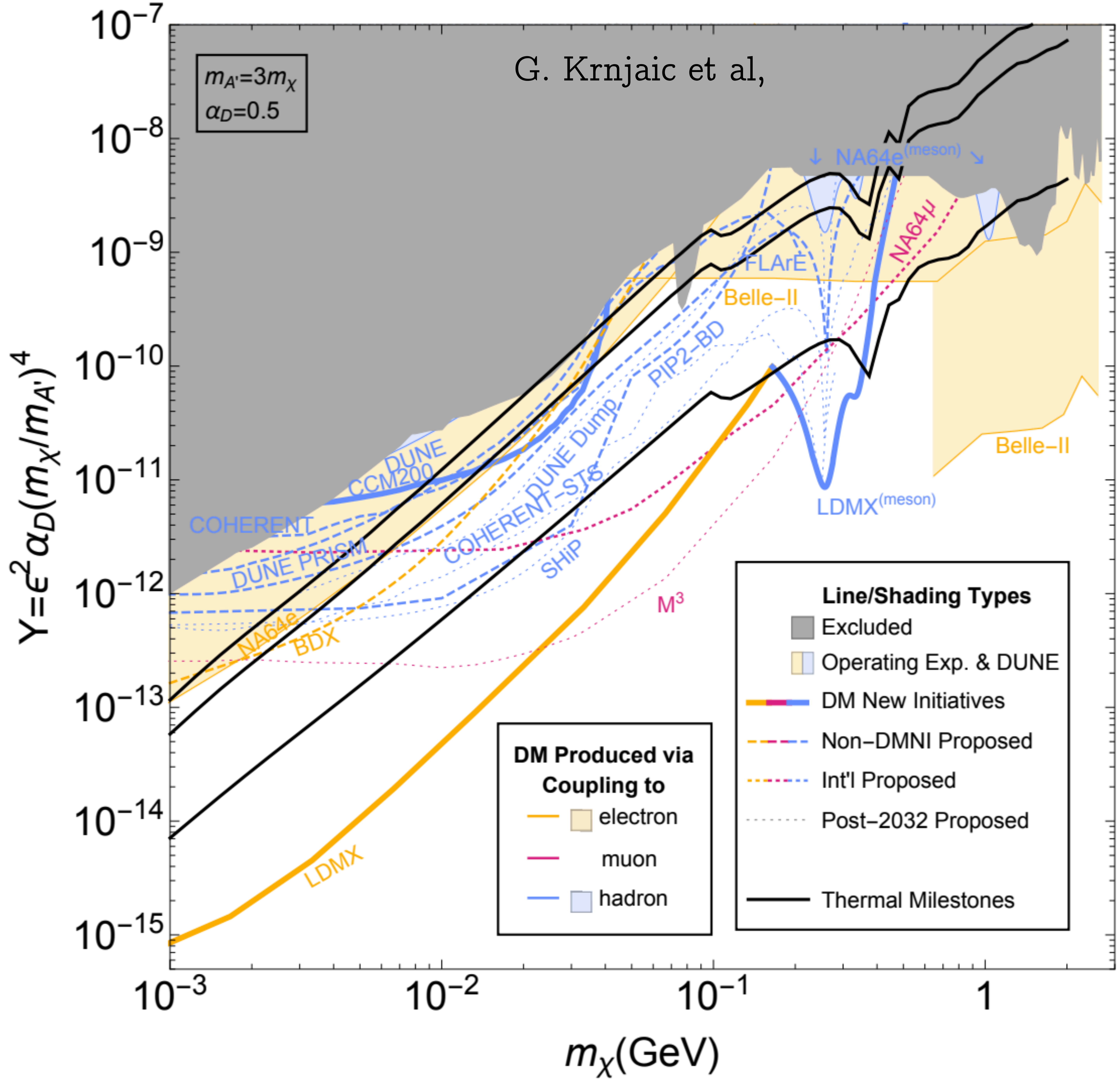
BaBar collab., PRL 119, 131804 (2017)



