Semi-Visible Dark Photons

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Nov 16 2022

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? ...?

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

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

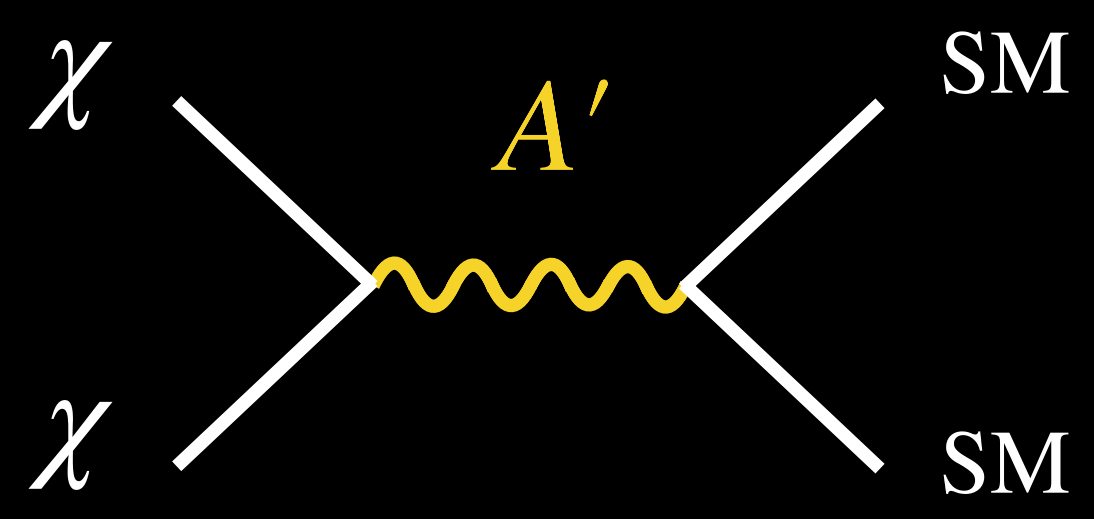

Renormalizable Portals:
(SM SINGLET) X (DS SINGLET)
DARK SECTOR (DS)
$\mathscr{L}_{\rm SM}$
$\overline{L}\widetilde{H}N$
Neutrino portal
Heavy neutrinos
$\frac{M_N}{2}\overline{N^c}N$
Neutrino masses?
$B_{\mu\nu}X^{\mu\nu}$
Vector portal
Dark photons
$G_{SM} \times U(1)_X$
New fundamental forces?
$S^\dagger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

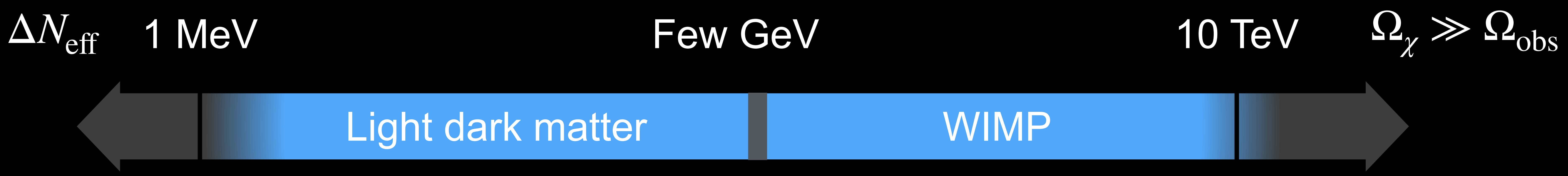
Dark U(1)$_X$ symmetry
$\overline{L}\widetilde{H}N$
Neutrino portal
$\mathcal{L} \supset \varepsilon e A'_\mu \bar{f}\gamma^\mu f$
$\mathcal{L} \supset g_D A'_\mu J^\mu_X$
Couples to some dark current.
It may contain:
A'
$J^\mu_{\rm EM}$
J^μ_X
Couples to electromagnetic current
1) dark matter
ψ
2) heavy neutral leptons
$\overline{L}\tilde{H}\psi$

Light Dark Matter

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

Predictive and testable!





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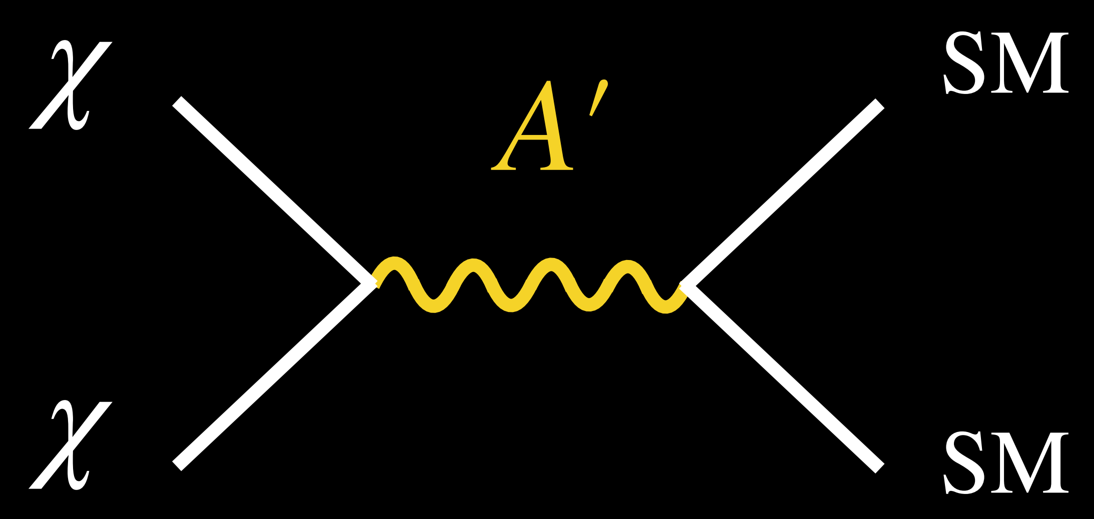
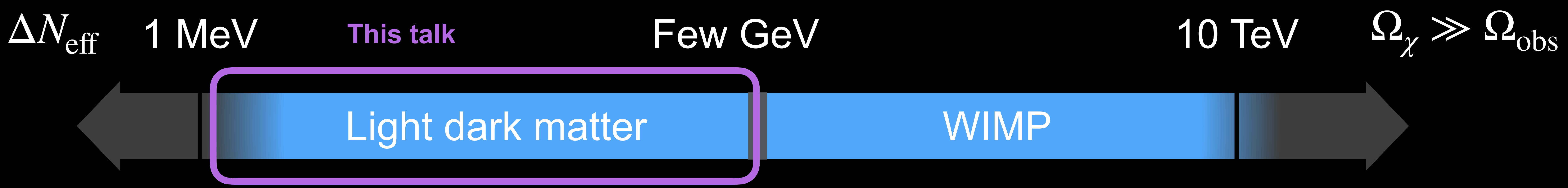


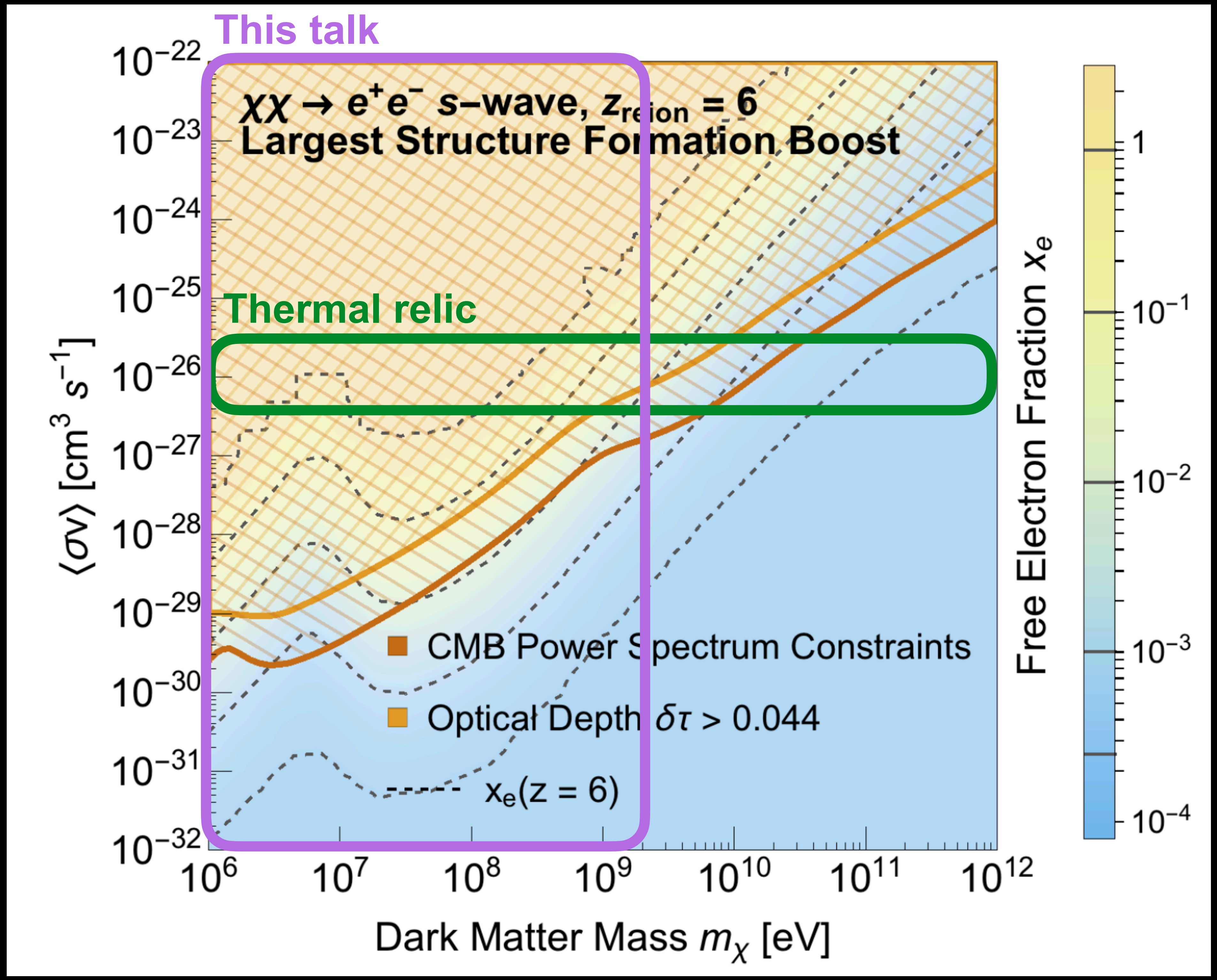


Light Dark Matter

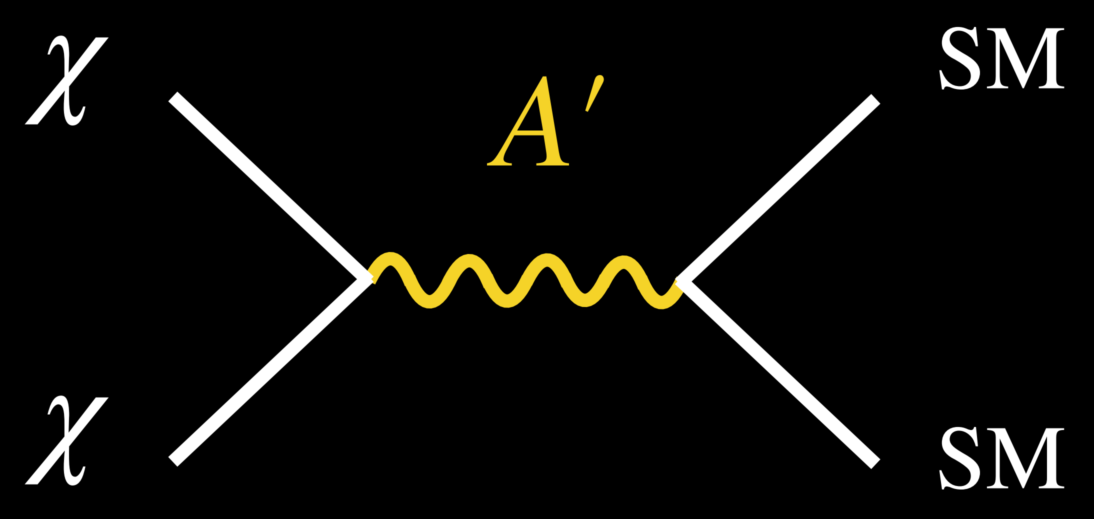
Freeze-out and CMB limits

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.



Light Dark Matter

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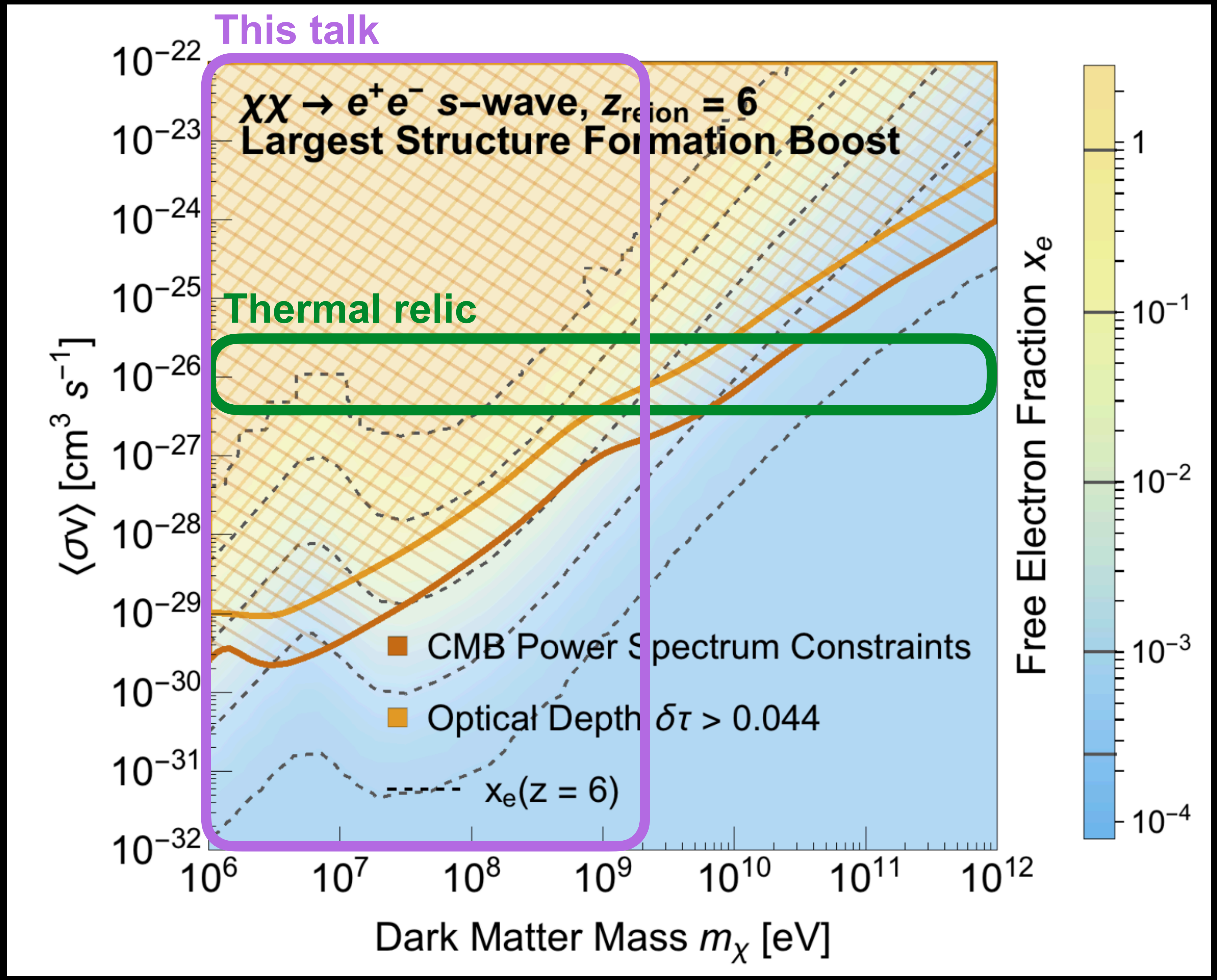


Solution 1) no charged states are produced,

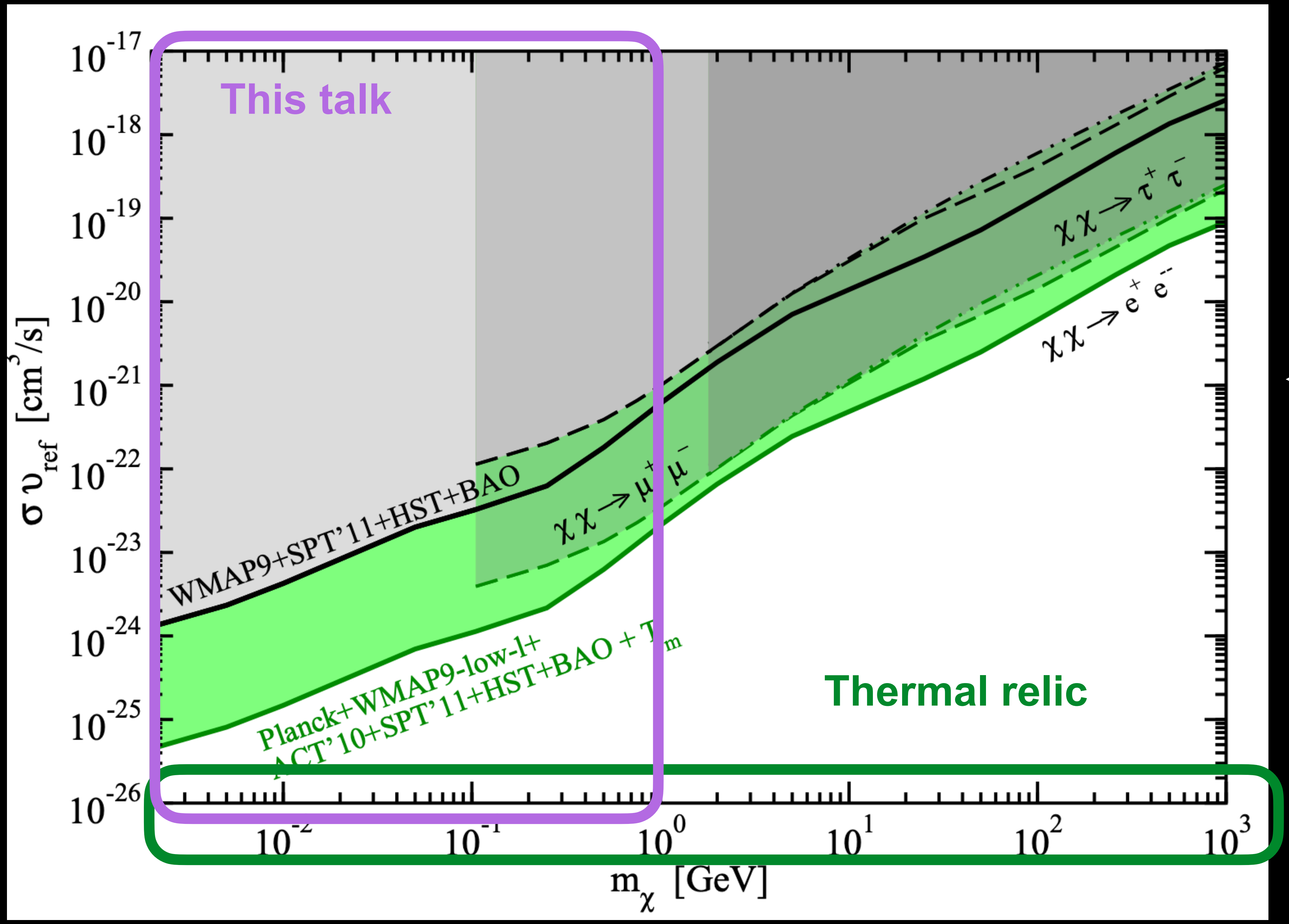
- "Neutrinophilic" dark matter
- Annihilations to dark states (secluded)

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 ≠ 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 ($\psi_2 \to \psi_1 + \dots$)

Light Dark Matter

Direct detection

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

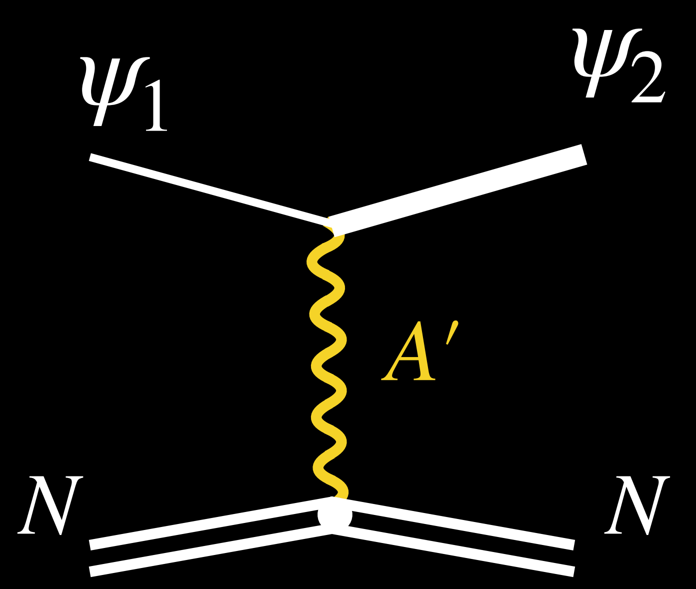
$$\frac{m_2 - m_1}{m_1} \equiv \Delta < \beta^2 \frac{m_N}{2(m_{\chi_1} + m_N)}$$

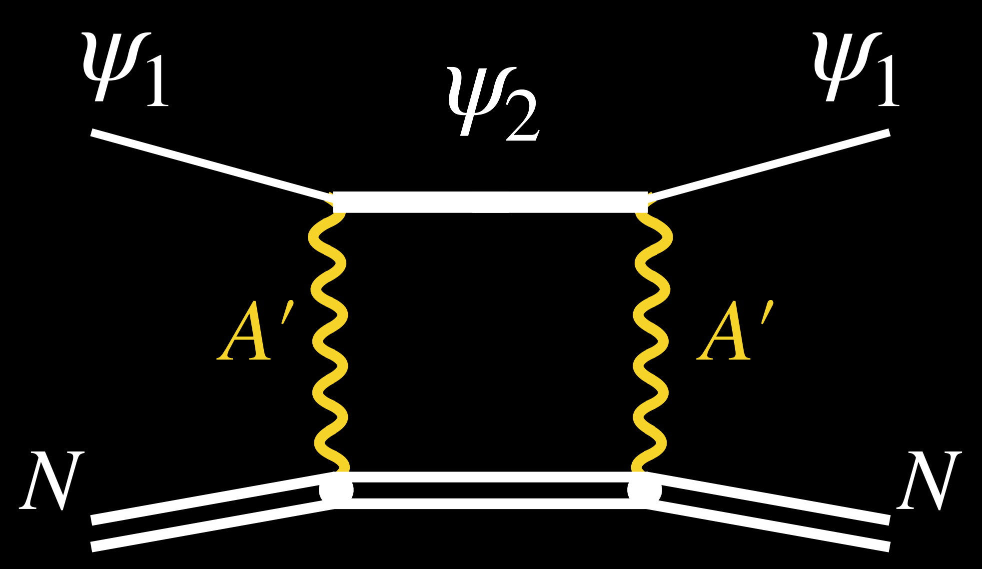
Thresholds are larger for lighter nuclei:

DAMA (Iodine 127) vs CDMS (Germanium 73)

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

Later excluded by CDMS and XENON.