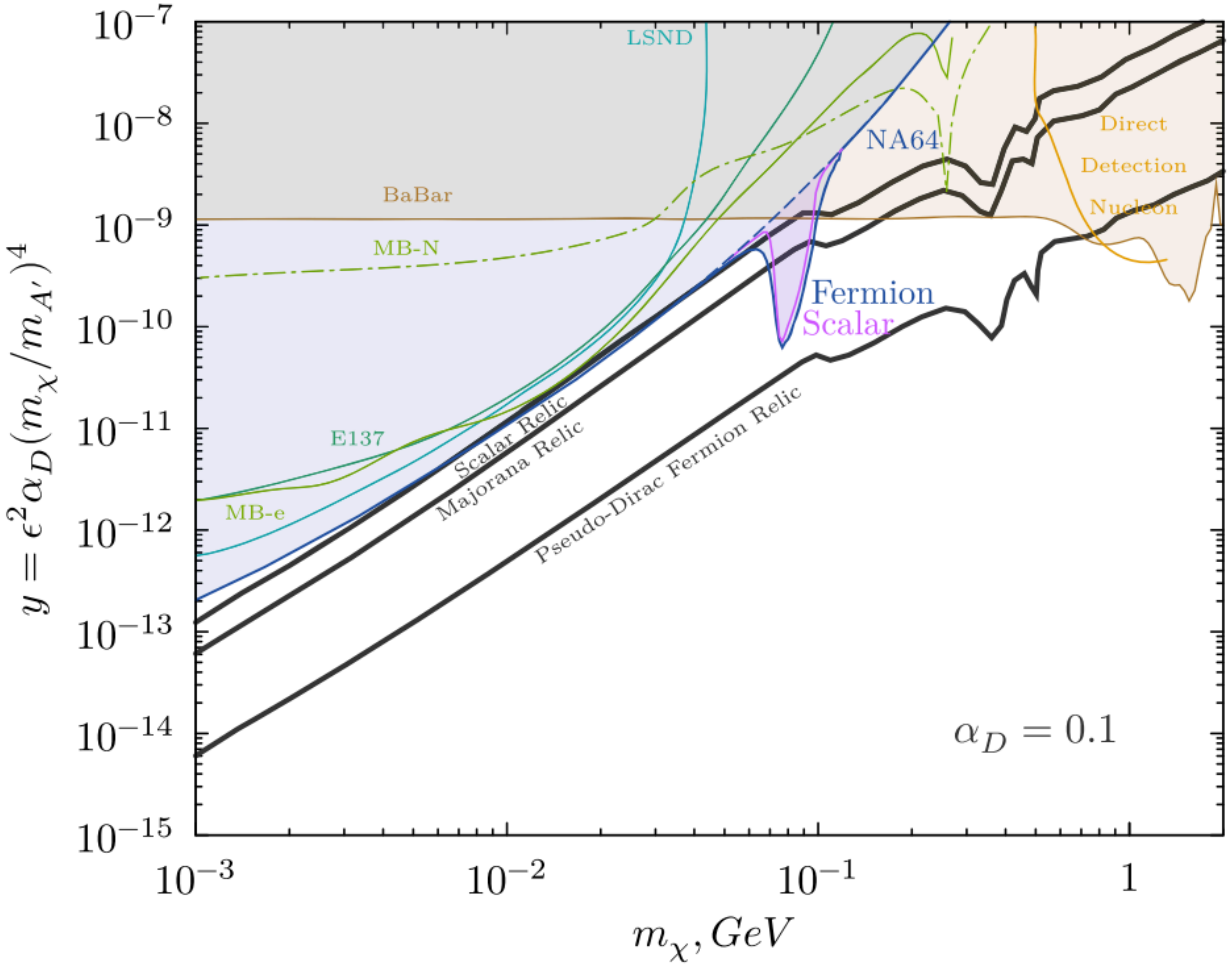


A single photon recoiling against an invisible massive particle. Dark photon mass reconstructed as:

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

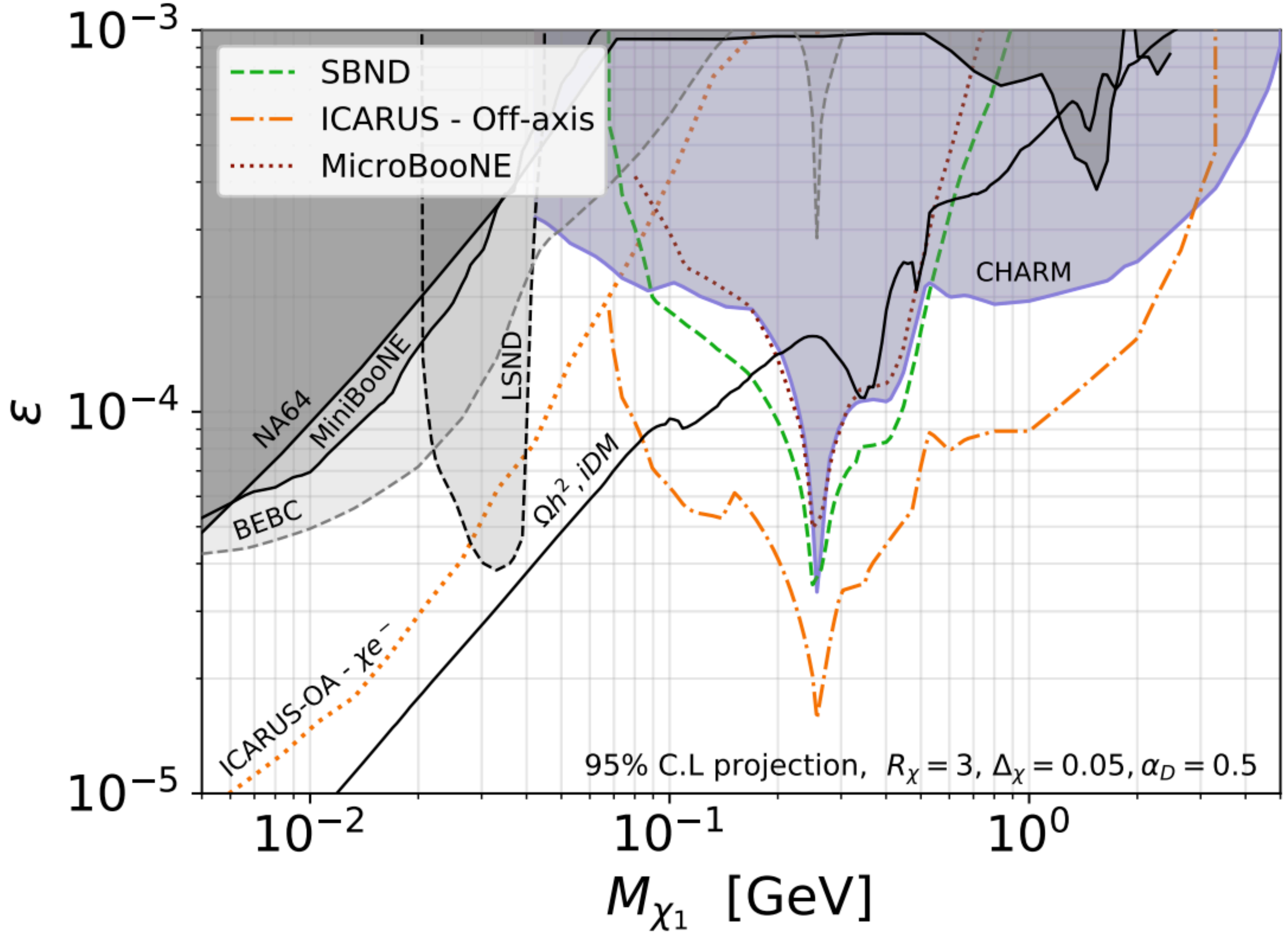


NA64 including resonant production.



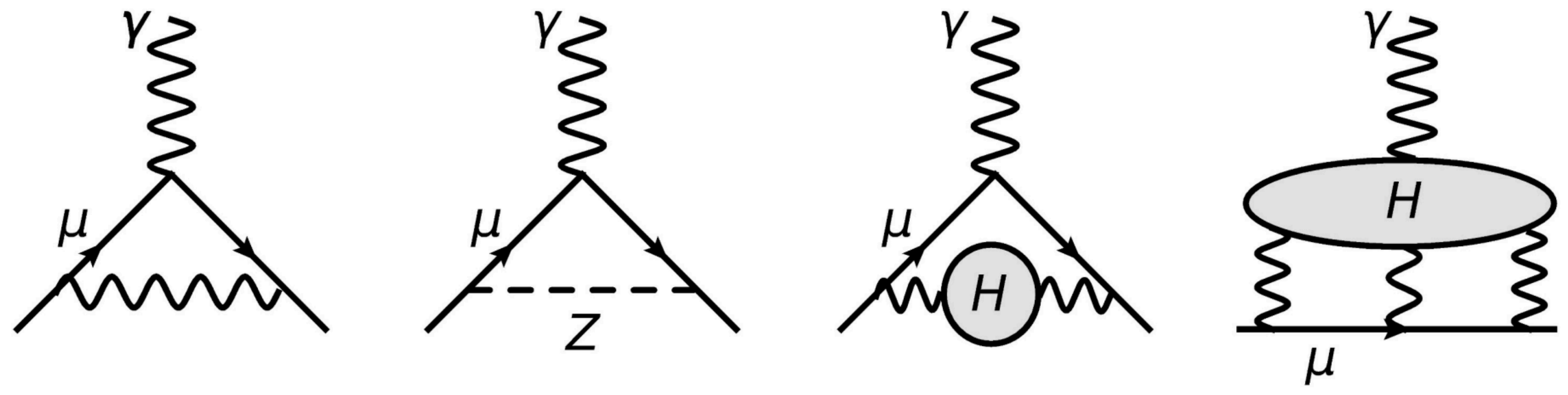
iDM at the Short-Baseline program at FNAL.