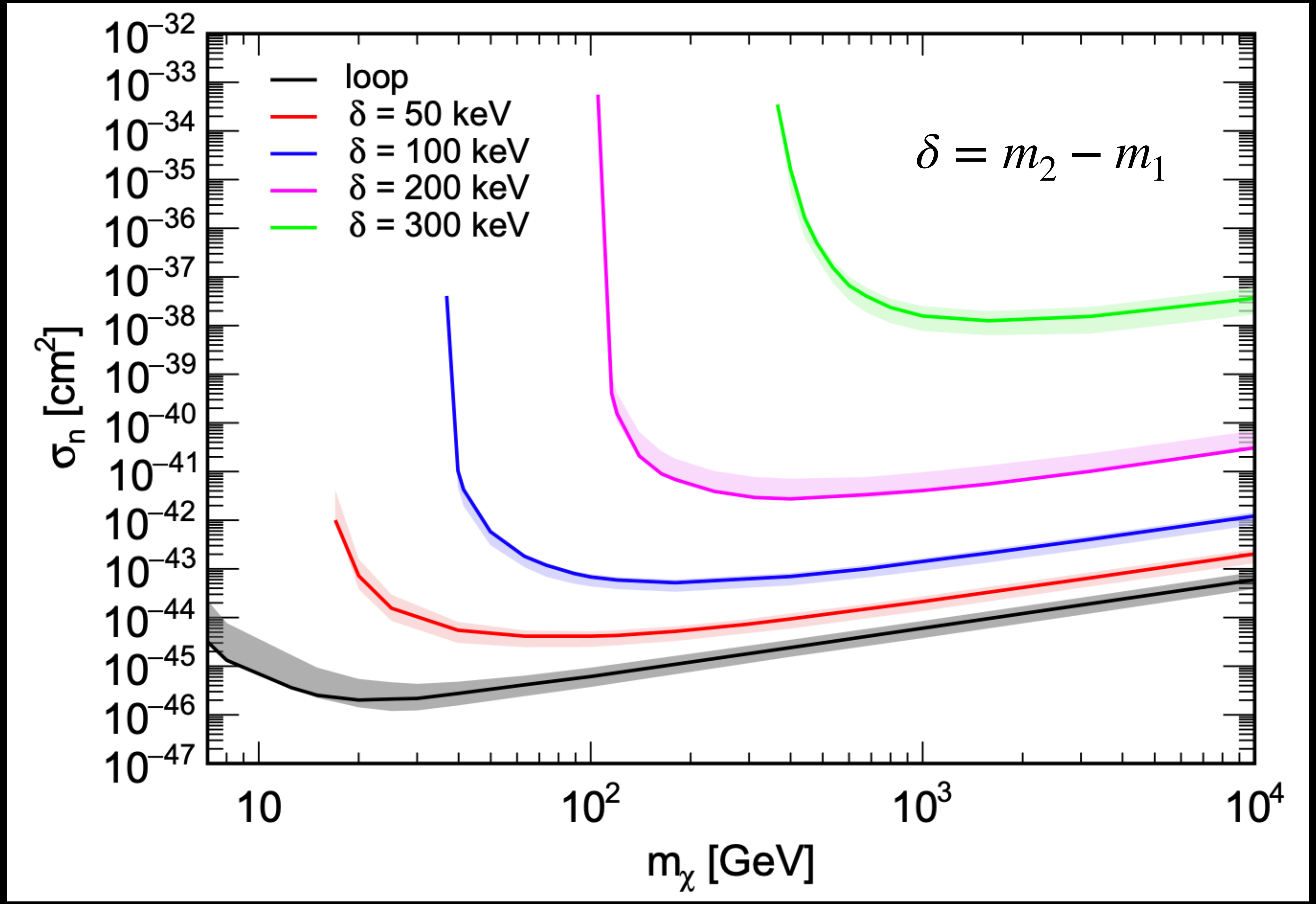




Challenging target for direct detection

when the mass splitting is large.

Latest limits from PandaX-II, arXiv:2205.08066



Light Dark Matter

Accelerator searches

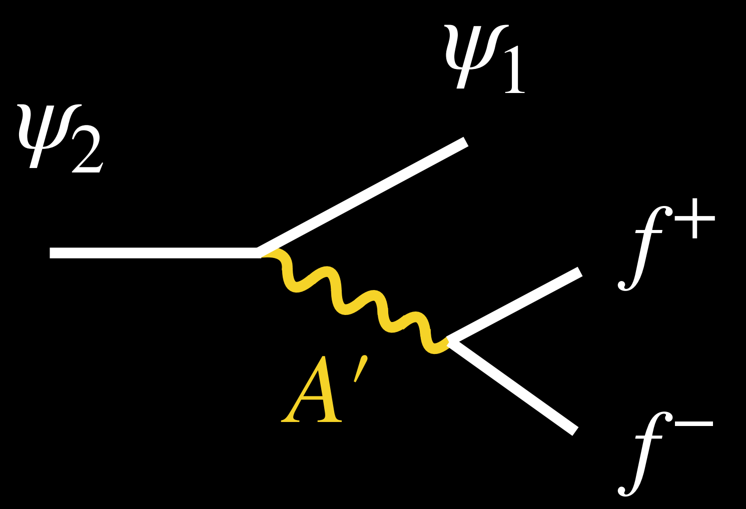
M. Duerr et al, arXiv:1911.03176

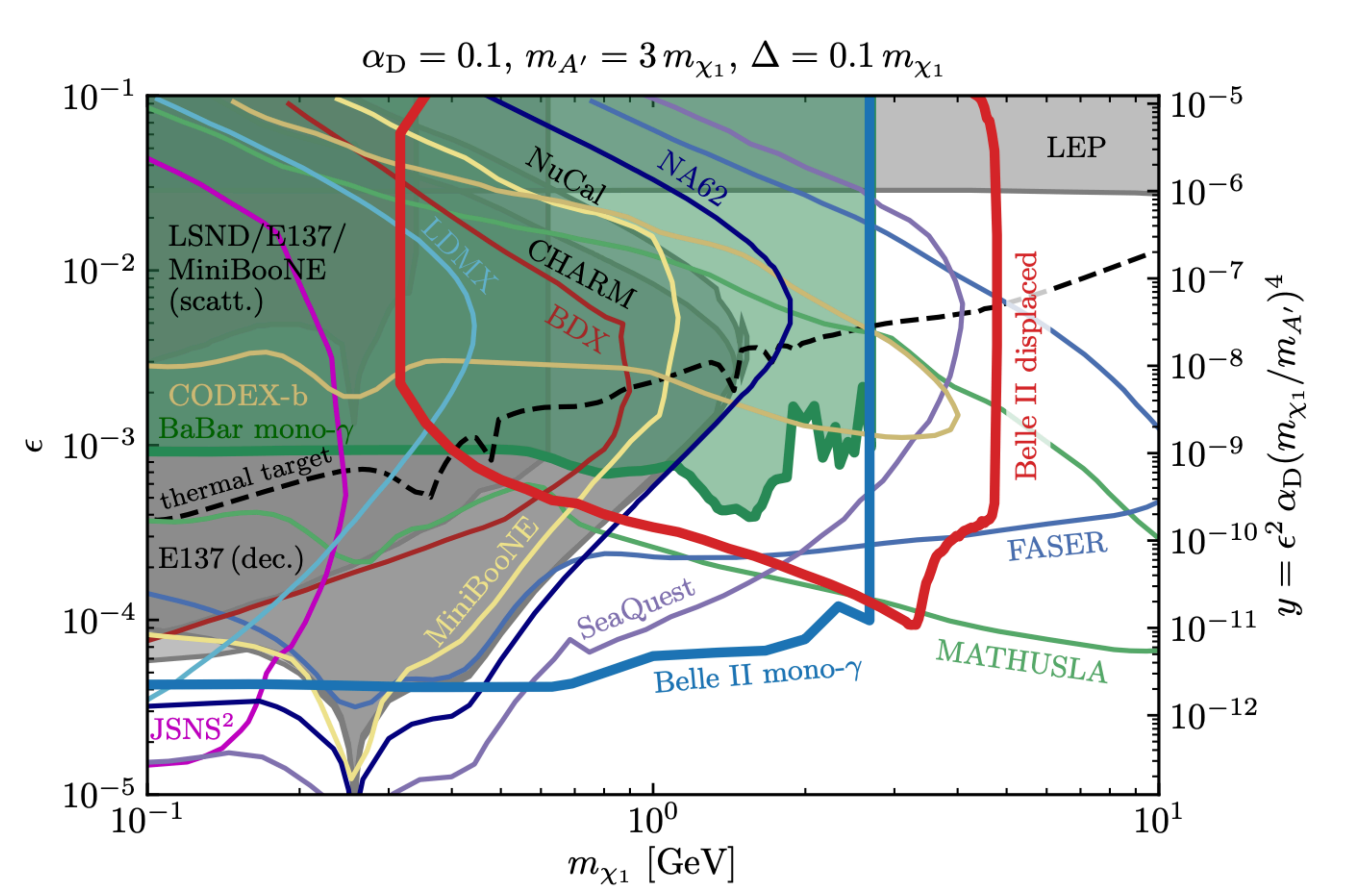
Relic density now depends on Δ as well as the usual parameters, **but same number of degrees of freedom**.

Heavy partner is now unstable and long-lived for small Δ.

Important input from the fixed target and collider experiments.

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





At larger values of Δ, fixed-target and collider experiments thrive.

Models of Heavy Neutral Fermions (HNFs)

QED is rather... boring.

All particles form exact Dirac pairs because of charge conservation.

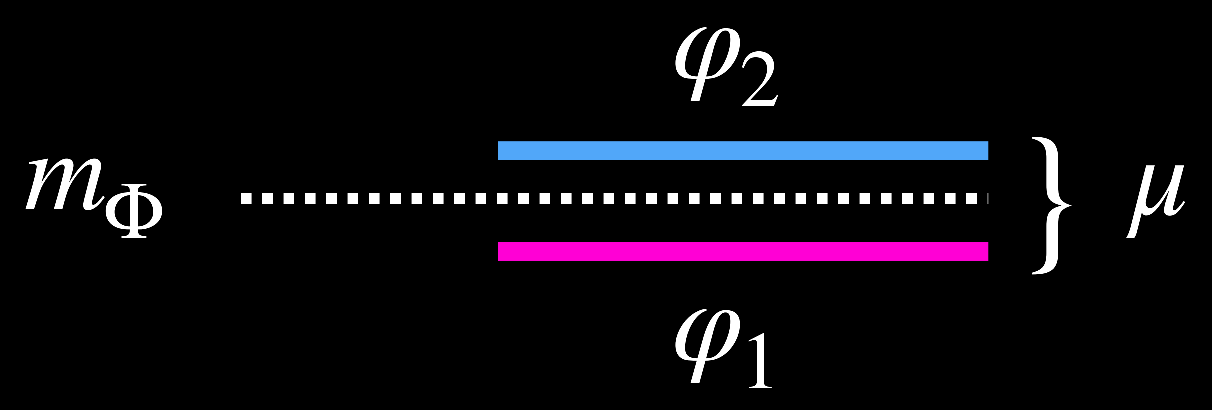
$$Q(e_L) = Q(e_R)$$

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

Light Dark Matter

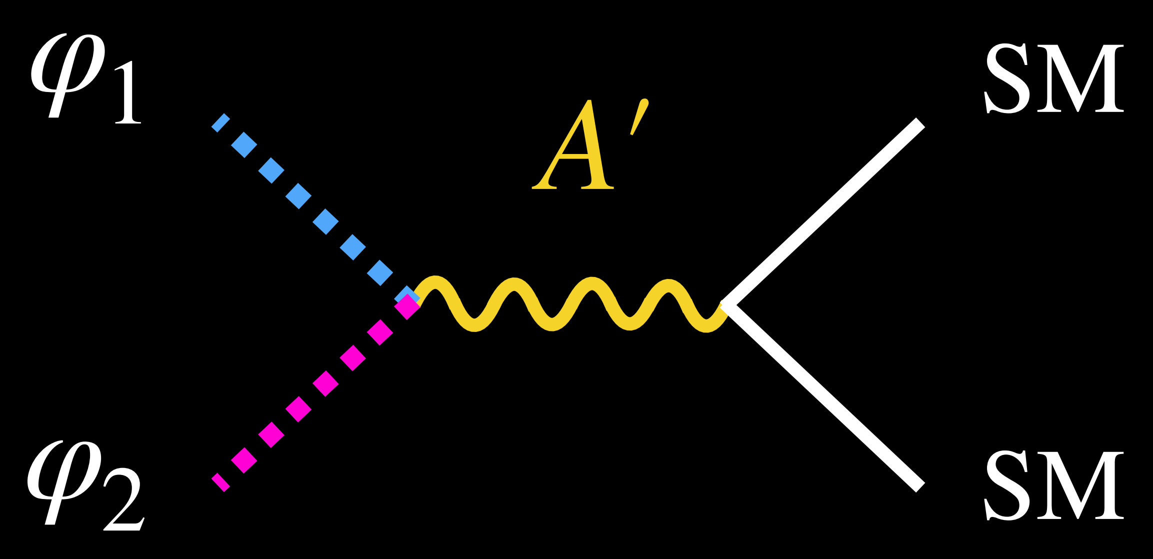
Models of Co-Annihilation — Complex scalar

$U(1)_X$ 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.

Models of Heavy Neutral Fermions (HNFs)

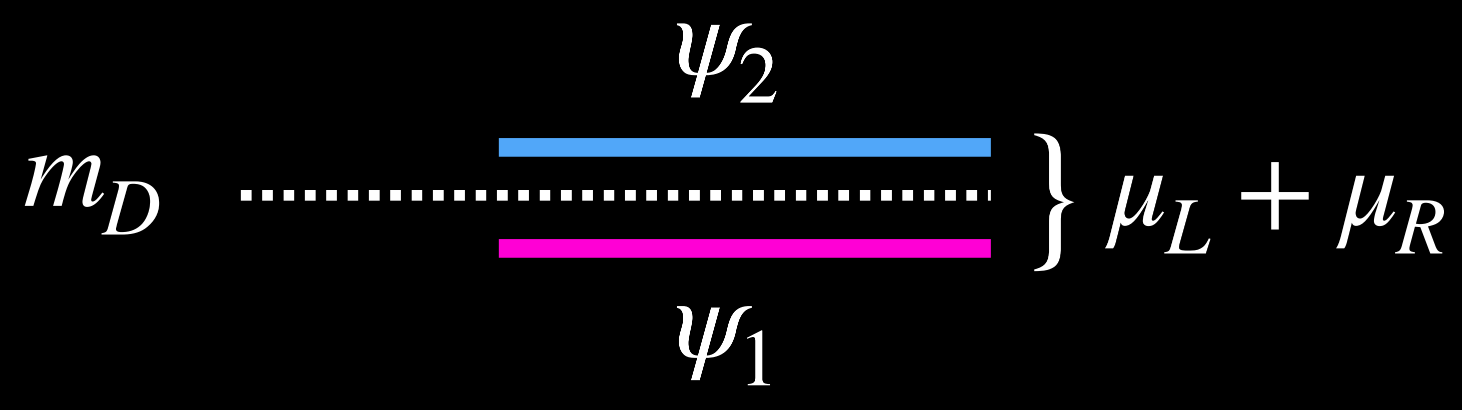
Model 1 — Inelastic Dark Matter

Light Dark Matter

Models of Co-Annihilation — inelastic Dark Matter

χ_L χ_R

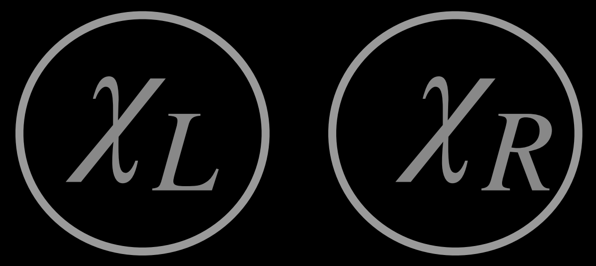
$U(1)_X$ charged fermion $\chi = \chi_L + \chi_R$. In addition to the Dirac mass the dark fermion can be split by Majorana masses, again breaking the $U(1)_X$ by 2 units.



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

Light Dark Matter

Models of Co-Annihilation — inelastic Dark Matter



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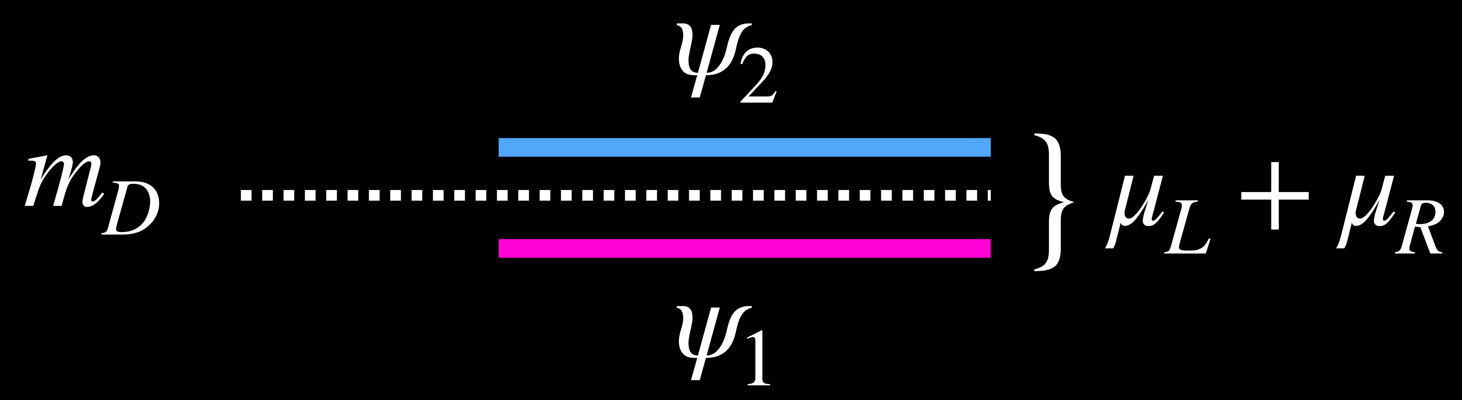

$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2} \begin{pmatrix} \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} \mu & m_D \\ m_D & \mu \end{pmatrix} \begin{pmatrix} \chi_L^c \\ \chi_R \end{pmatrix} \qquad \tan 2\theta = \frac{2m_D}{\mu_R - \mu_L} \to \infty$$

If $\mu \equiv \mu_L = \mu_R$, fermions maximally mix.

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

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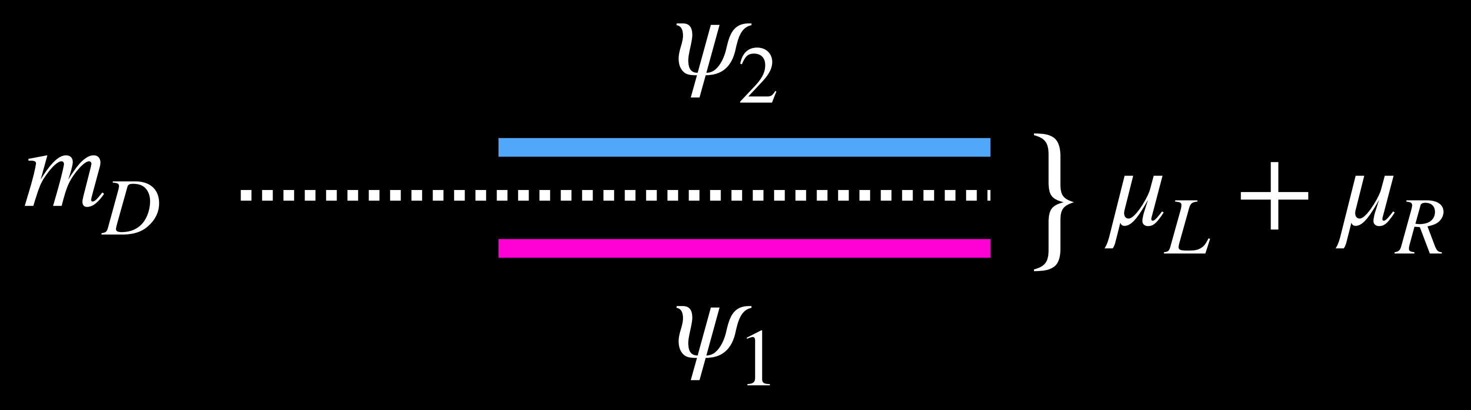

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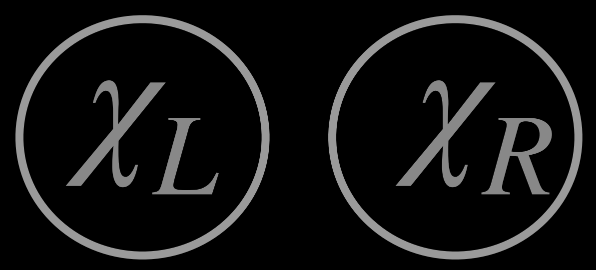
$$\psi_+ \equiv \frac{\chi_L^c + \chi_R}{\sqrt{2}}, \quad \psi_- \equiv \frac{\chi_L^c - \chi_R}{\sqrt{2}}$$

We find an enhanced symmetry ($\psi_L^c \leftrightarrow \psi_R$, or charge conjugation):

$$C(\psi_+) = +1, \quad C(\psi_-) = -1, \quad C(A') = -1. \qquad J_X^\mu = \overline{\psi_+}\gamma^\mu\psi_- = \overline{\psi_2}\gamma^\mu\psi_1$$

Light Dark Matter

Models of Co-Annihilation — inelastic Dark Matter



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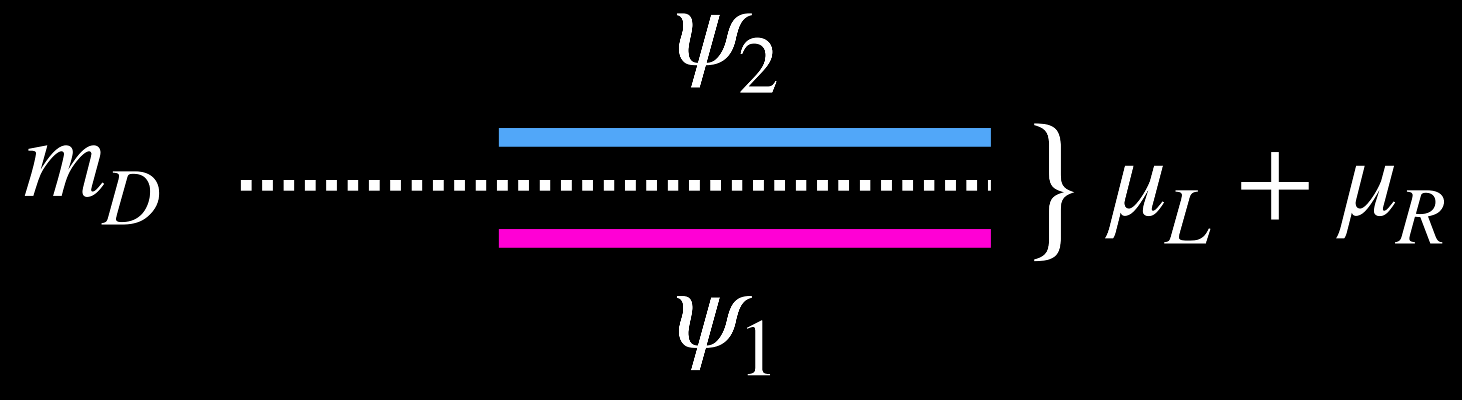
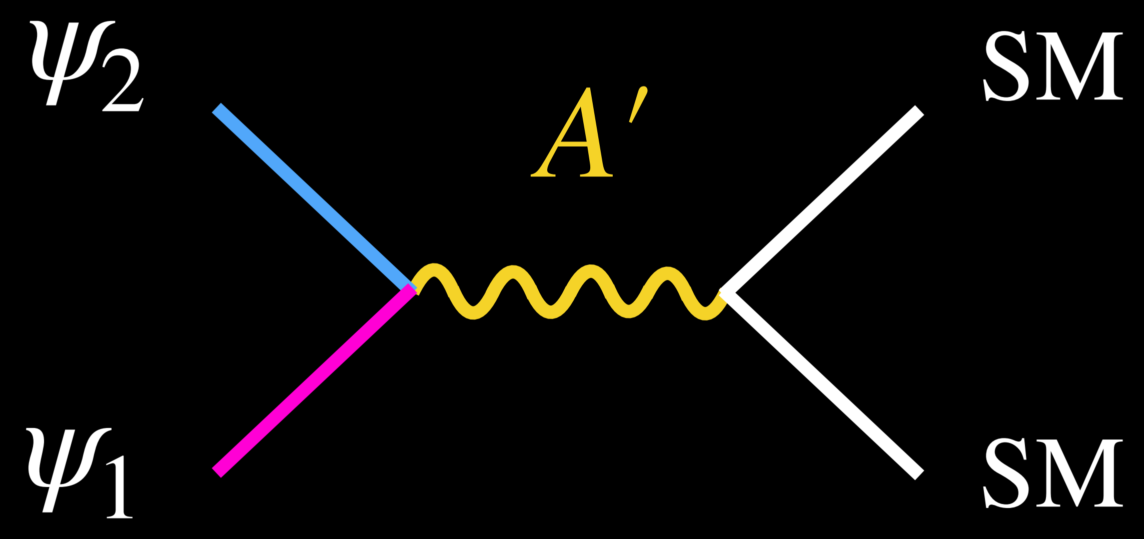
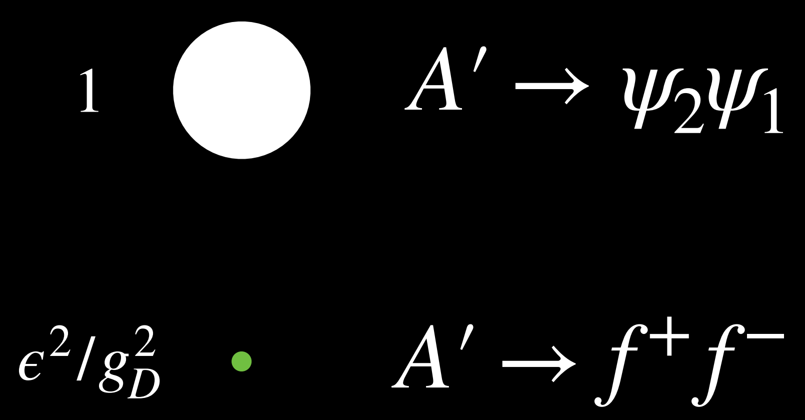


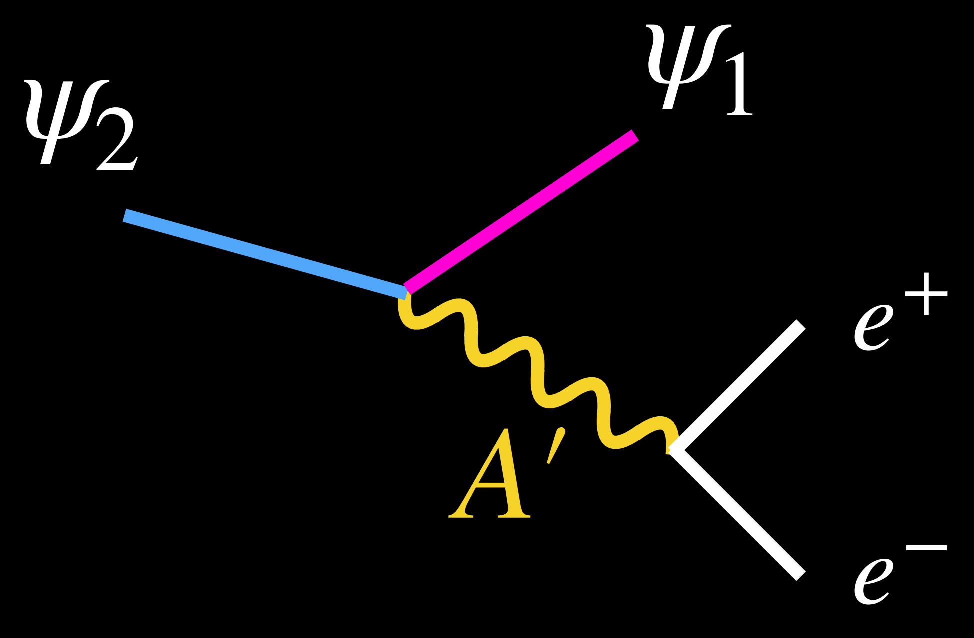
$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2} \begin{pmatrix} \overline{\chi_L} & \overline{\chi_R^c} \end{pmatrix} \begin{pmatrix} \mu & m_D \\ m_D & \mu \end{pmatrix} \begin{pmatrix} \chi_L^c \\ \chi_R \end{pmatrix}$$



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

Dark photon decay branching ratios:





Models of Heavy Neutral Fermions (HNFs)

Model 2 — Mixed Inelastic Dark Matter

Light Dark Matter

Mixed Inelastic Dark Matter — mixed iDM

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 a Majorana fermion, breaking $U(1)_X$ by 1 unit.

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

Or heavy neutrino $L\tilde{H}\eta_L^c$?

Light Dark Matter

Mixed Inelastic Dark Matter — mixed iDM

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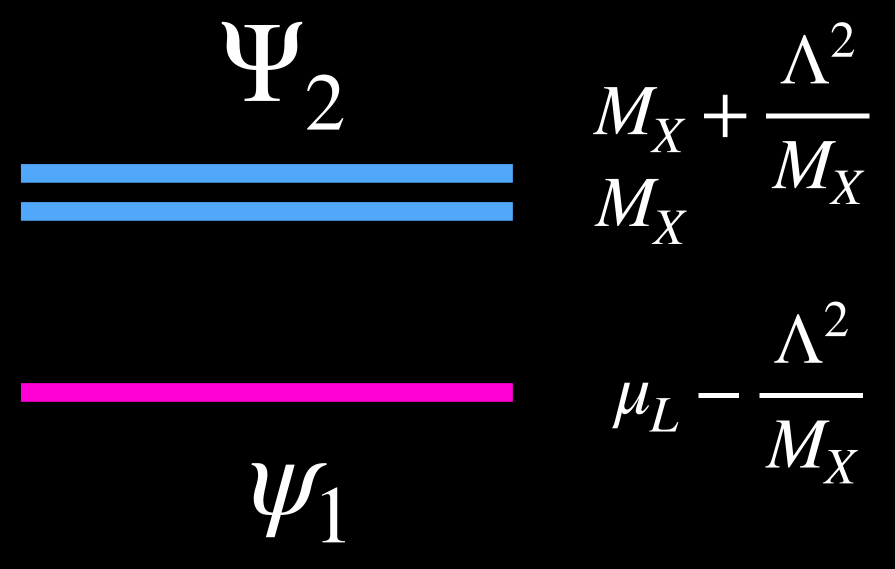

$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2}\left(\overline{\eta_L} \quad \overline{\chi_L} \quad \overline{\chi_R^c}\right)\begin{pmatrix}\mu_L & \Lambda & \Lambda \\ \Lambda & 0 & M_X \\ \Lambda & M_X & 0\end{pmatrix}\begin{pmatrix}\eta_L^c \\ \chi_L^c \\ \chi_R\end{pmatrix} \longrightarrow \begin{pmatrix}\mu_L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

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

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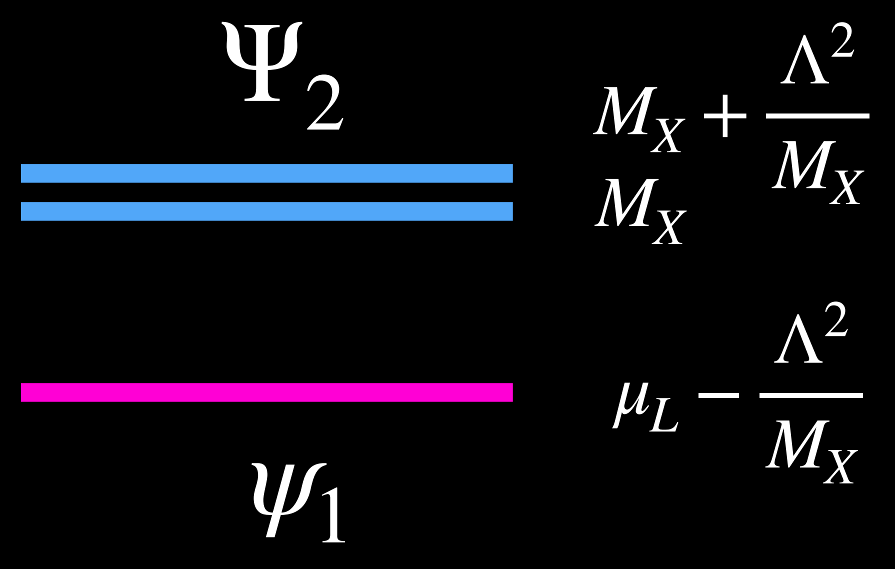


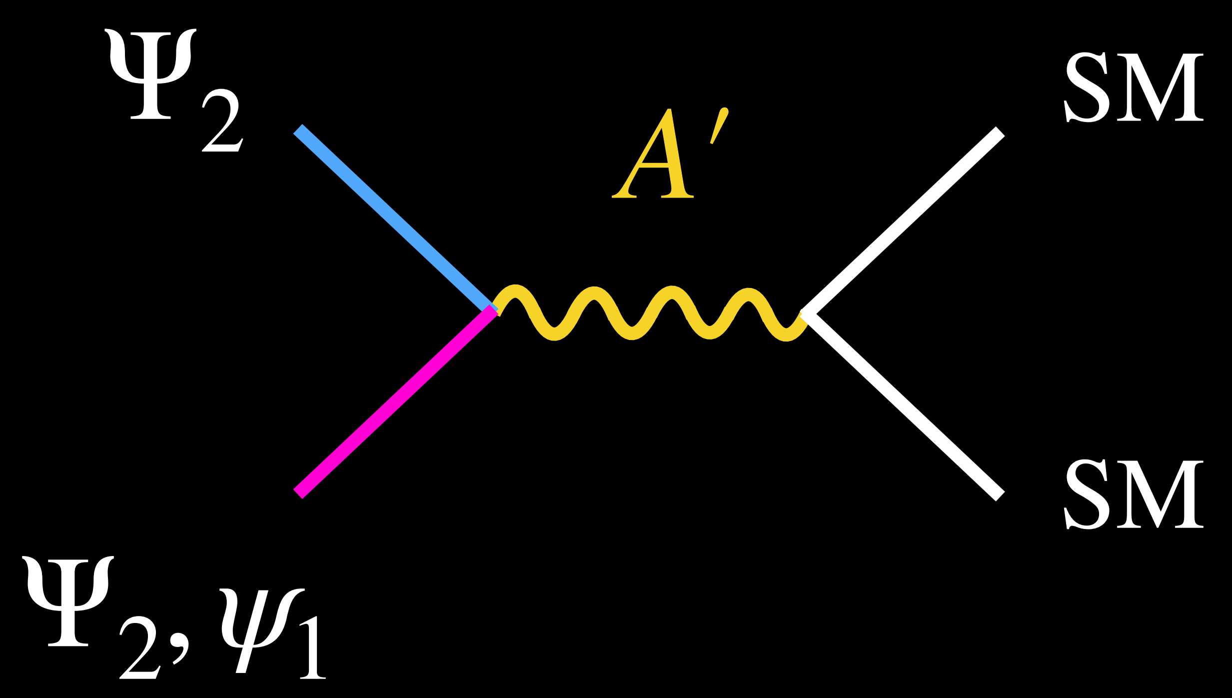
$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2}\left(\overline{\eta_L} \quad \overline{\chi_L} \quad \overline{\chi_R^c}\right)\begin{pmatrix} \mu_L & \Lambda & \Lambda \\ \Lambda & 0 & M_X \\ \Lambda & M_X & 0 \end{pmatrix}\begin{pmatrix} \eta_L^c \\ \chi_L^c \\ \chi_R \end{pmatrix} \longrightarrow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

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

$$\tan 2\theta = \frac{2\Lambda}{M_X - \mu_L}$$

Dark photon decay branching ratios:

- 1 — $A' \to \Psi_2 \Psi_2$
- θ^2 — $A' \to \psi_1 \Psi_2$
- 0 — $A' \not\to \psi_1 \psi_1$
- ϵ^2 / g_D^2 — $A' \to f^+ f^-$



Models of Heavy Neutral Fermions (HNFs)

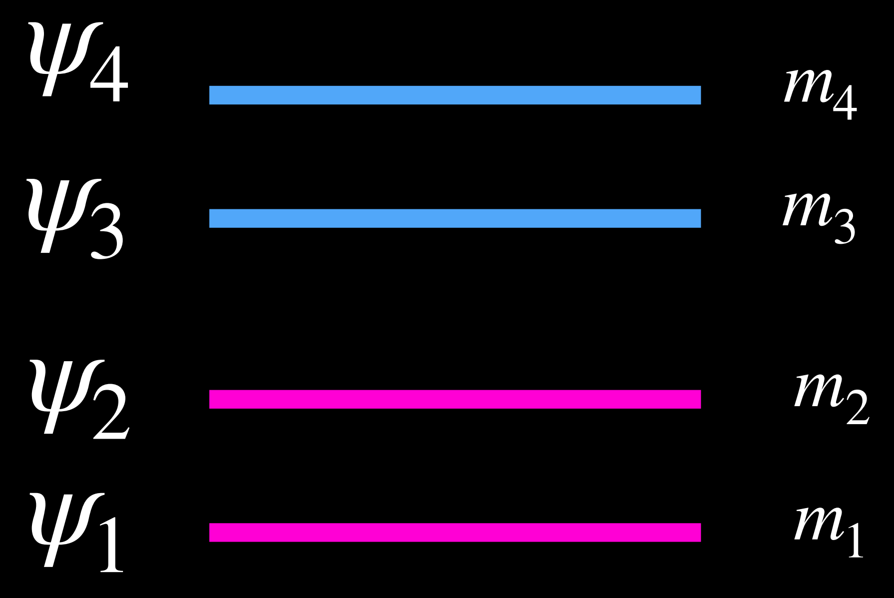
Model 3 — Inelastic Dirac Dark Matter

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.

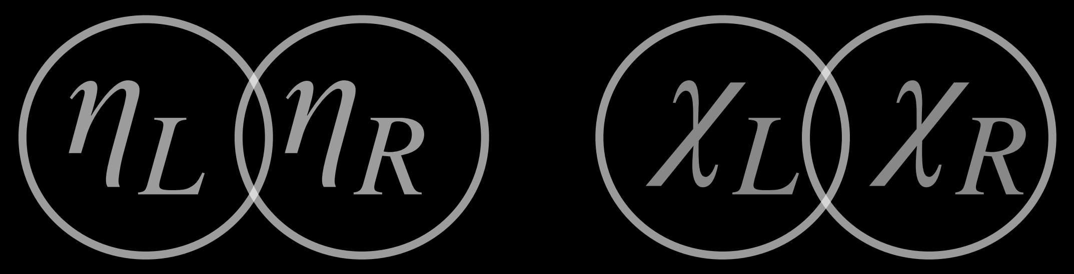
$$\mathscr{L}_{\rm mass} \supset \frac{1}{2}\begin{pmatrix}\overline{\eta_L} & \overline{\eta_R^c} & \overline{\chi_L} & \overline{\chi_R^c}\end{pmatrix}\begin{pmatrix} 0 & M_1 & 0 & M_L \\ M_1 & 0 & M_R & 0 \\ 0 & M_R & 0 & M_2 \\ M_L & 0 & M_2 & 0 \end{pmatrix}\begin{pmatrix}\eta_L^c \\ \eta_R \\ \chi_L^c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



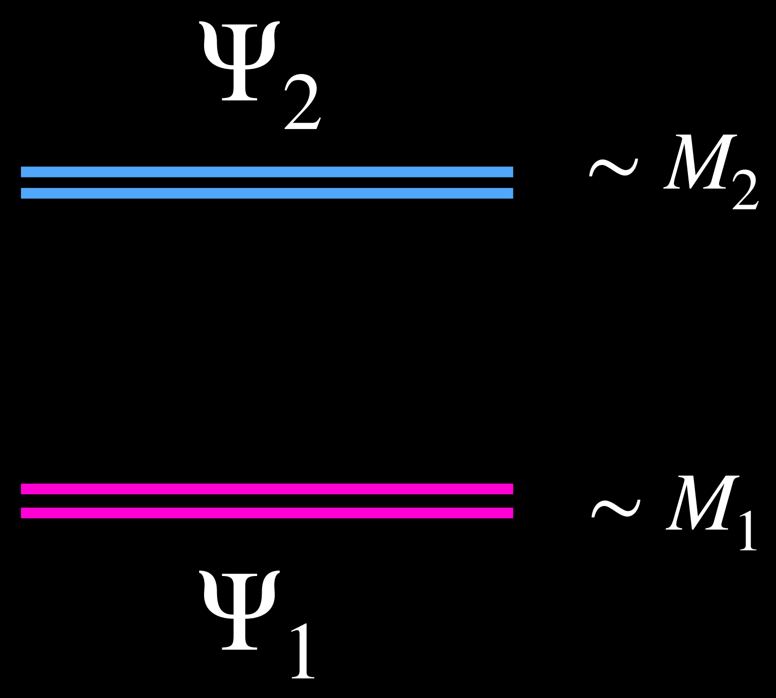
Or heavy neutrinos $L\tilde{H}\eta_R$ and $L\tilde{H}\eta_L^c$?

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.

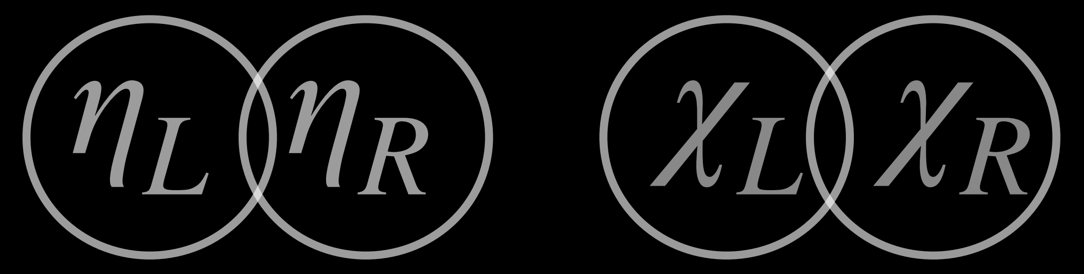


$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2} \begin{pmatrix} \overline{\eta_L} & \overline{\chi_L} \end{pmatrix} \begin{pmatrix} M_1 & M_R \\ M_L & M_2 \end{pmatrix} \begin{pmatrix} \eta_R \\ \chi_R \end{pmatrix}$$

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

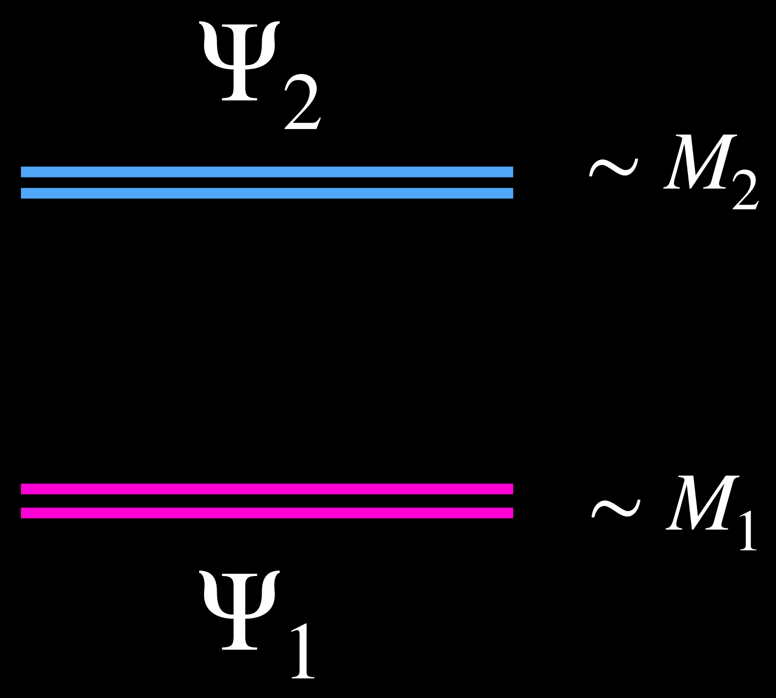
Light Dark Matter

Inelastid Dirac Dark Matter — i2DM



A. Filomonova et al, arXiv:2201.08409

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



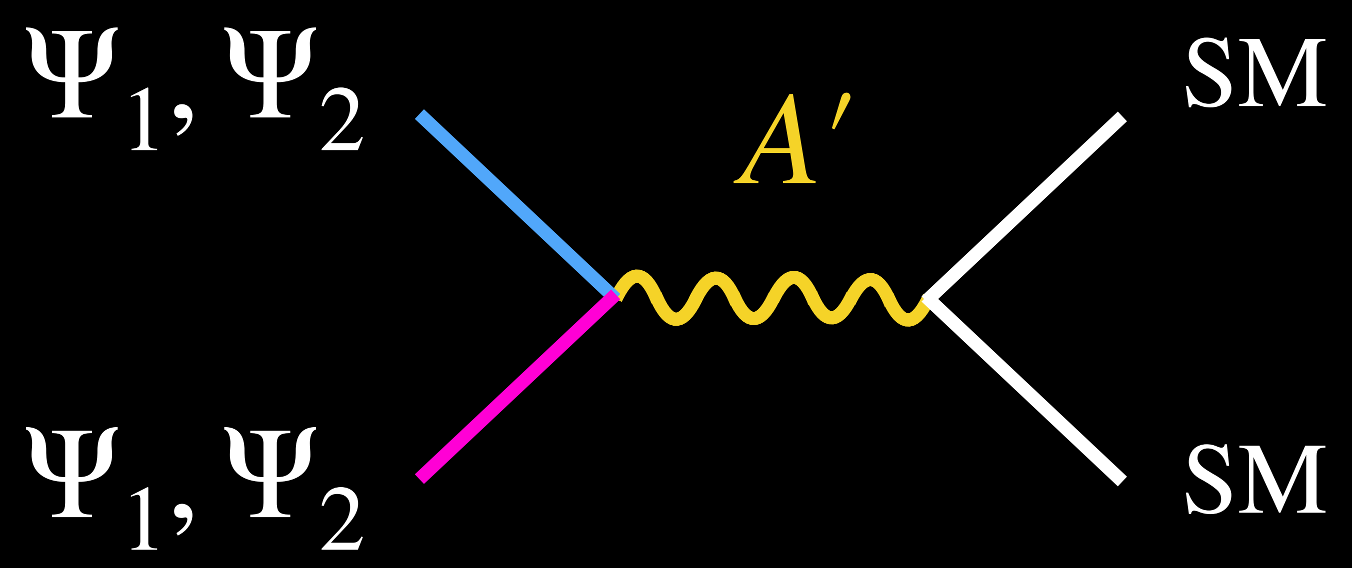
$$\mathscr{L}_{\text{mass}} \supset \frac{1}{2} (\overline{\eta_L} \quad \overline{\chi_L}) \begin{pmatrix} M_1 & M_R \\ M_L & M_2 \end{pmatrix} \begin{pmatrix} \eta_R \\ \chi_R \end{pmatrix}$$