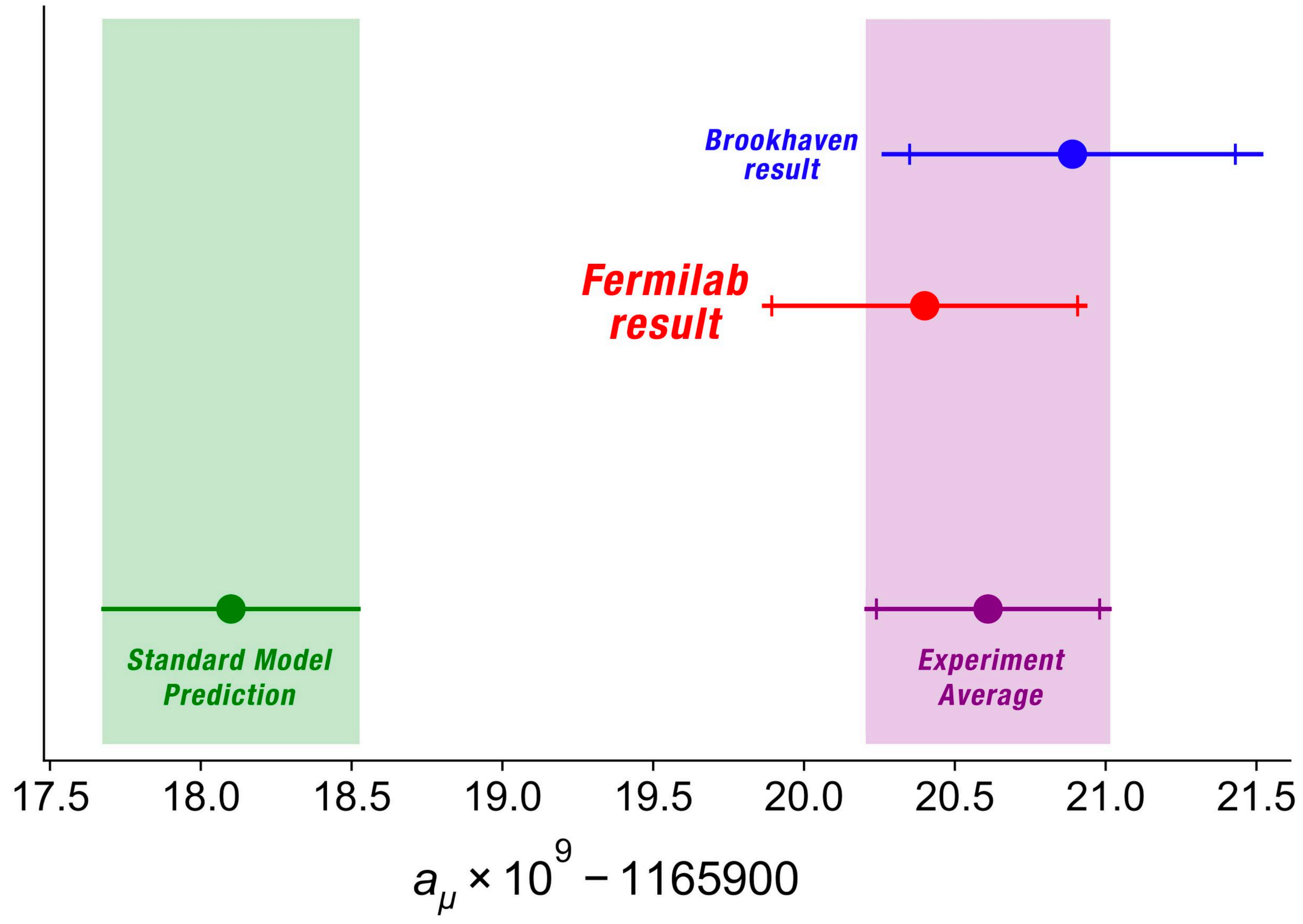
B. Batell et al, arXiv:2106.04584



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

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 reac

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

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

`DarkNews`, a Python-based generator for dark neutrino sectors

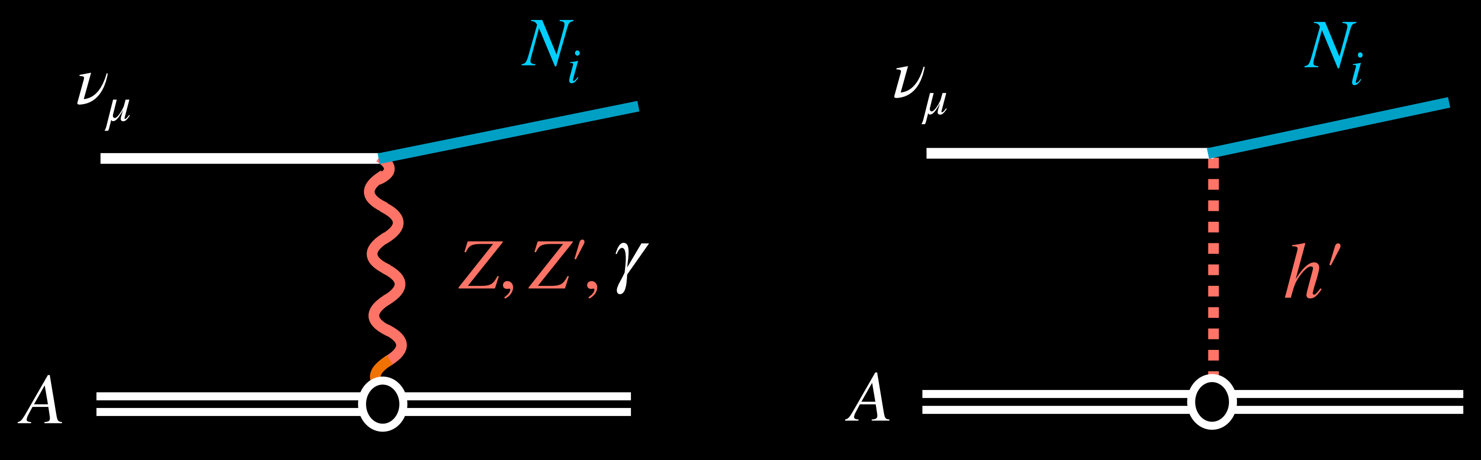
A. Abdullahi, J. Hoefken, MH, D. Massaro, S. Pascoli, arXiv:2207.04137