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

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 — $A' \to f^+f^-$



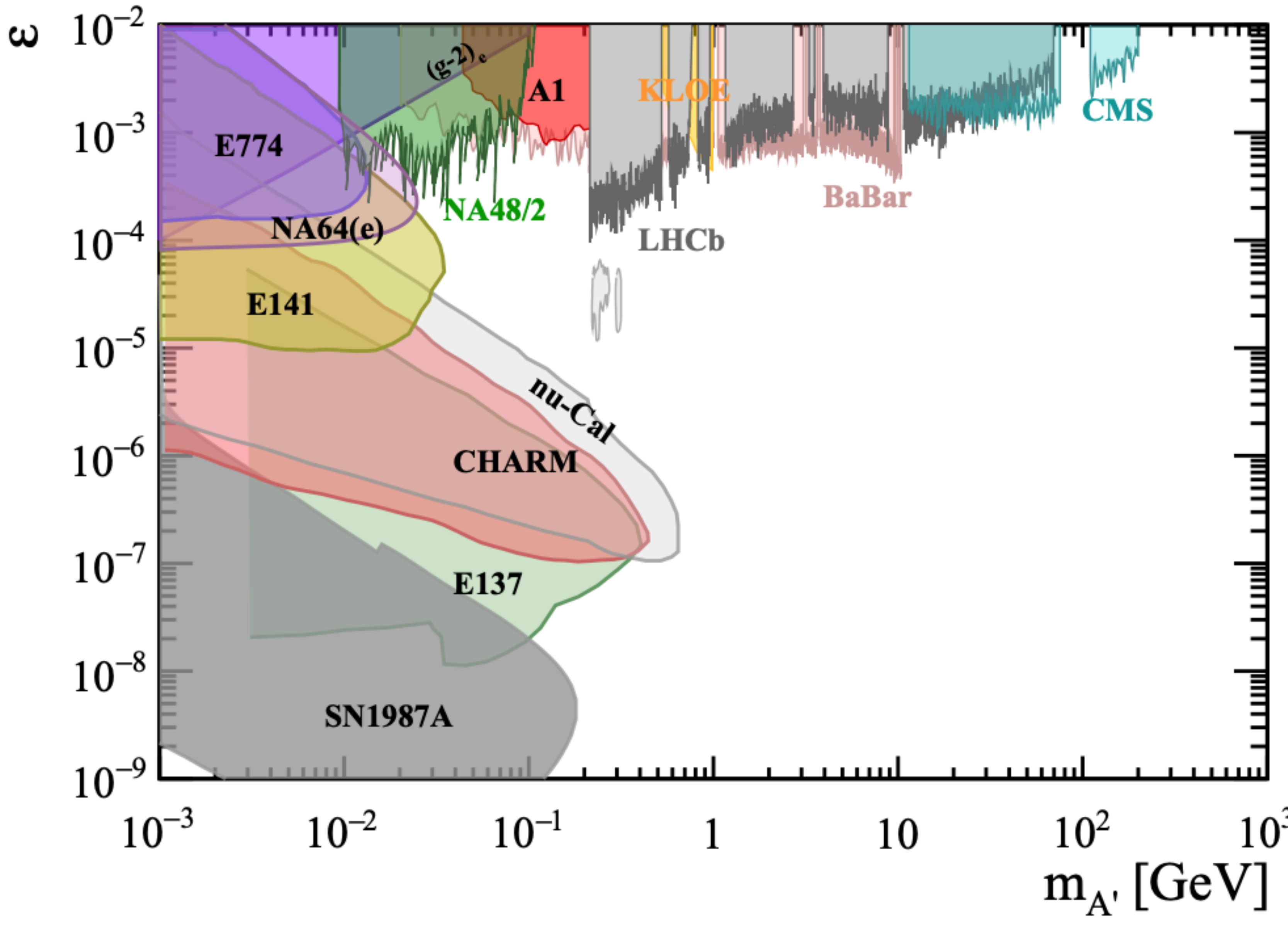
Phenomenology

Semi-visible dark photons

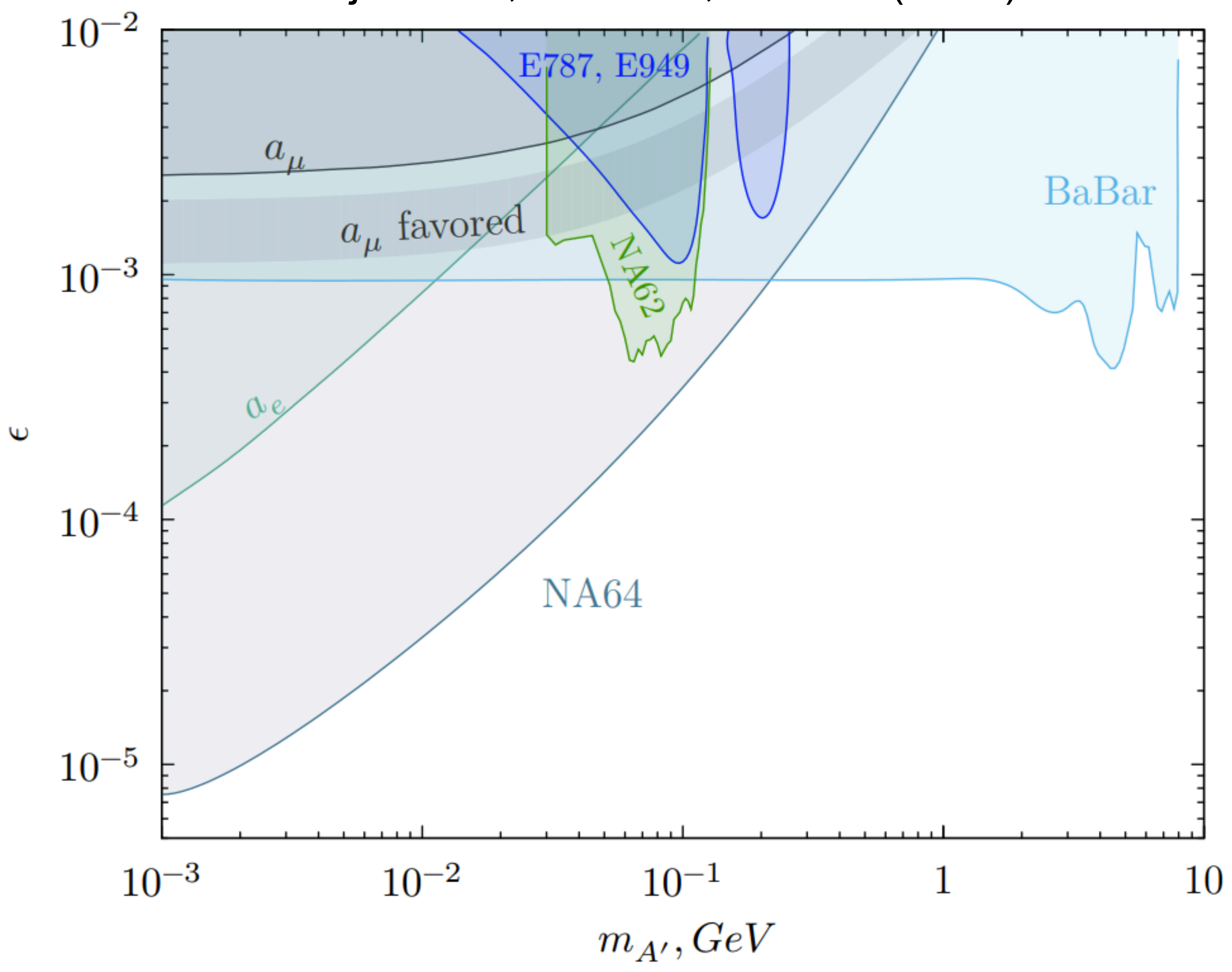
Dark Photons

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

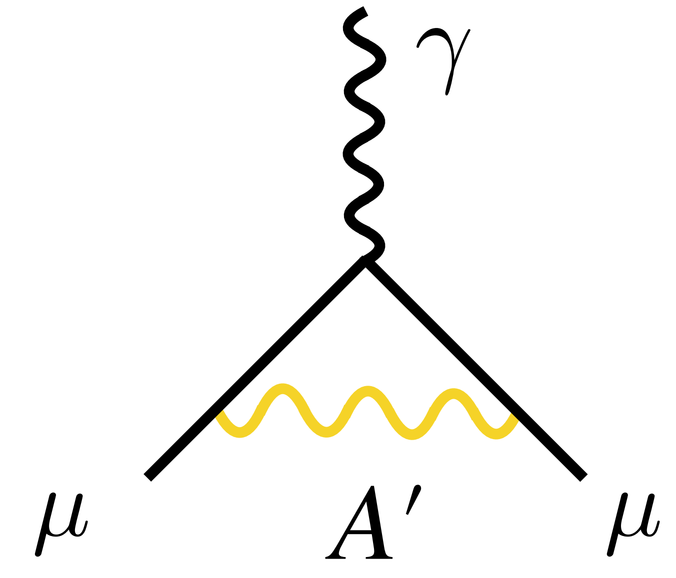
M. Fabbrichesi et al,
SpringerBriefs in Physics 2020, 2005.01515



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



Hypothetical vector bosons contribute positively:



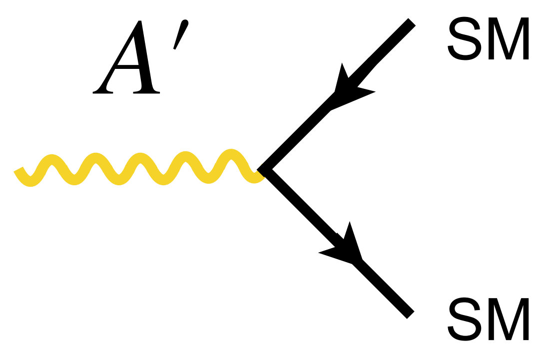
$$\Delta a_\mu^{A'} \sim \frac{\varepsilon^2 \alpha}{3\pi} \frac{m_\mu^2}{m_{A'}}$$

for

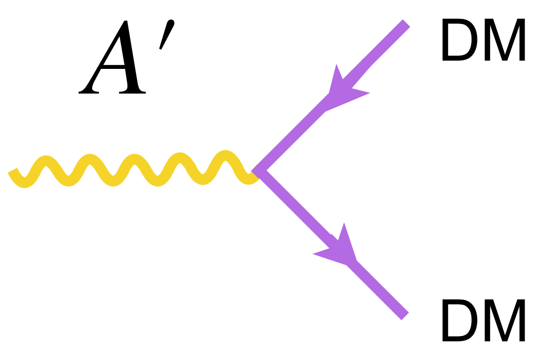
$$m_\mu \ll m_{A'}$$

Pospelov, PRD80:095002,2009

Visible:



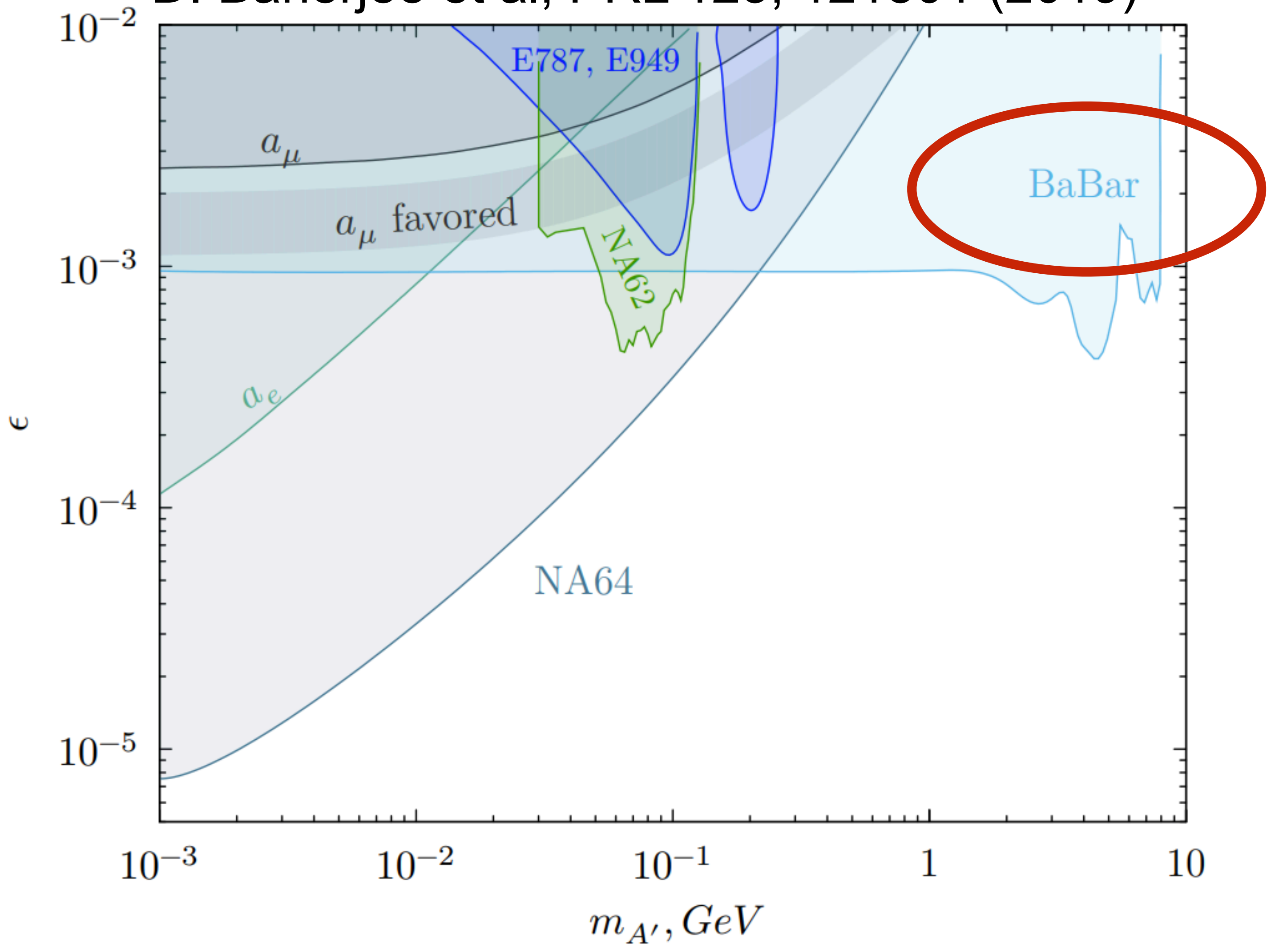
Invisible:



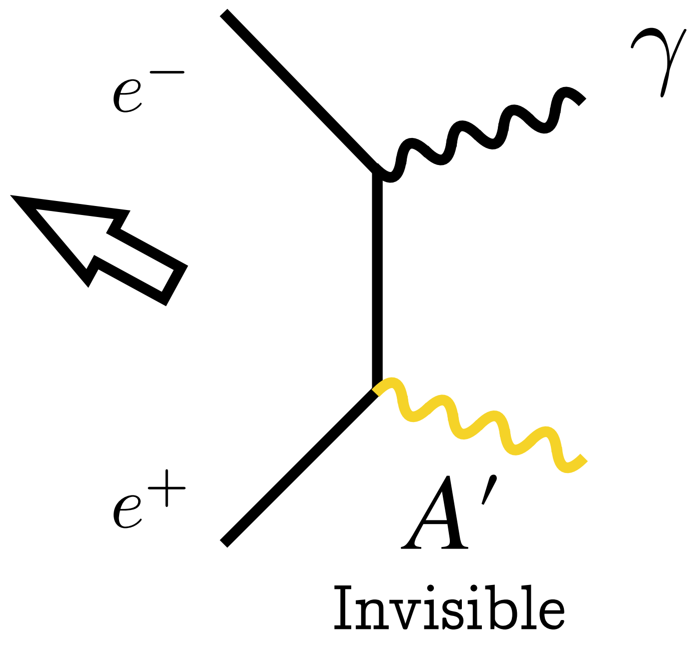
Dark Photons at BaBar

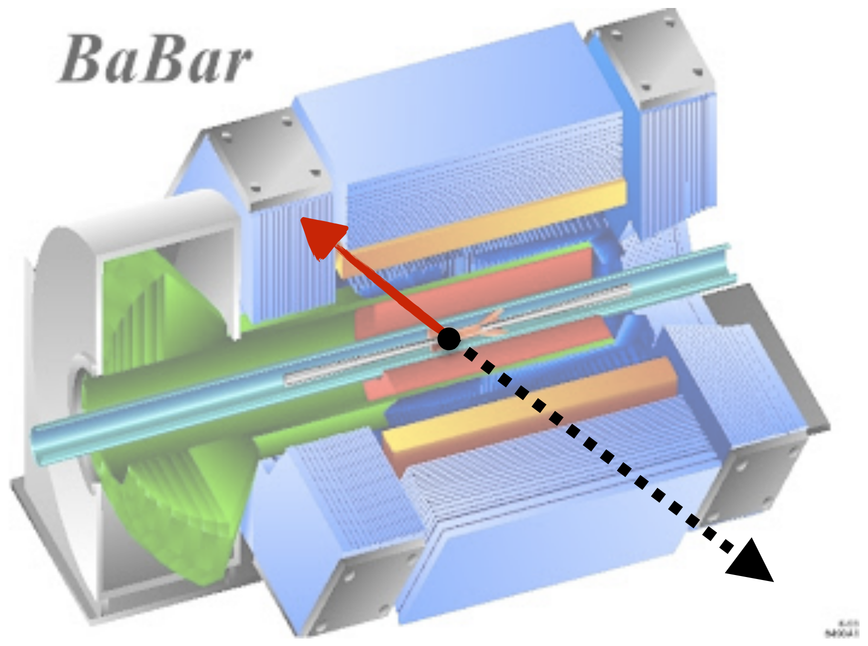
Initial state radiation searches (monophotons)

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



ISR monophoton





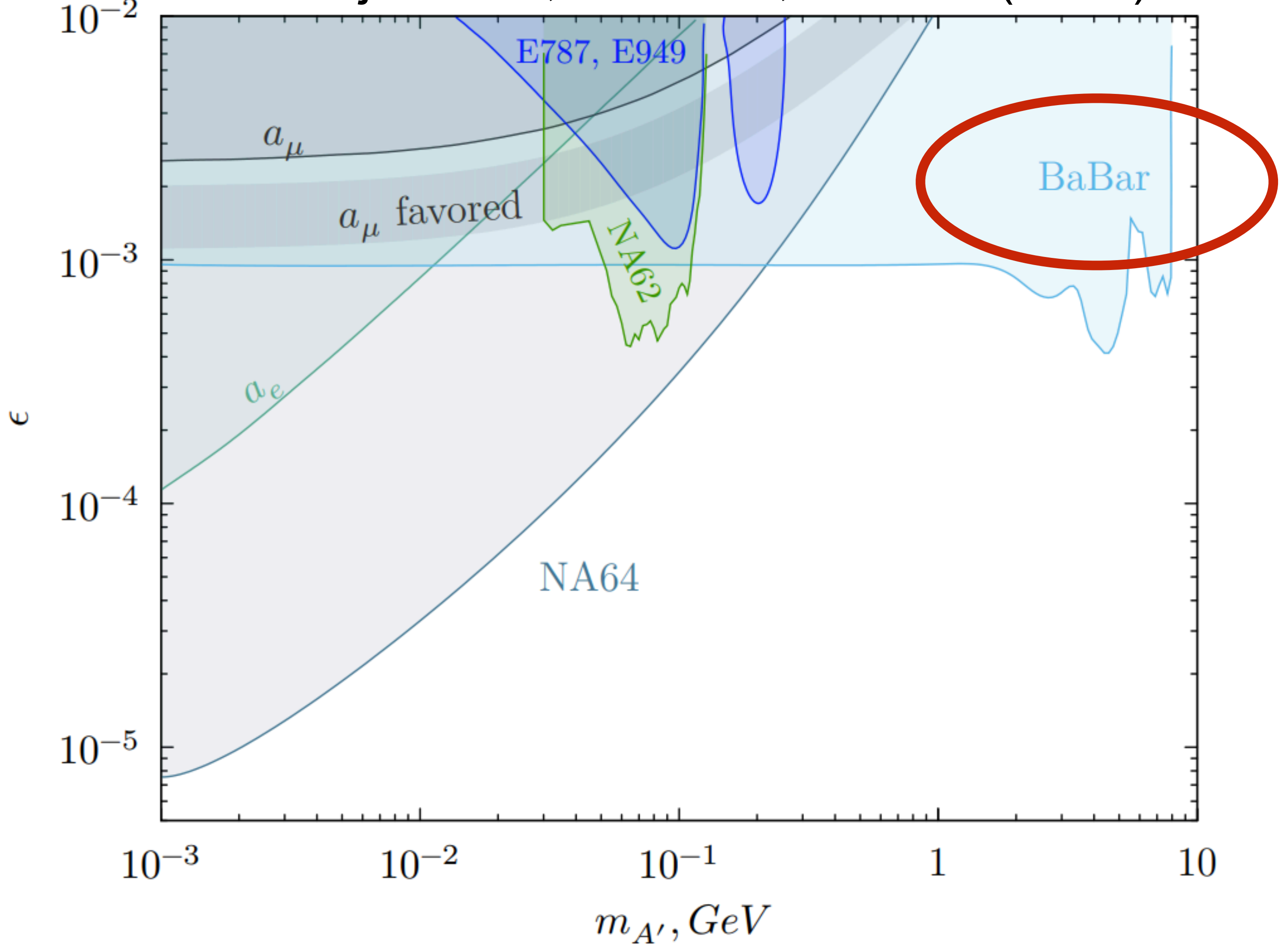
A single photon recoiling against an invisible massive particle. Dark photon mass reconstructed as:

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

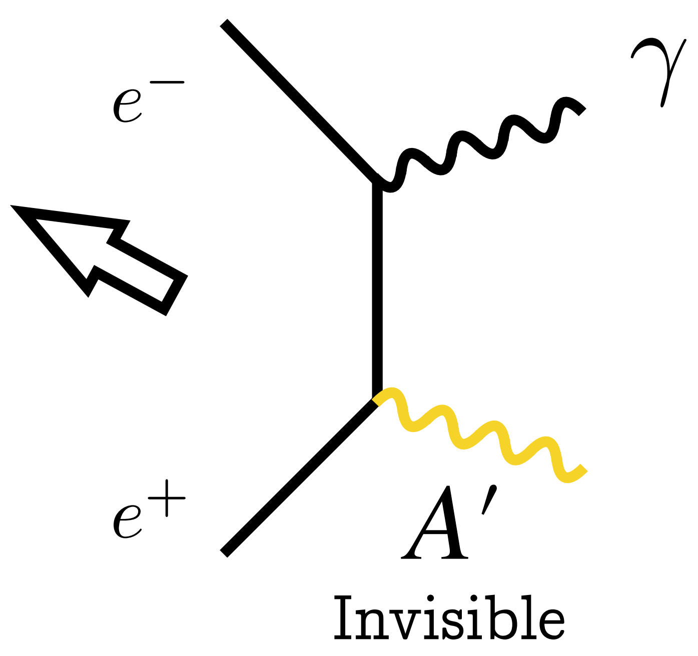
Dark Photons at BaBar

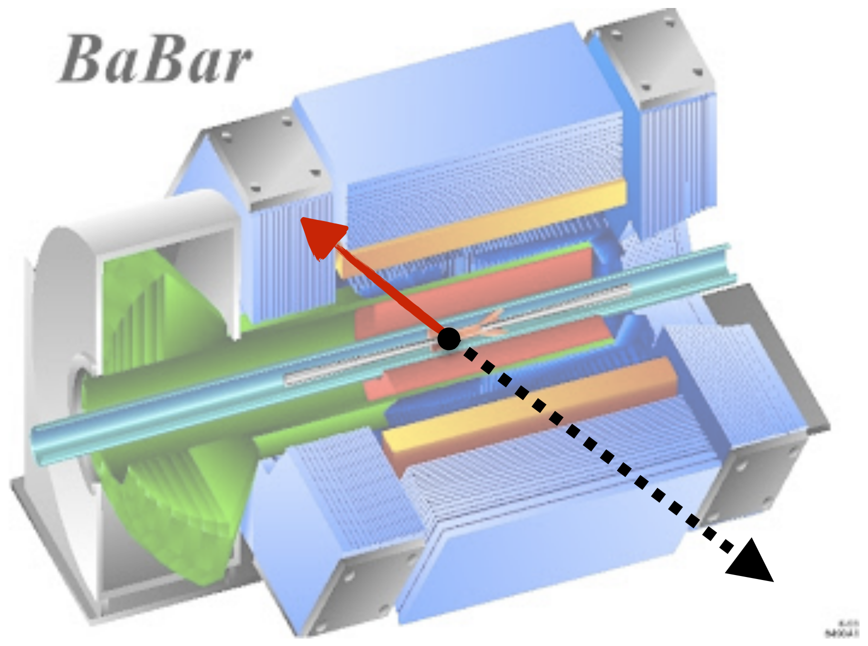
Initial state radiation searches (monophotons)

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

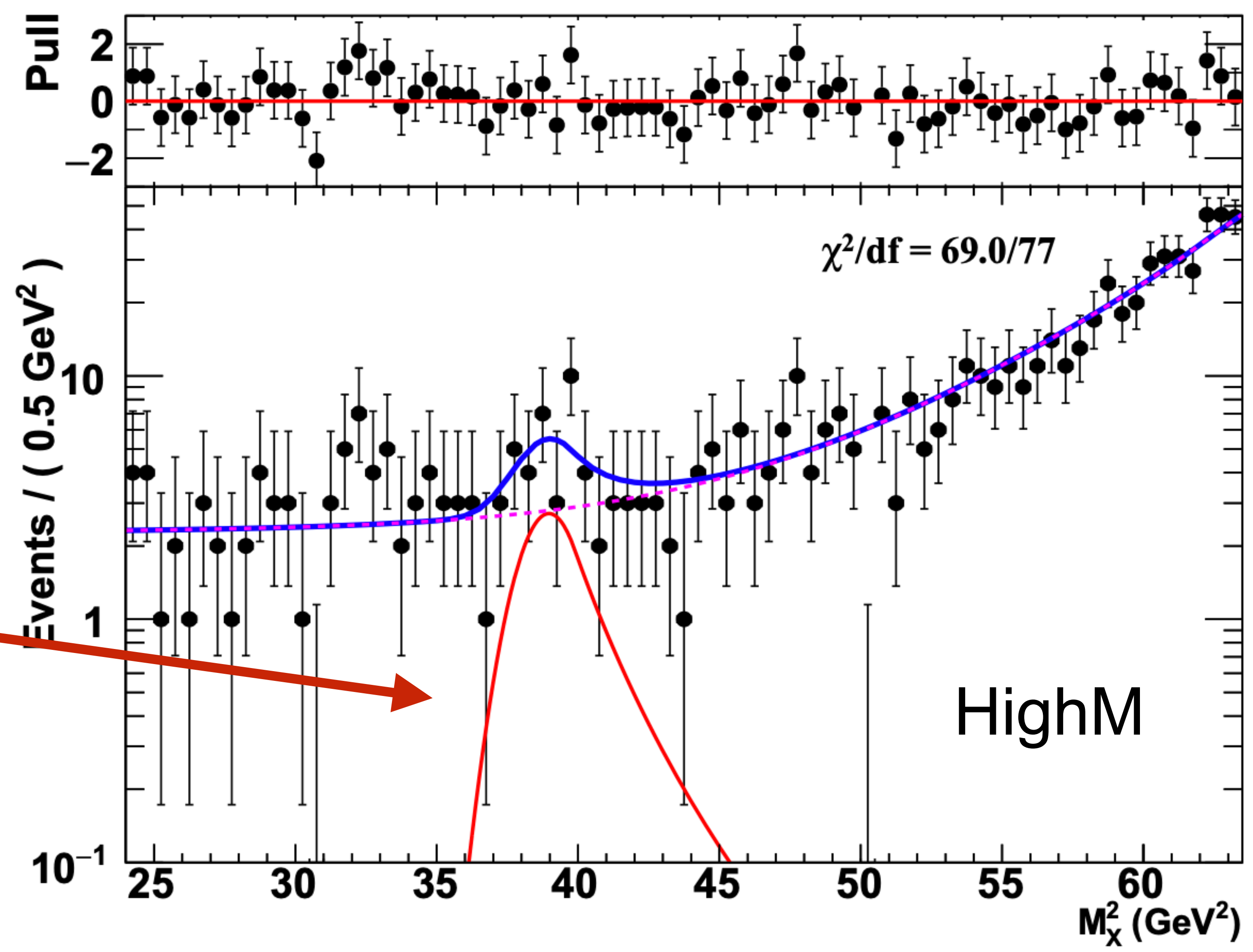


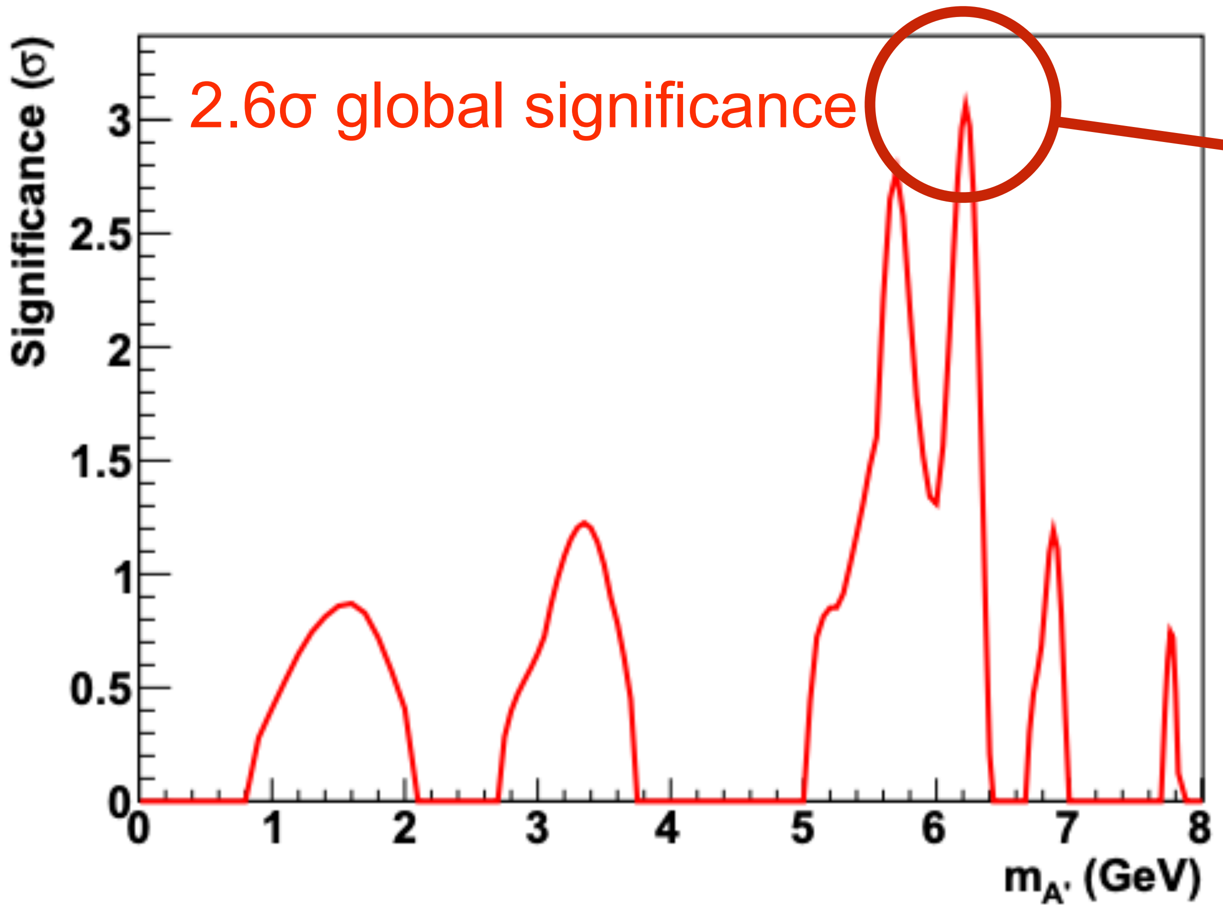
ISR monophoton





BaBar collab., PRL 119, 131804 (2017)





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Dark Photons at BaBar

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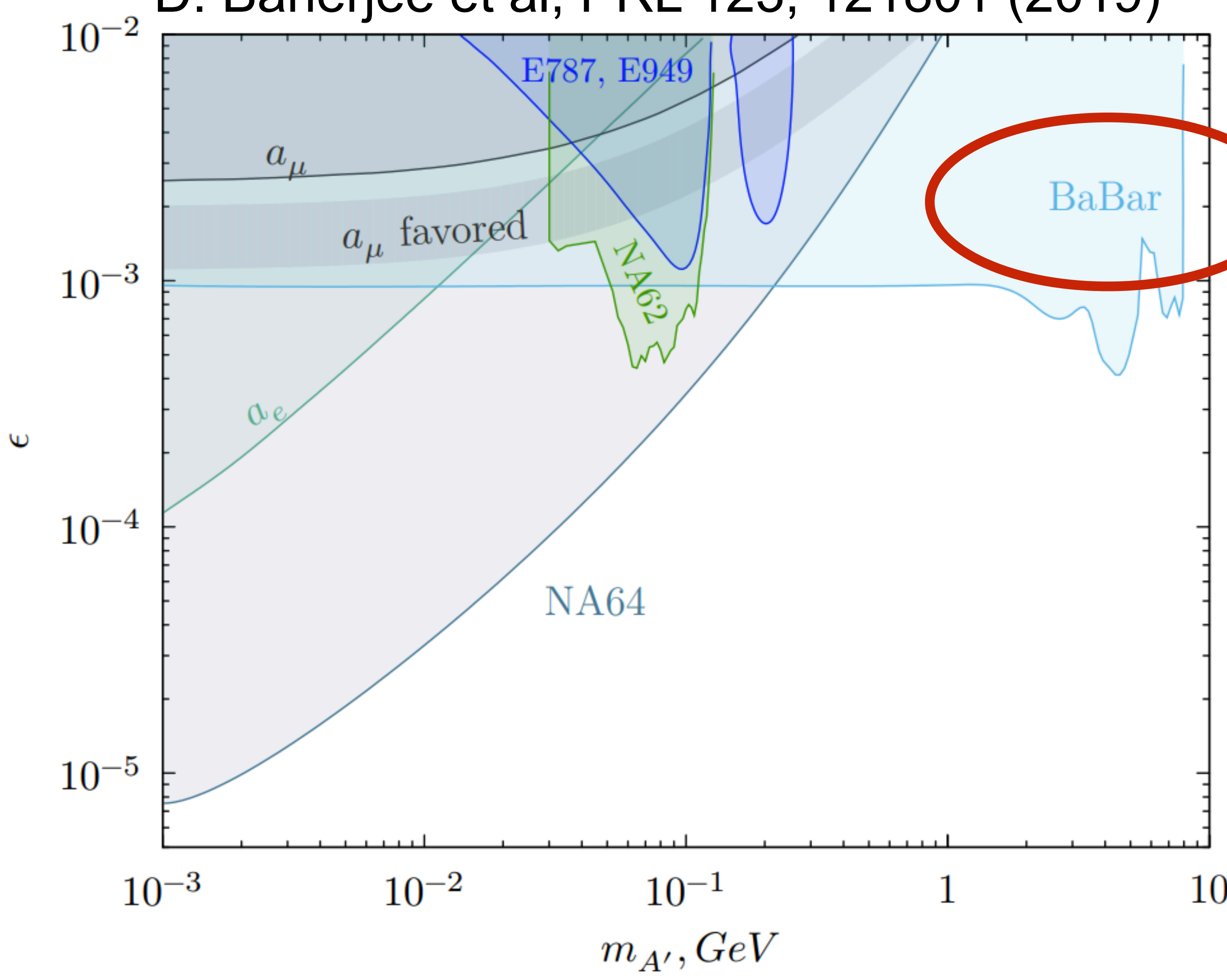
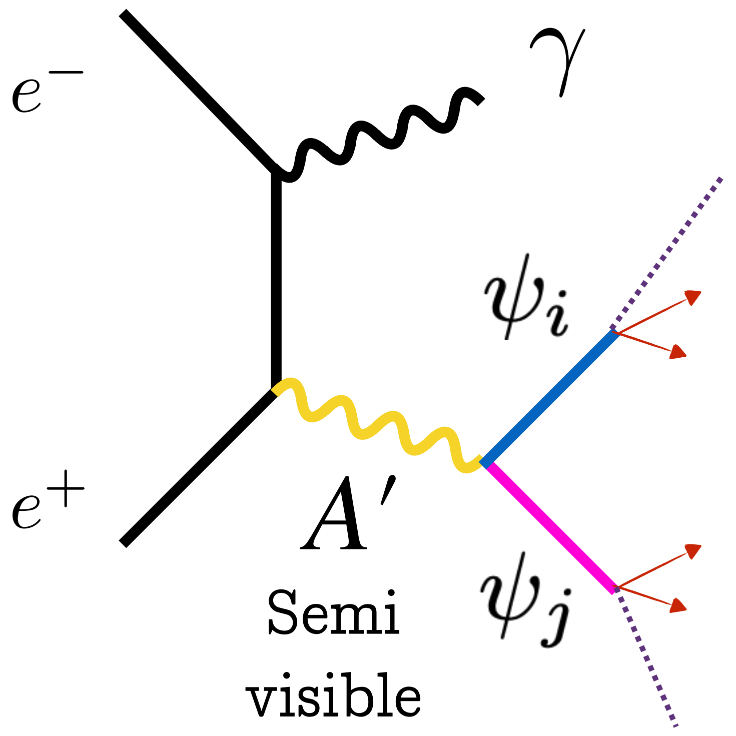
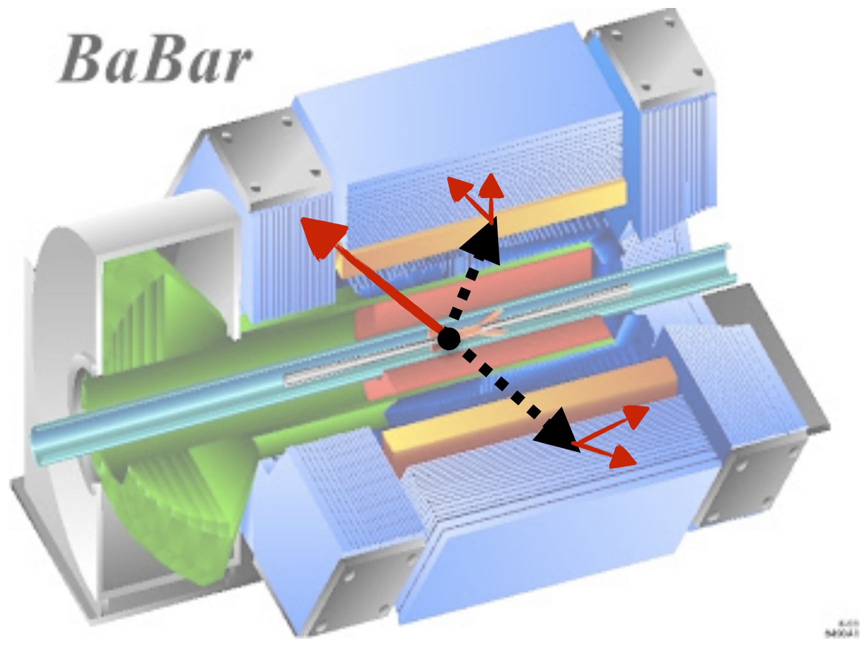
D. Banerjee et al, PRL 123, 121801 (2019)

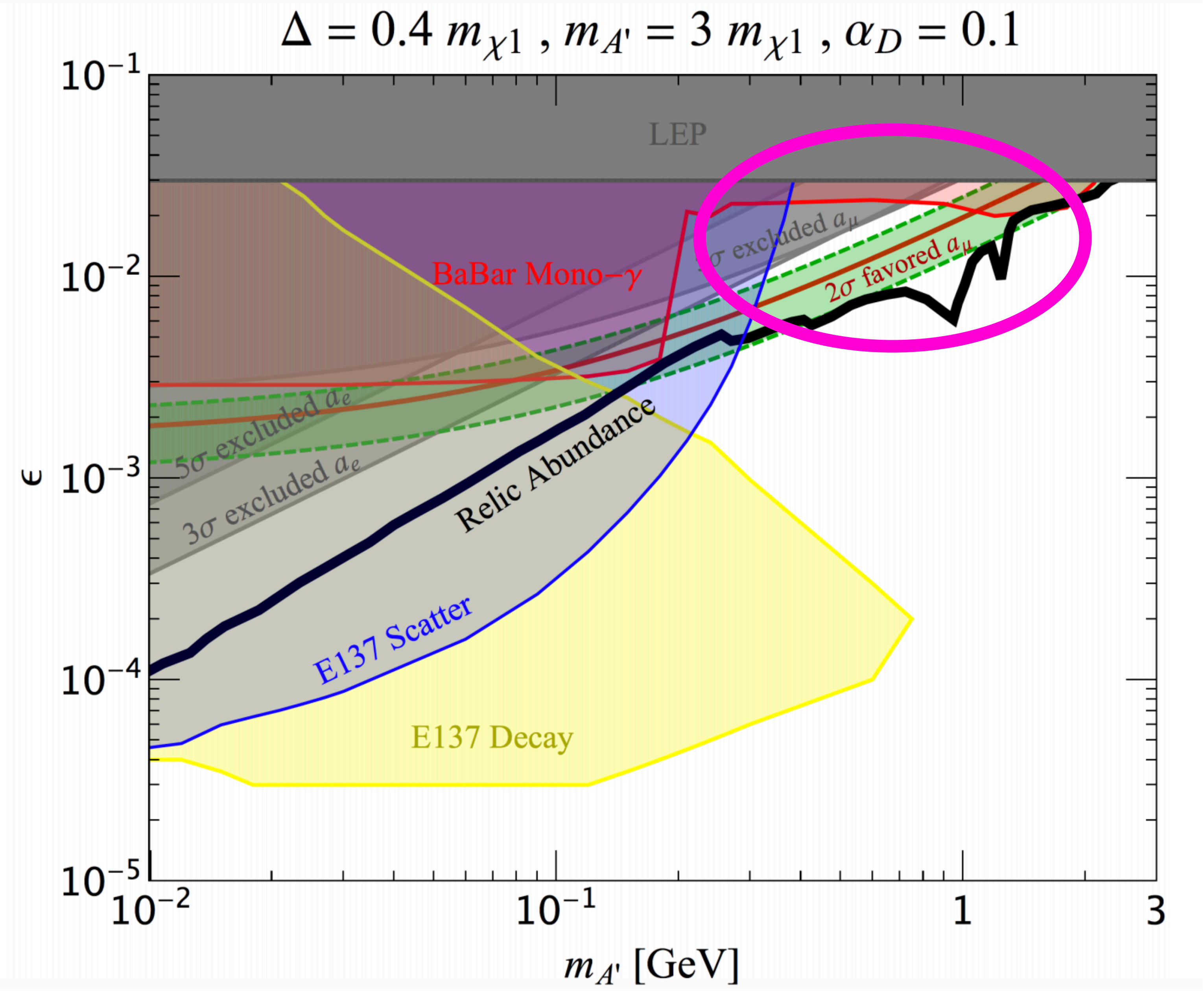


ISR monophoton





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



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

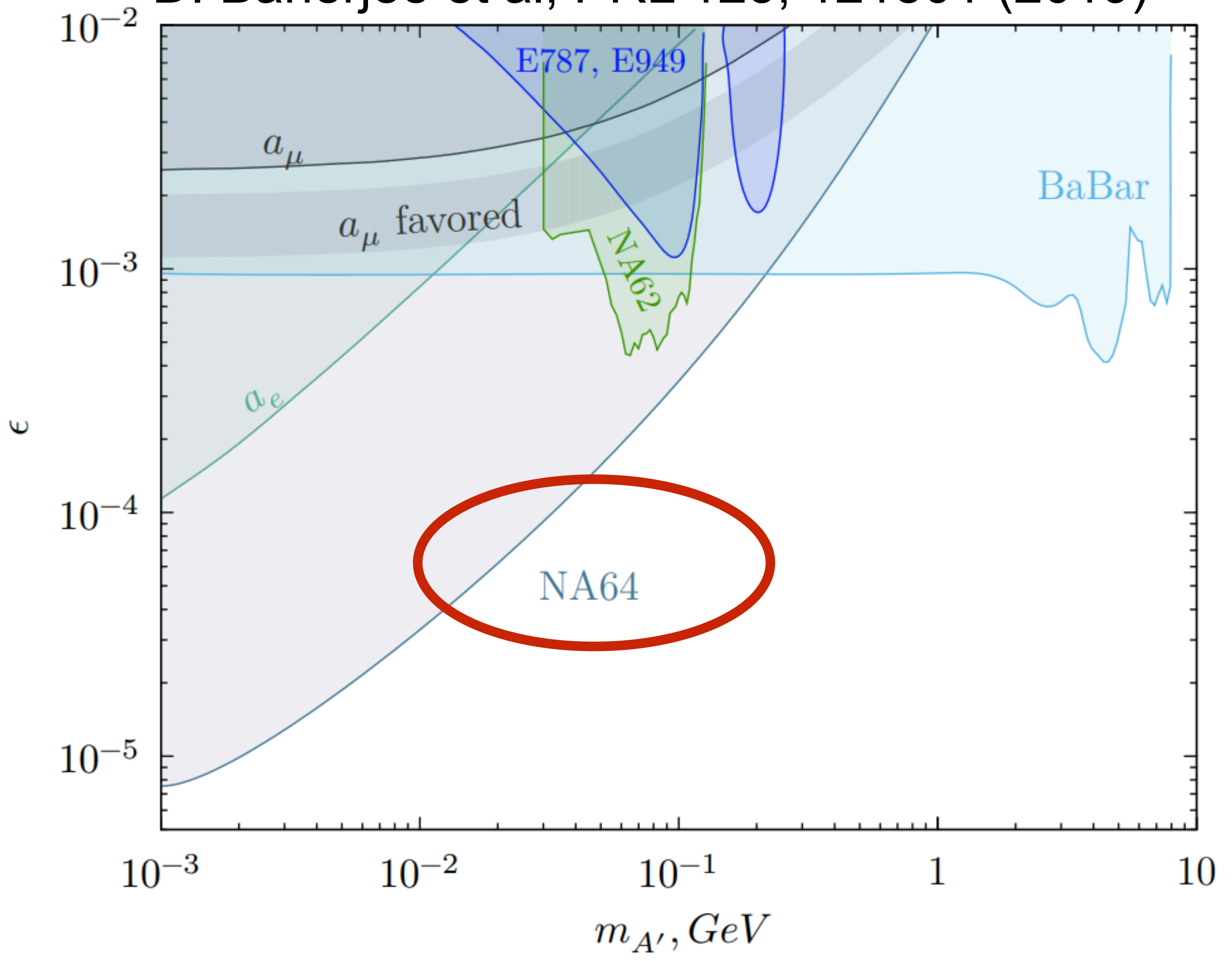
For example, taking $\varepsilon \sim 0.02$, $m_{A'} \sim 1\,\text{GeV}$ we need $P_{\text{missing}\,A'} \lesssim 2.2 \times 10^{-3}$

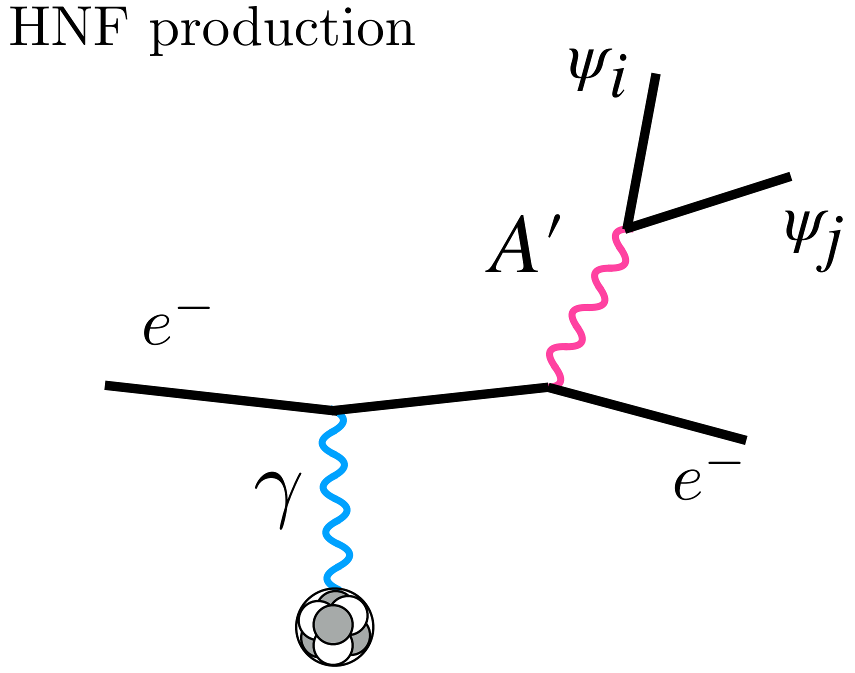
New $(g\text{-}2)_\mu$ region of interest around dark photon masses of 0.3 to 3 GeV.