`DarkNews` is a fast MC generator for new physics in neutrino-nucleus scattering.
Including vector, scalar, and dipole mediators. Models with up to 3 HNLs.

Focused on GeV accelerator experiment, including the processes:

Scattering:

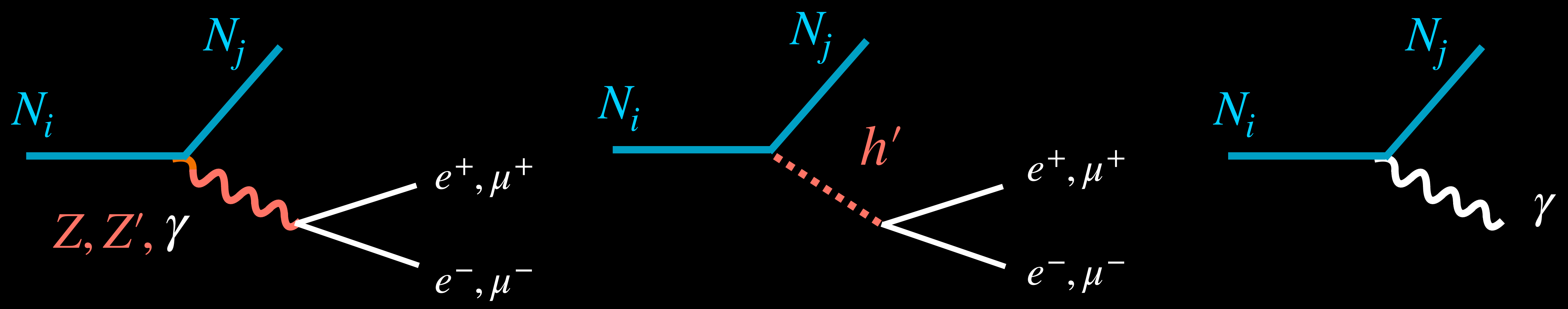
$\nu A \to N A$
(Coherent & QE peak)



Helicity conserving or flipping $\nu \to N$

HNL decay:

$N \to \nu \ell^+ \ell^-$
or
$N \to \nu\gamma$



N may be Majorana or Dirac, with either helicity states.