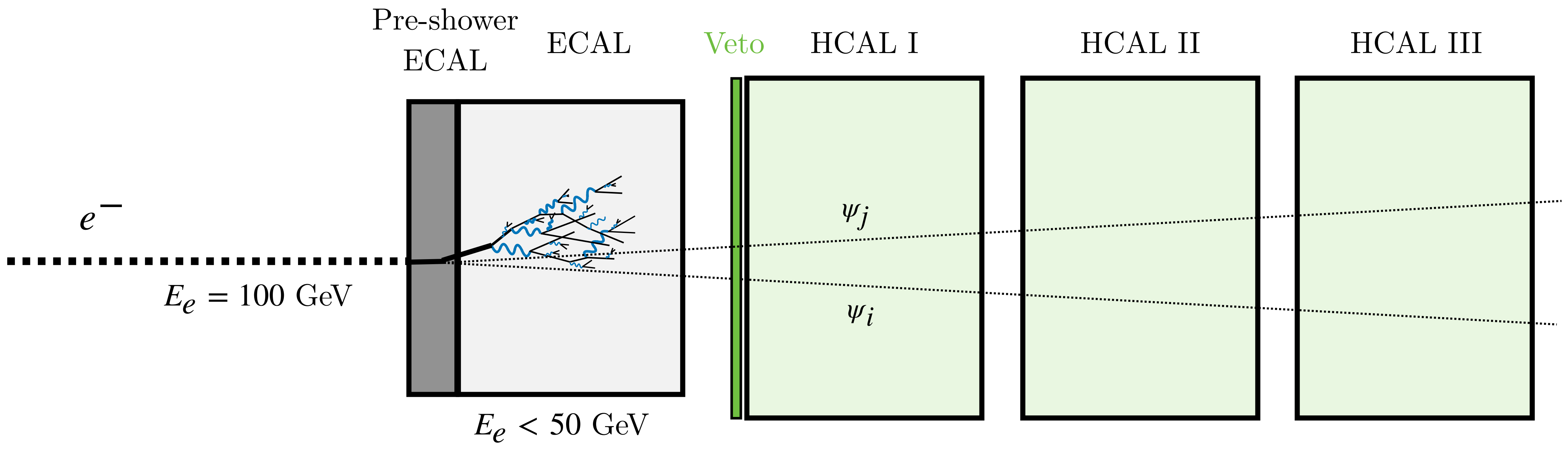
Searches for invisible dark photons at NA64

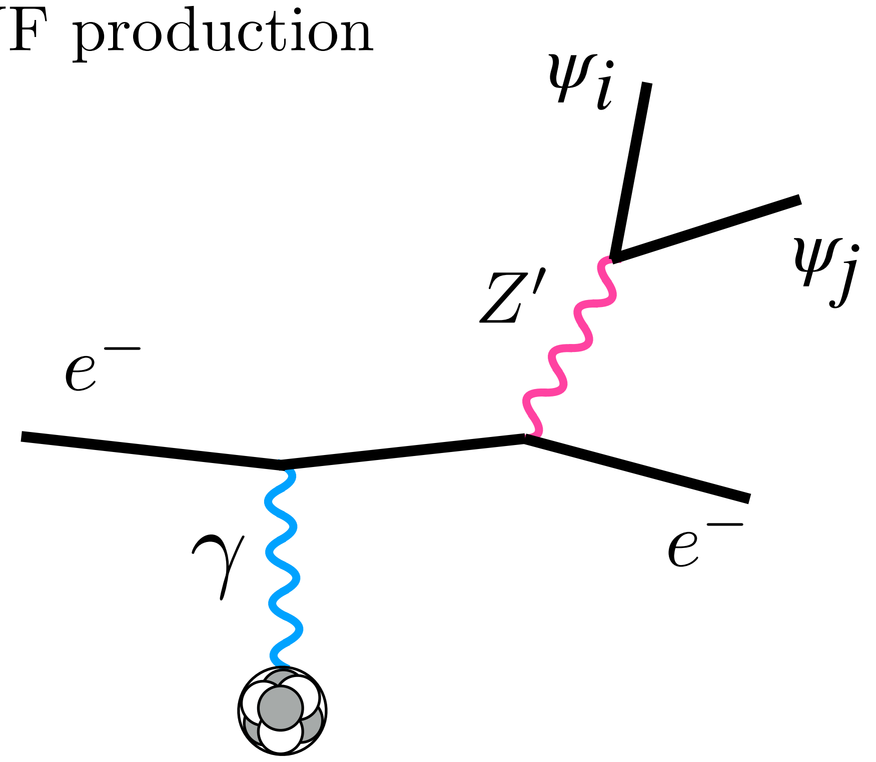
Electrons on target

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







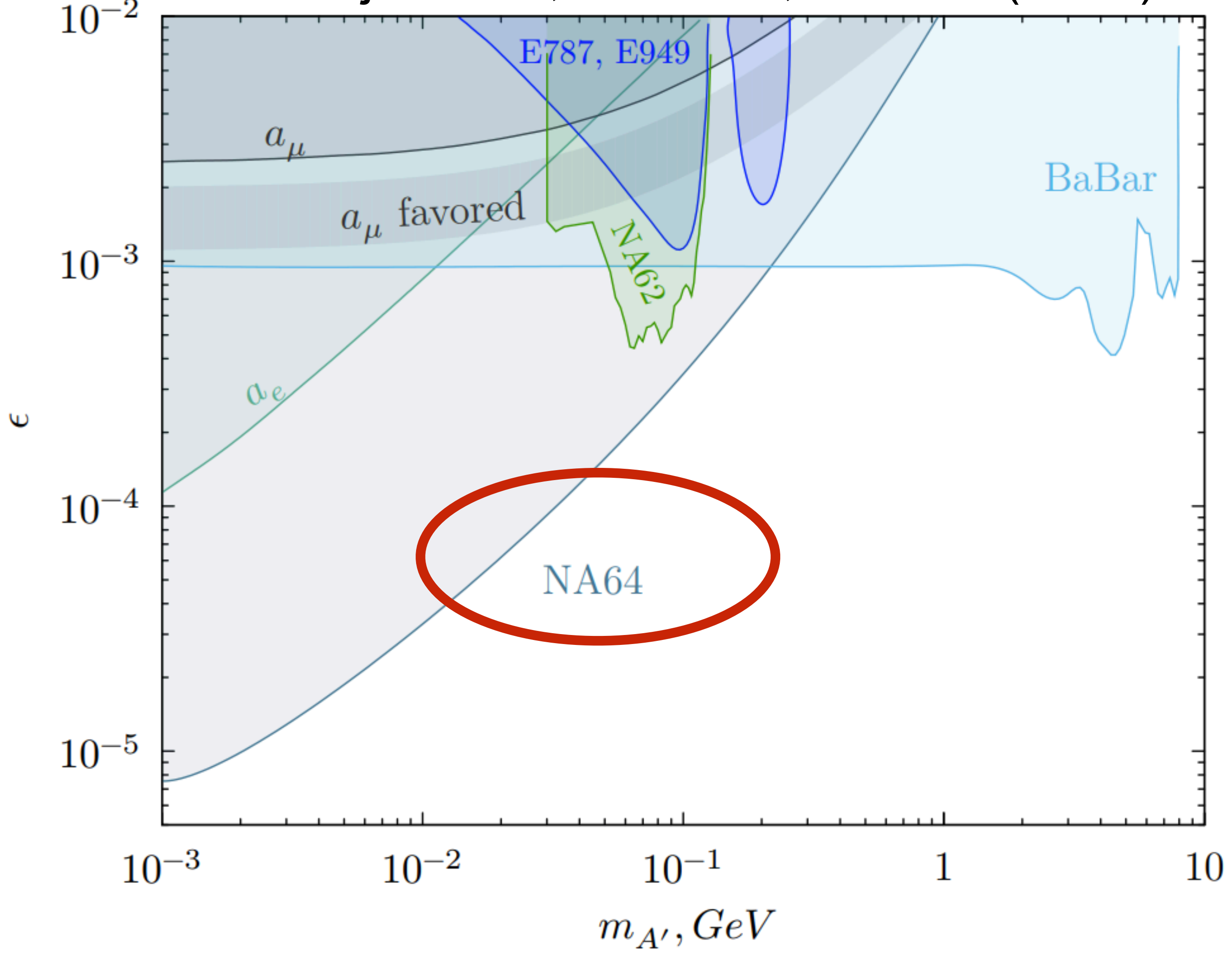


Fixed-target searches for invisible A’ also very sensitive.

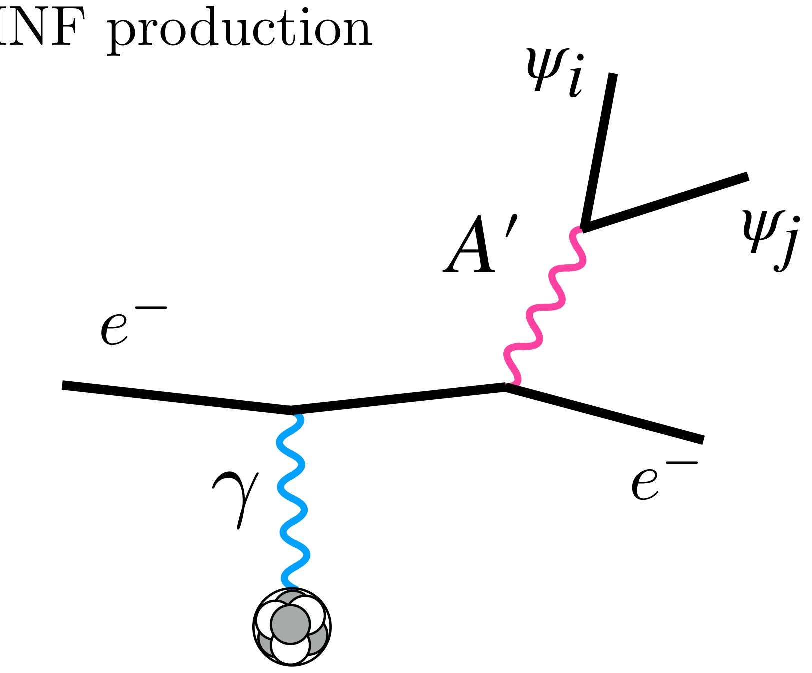
Searches for invisible dark photons at NA64

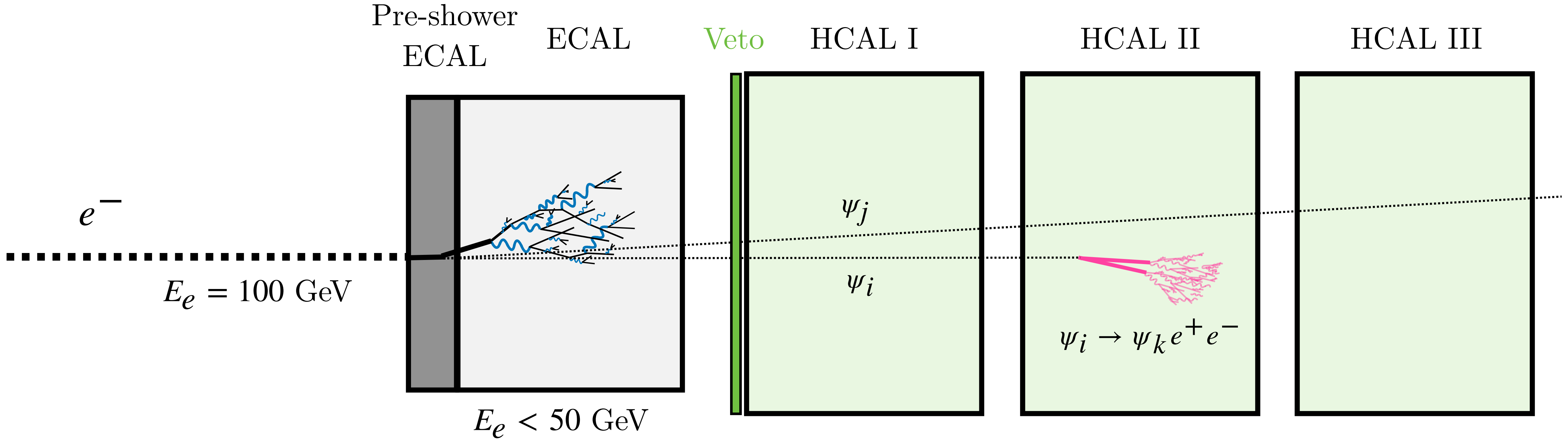
Electrons on target

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

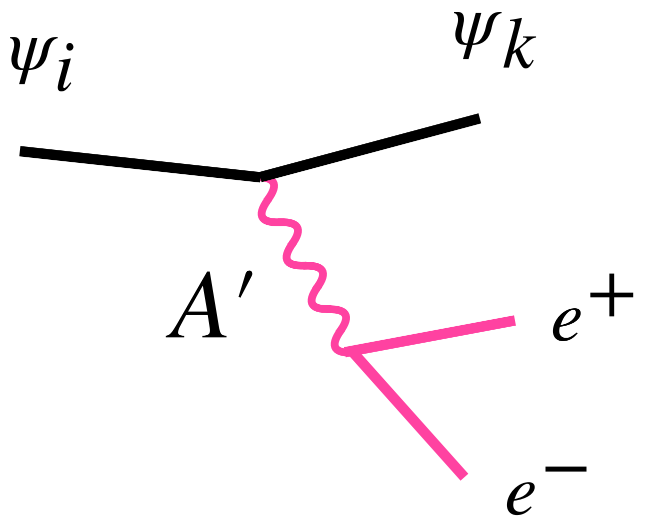


HNF production

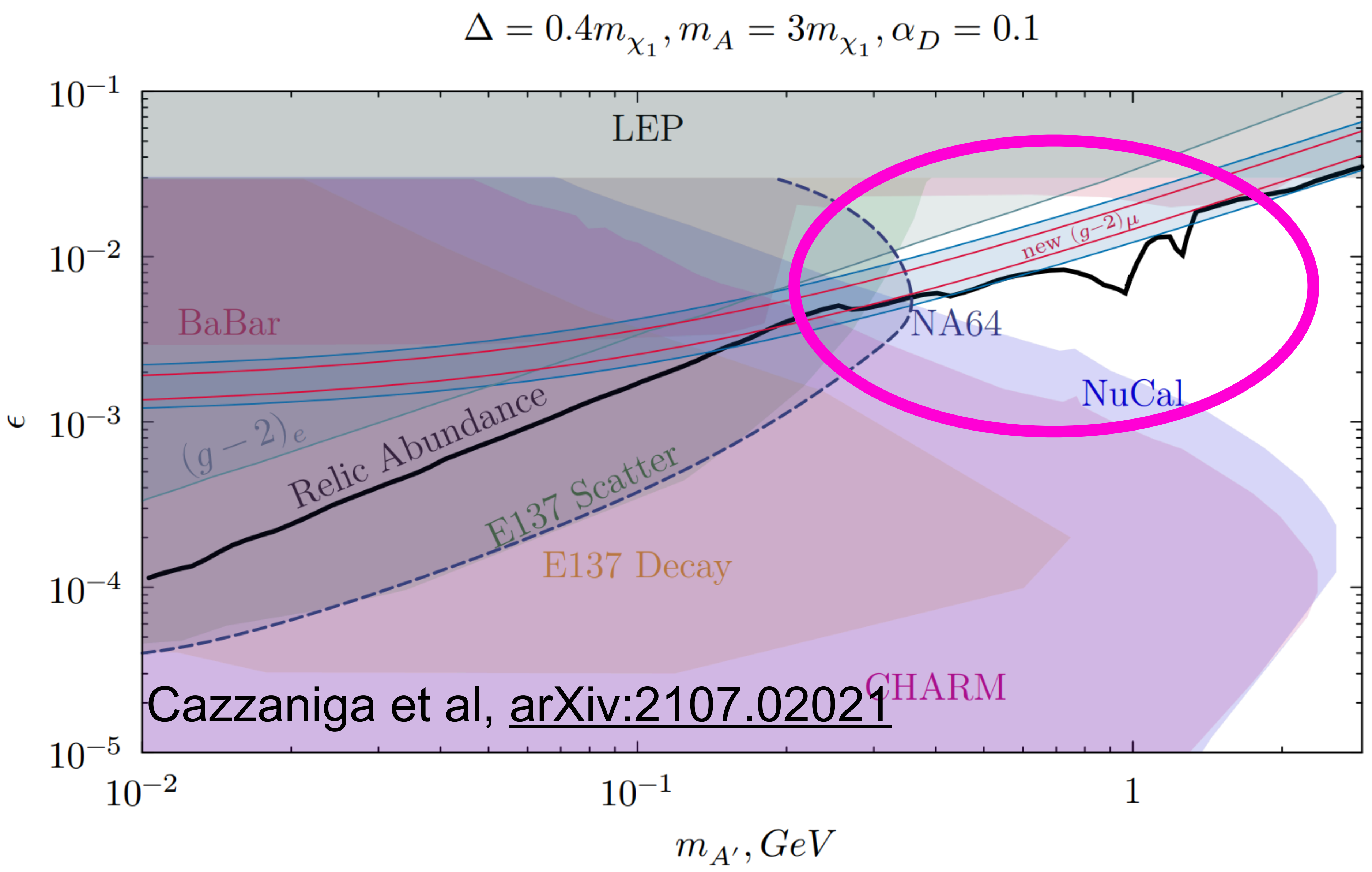




HNF decay

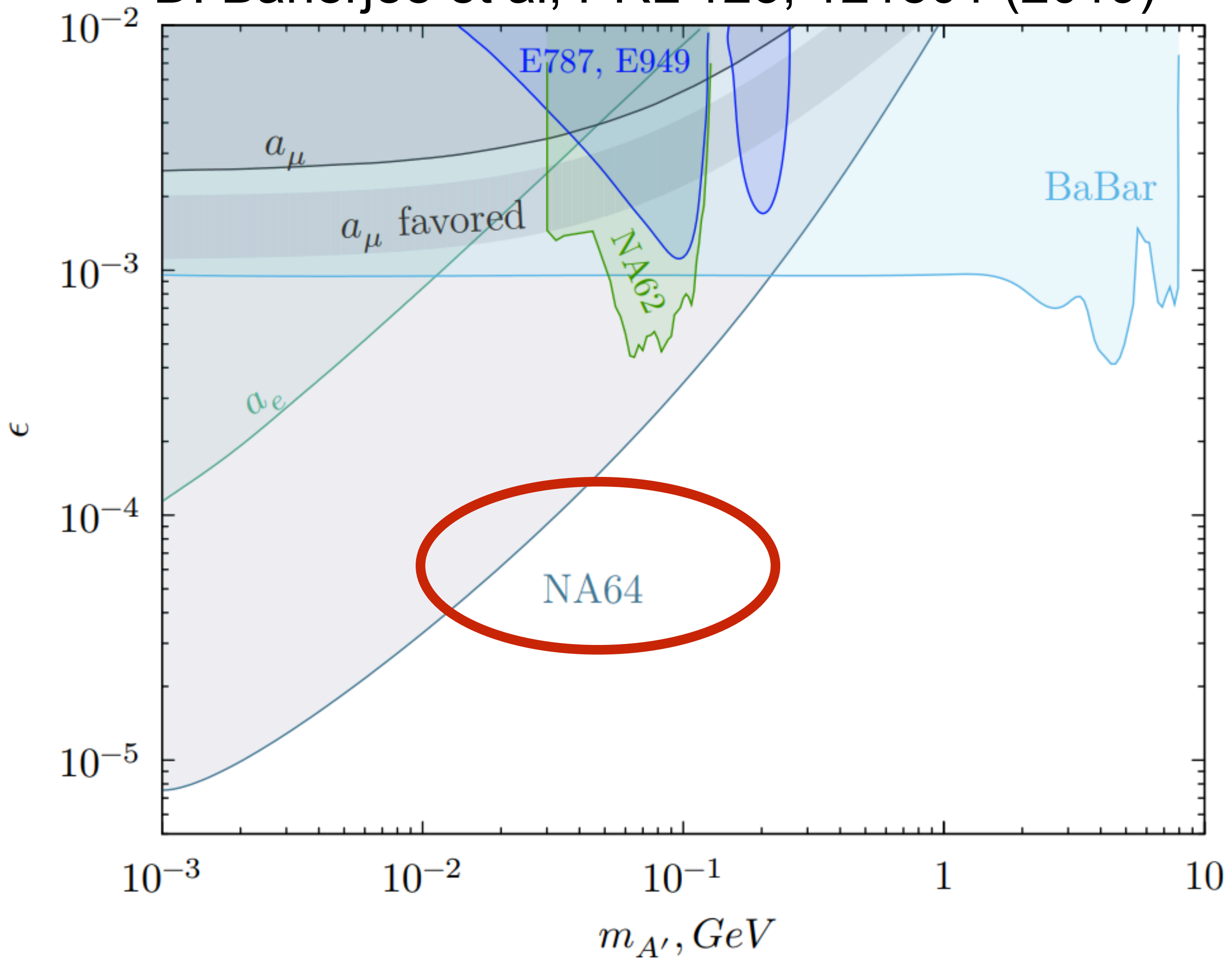


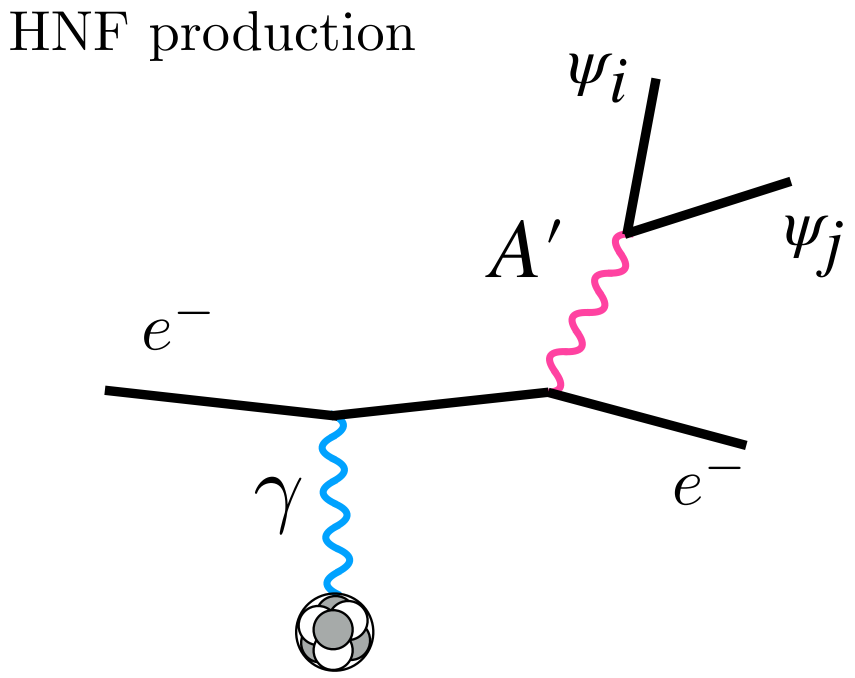
Fixed-target searches for semi-invisible A' with displaced decay. Getting close to the (g-2) region.

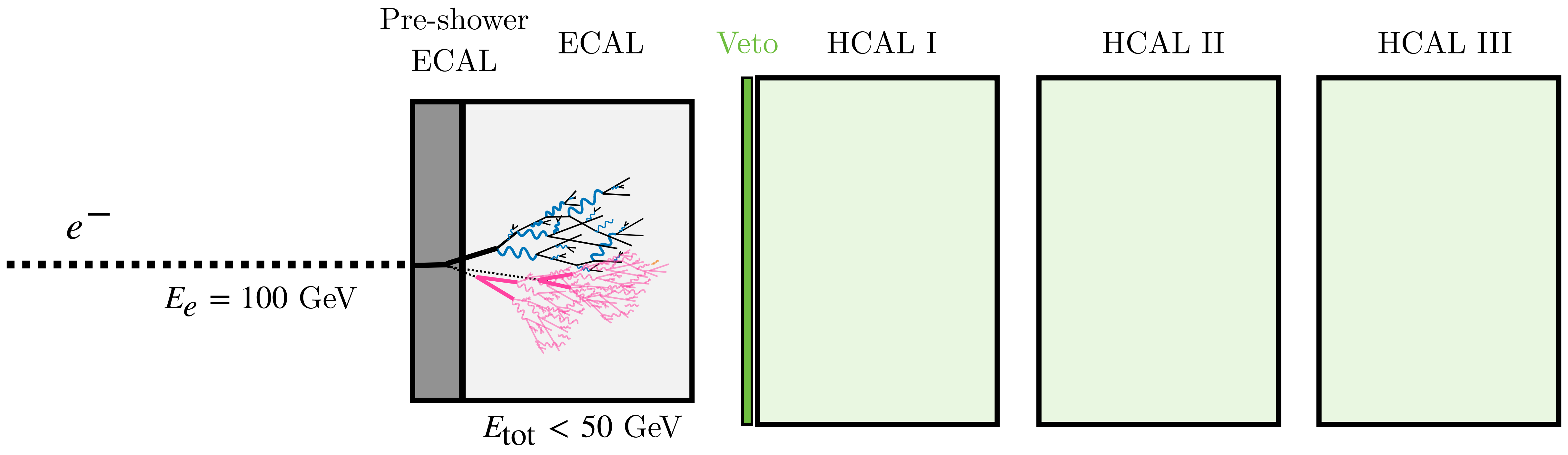


Electrons on target

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



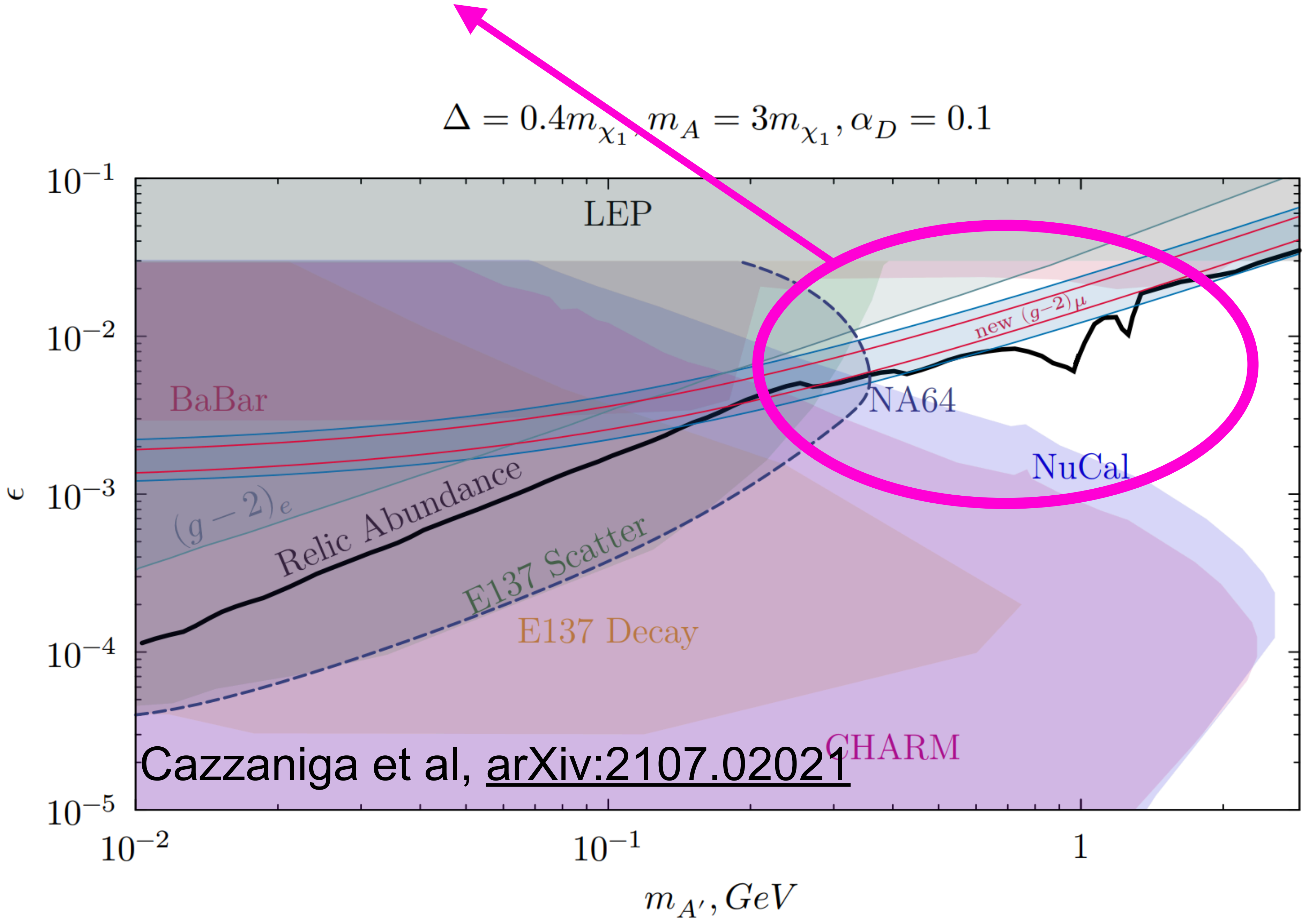




Currently, the g-2 region is where prompt decays happen.

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

Currently being performed by the collaboration!

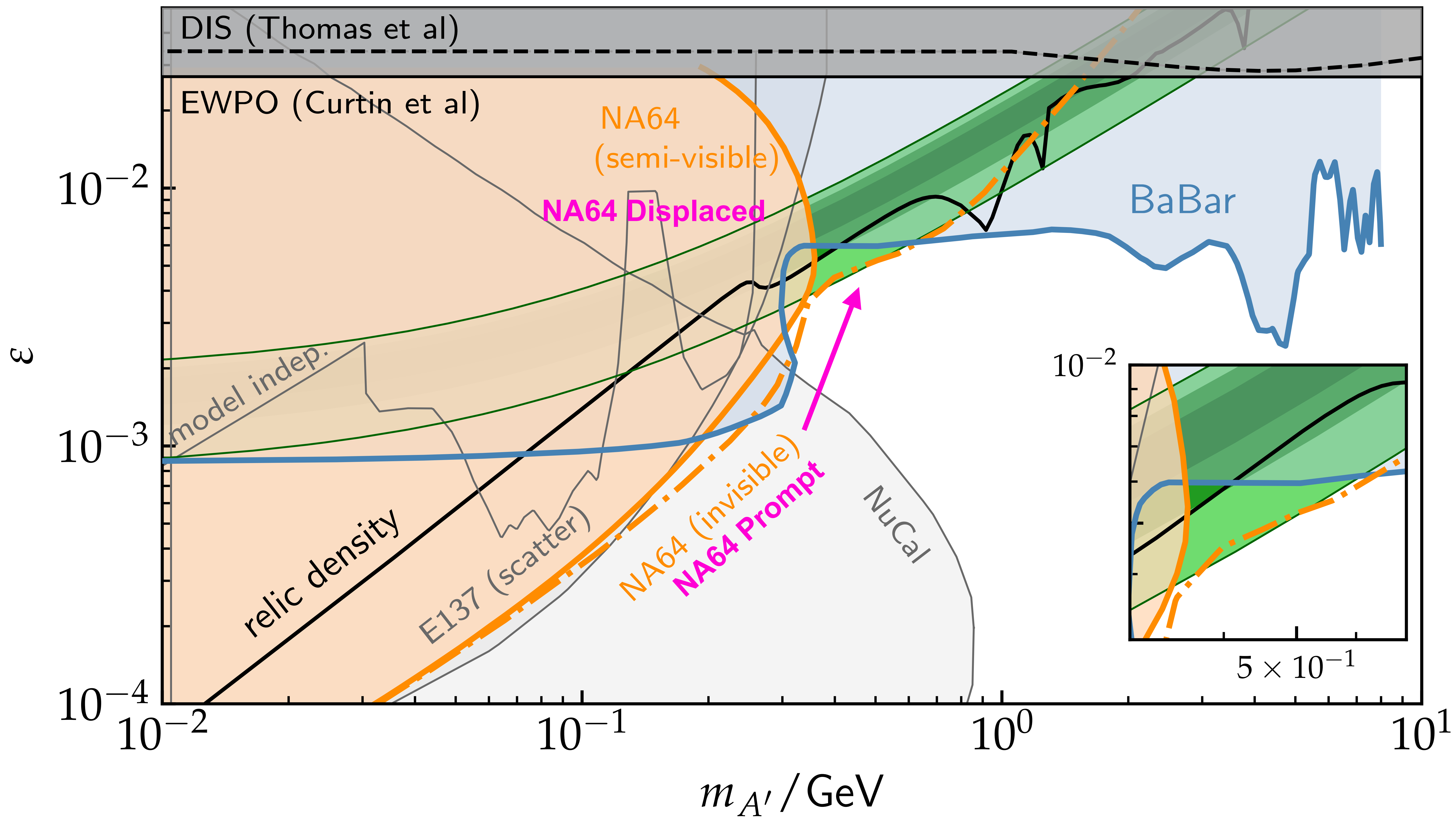


Results

Our own simulation of BaBar and NA64

χ_L χ_R

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



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

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

$$J^\mu_X = \overline{\psi_2}\gamma^\mu\psi_1$$

*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

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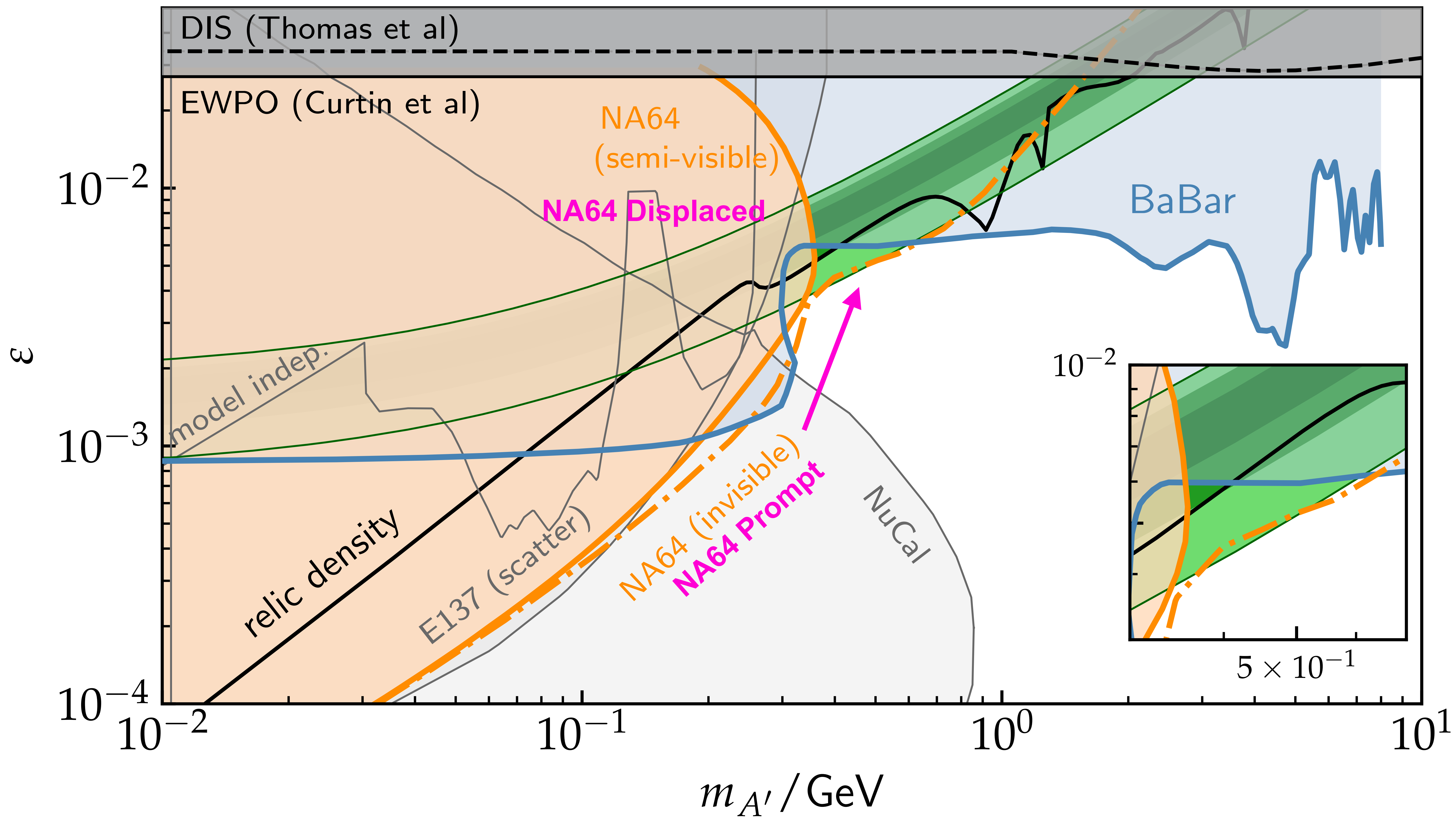

Very small parameter space that can explain $(g\text{-}2)_\mu$

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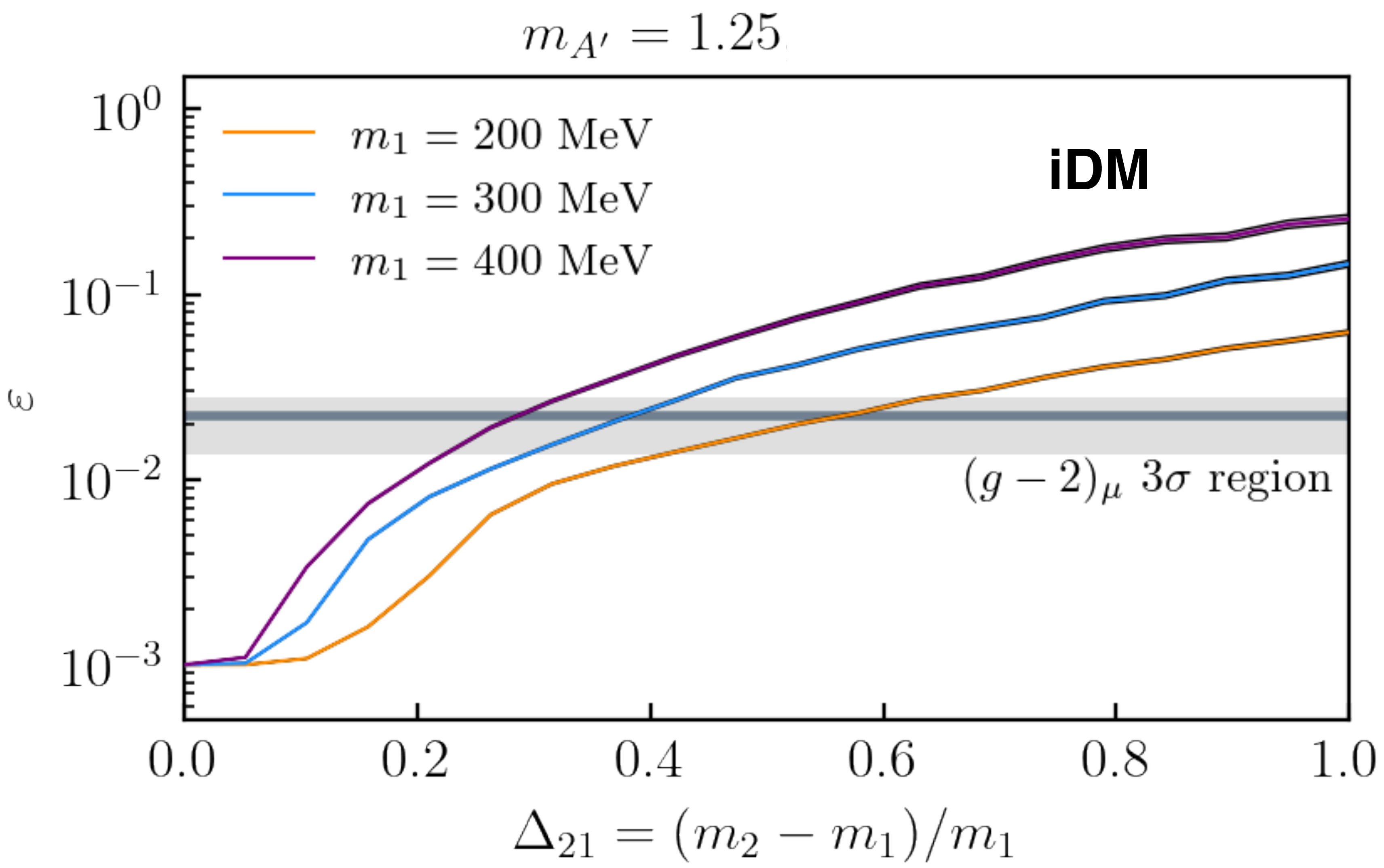
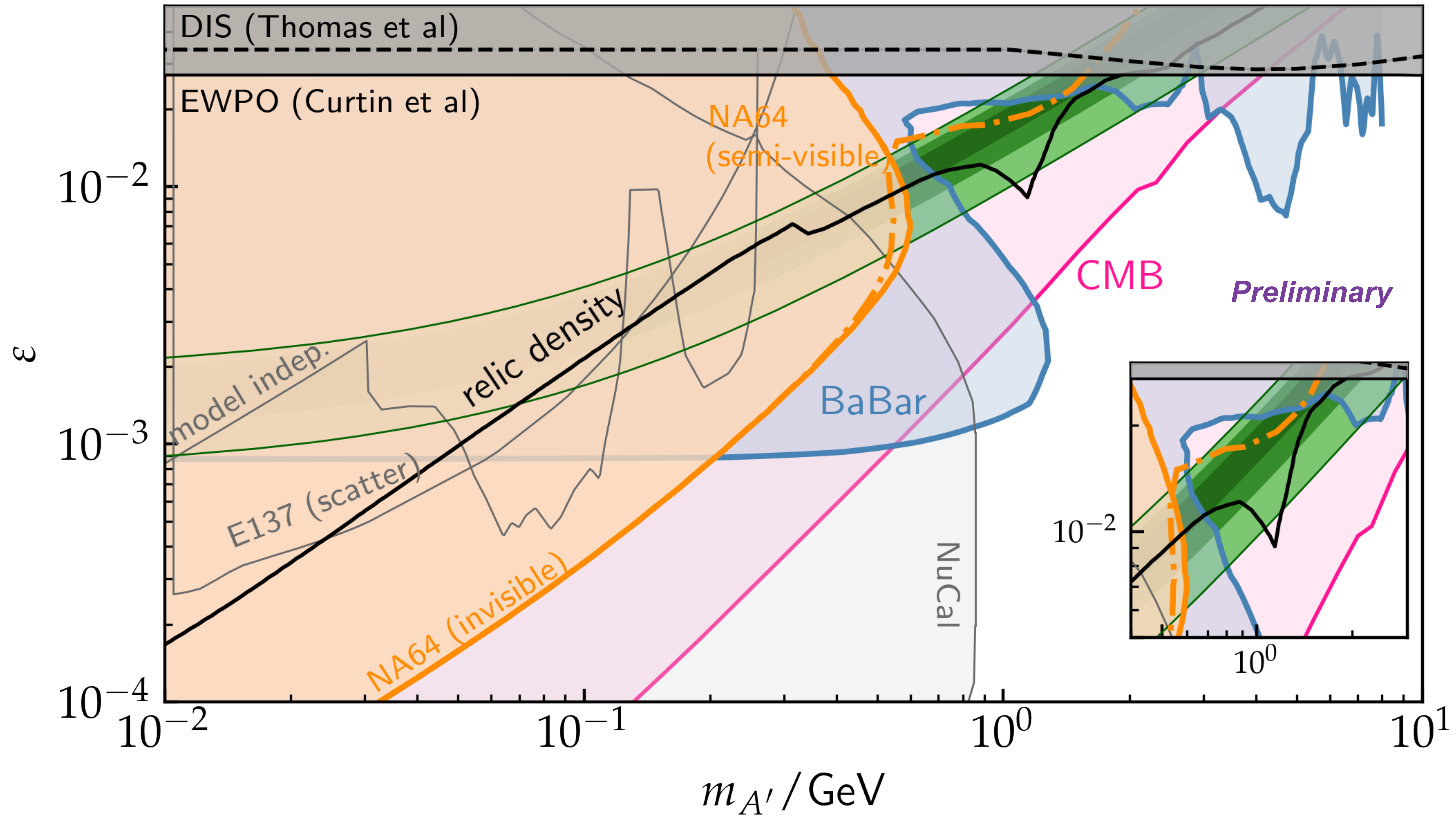


*Updated G. Mohlabeng (2019) with new energy thresholds and angular cuts. BaBar selection assumes E_e > 100 MeV for all tracks and less pessimistic assumptions than M. Duerr et al, arXiv:1911.03176.

i2DM: $\Delta_{21} = 0.4, \quad m_1/m_{A'} = 0.33, \quad \alpha_D = 0.5, \quad \theta = 4.6^\circ$



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.

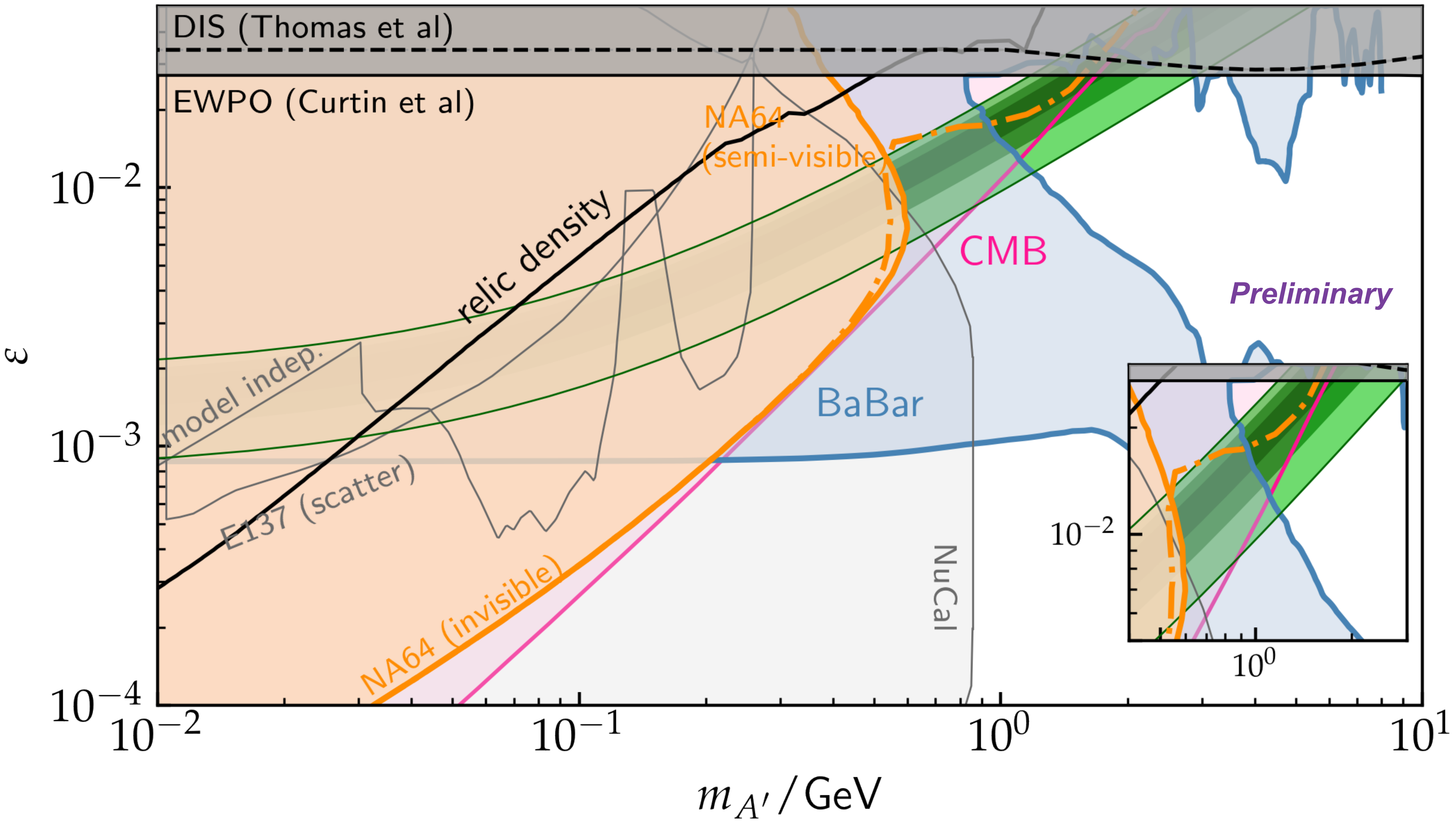
Not an issue if ψ_1 mixes with neutrinos, as it decays $\psi_1 \to \nu e^+ e^-$.

Results of our BaBar and NA64 simulations

Inelastic Dirac Dark Matter (i2DM)

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

i2DM: $\Delta_{21} = 0.4, \quad m_1/m_{A'} = 0.33, \quad \alpha_D = 0.5, \quad \theta = 2.3°$



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Results of our BaBar and NA64 simulations

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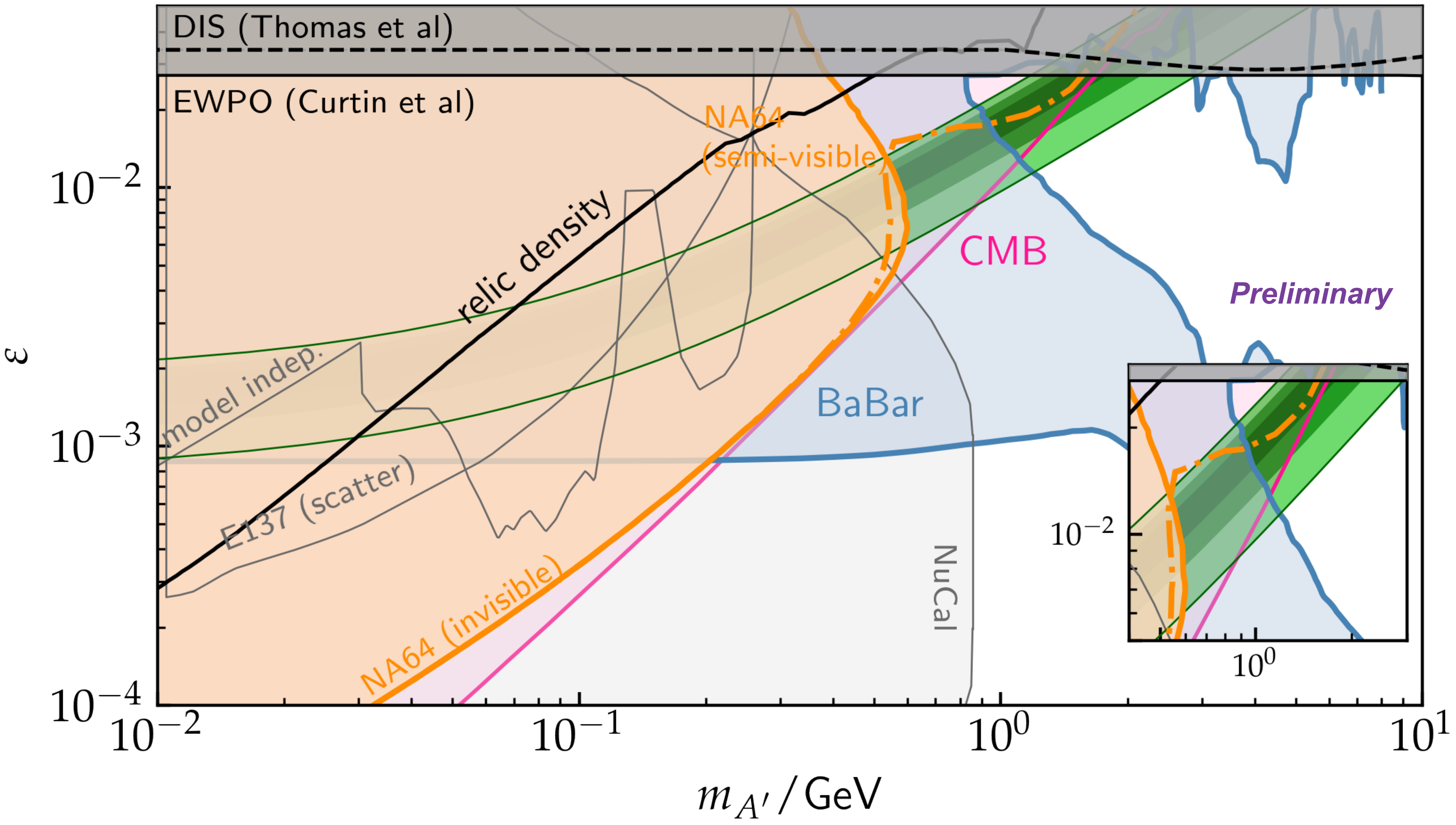
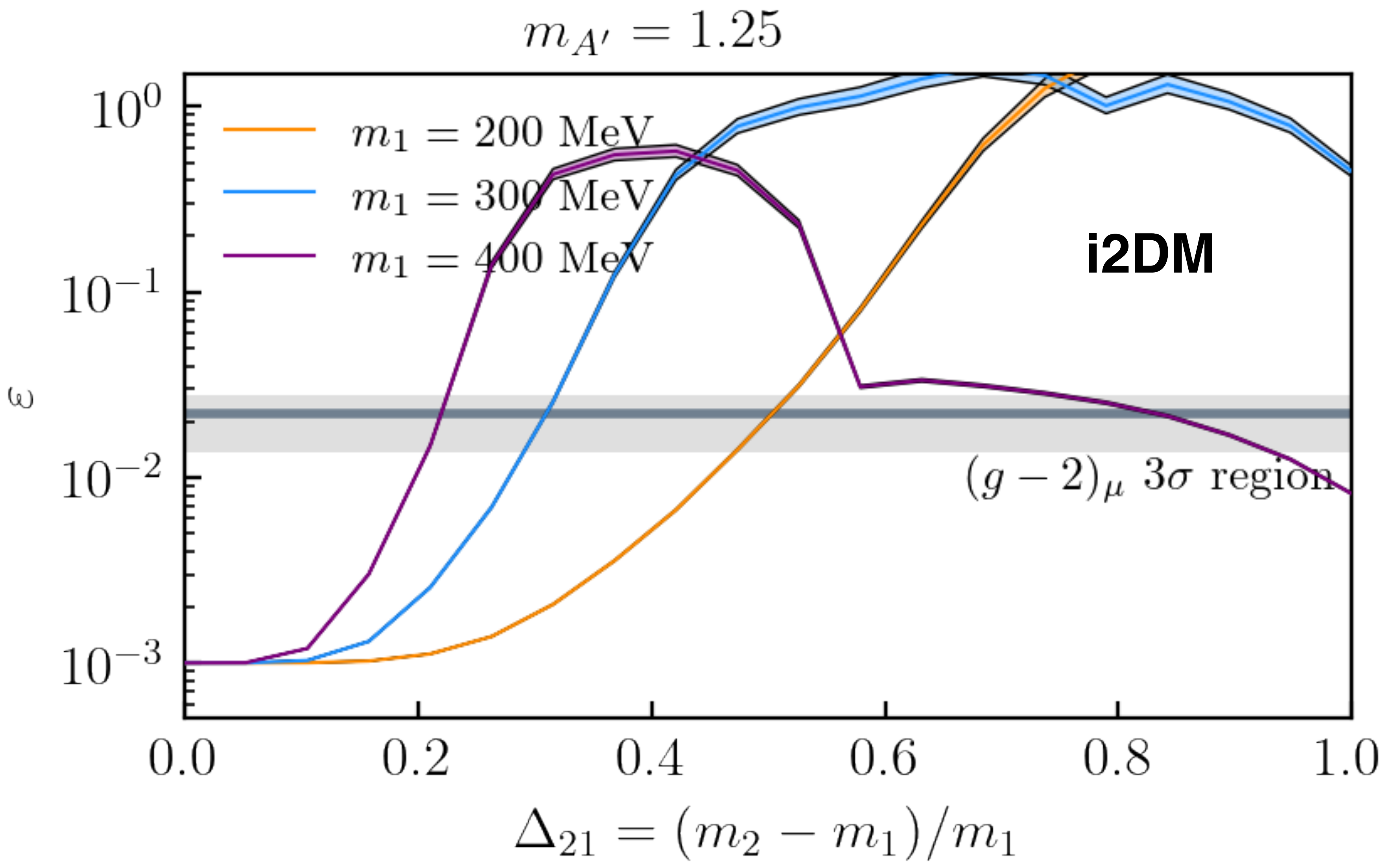
$\eta_L \eta_R \quad \chi_L \chi_R$

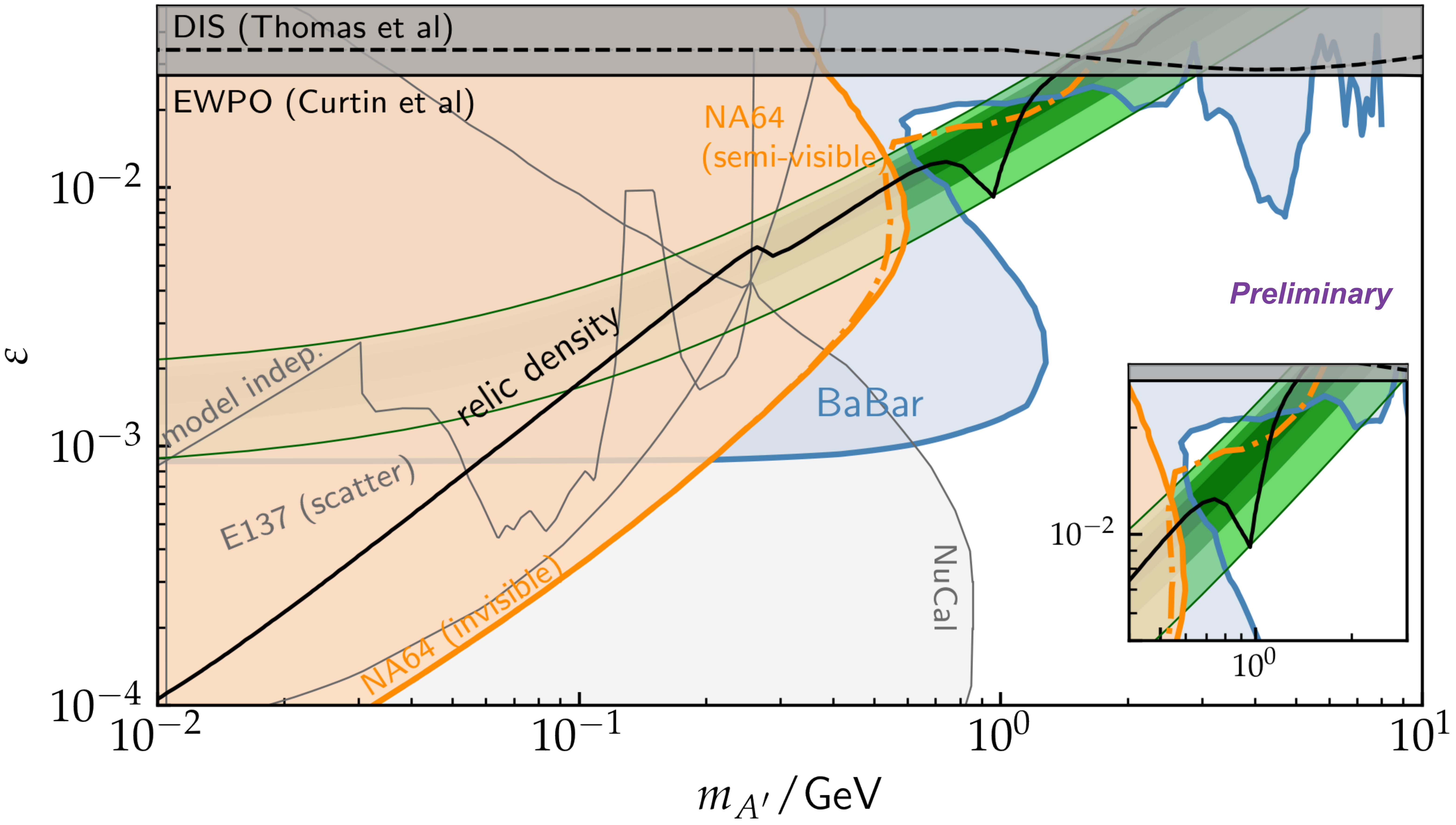
i2DM: $\Delta_{21} = 0.4, \quad m_1/m_{A'} = 0.33, \quad \alpha_D = 0.5, \quad \theta = 2.3°$



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



mixed-iDM: $\Delta_{21} = 0.4$, $m_1/m_{A'} = 0.33$, $\alpha_D = 0.5$, $\theta = 18^\circ$



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, and CMB does not constrain it.

Relic density is governed by

$$\Psi_2 f_{SM} \to \psi_1 f_{SM}$$

and

$$\Psi_2\Psi_2 \to f_{SM}f_{SM},\ \Psi_2\psi_1 \to f_{SM}f_{SM}$$

and is insensitive to 11 vertex.

Results of our BaBar and NA64 simulations

A dark Dirac fermion seesaw

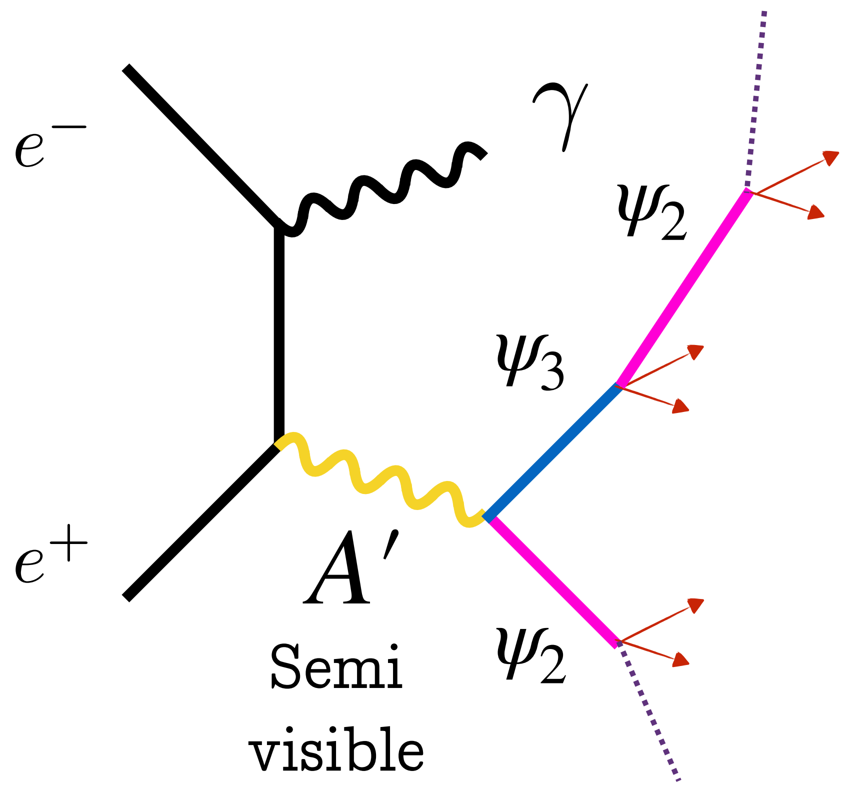
η_L χ_L χ_R

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

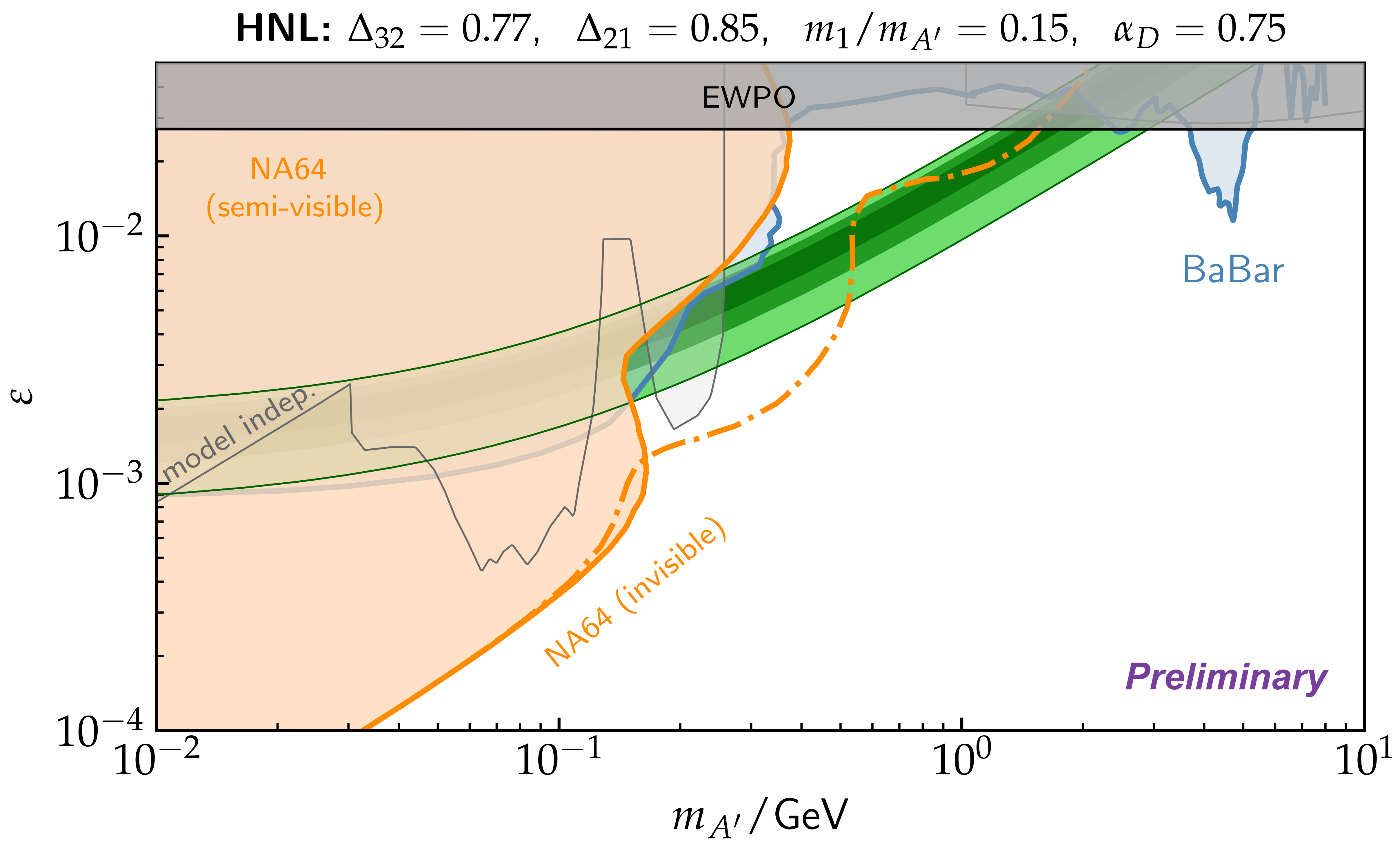
(if HNF $\equiv$ HNL)

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

Rather extreme point of parameter space.



3 (e^+e^-) pairs



Explanation is **possible…** but:

i) Landau pole below EW scale,

ii) s-channel production can dominate.

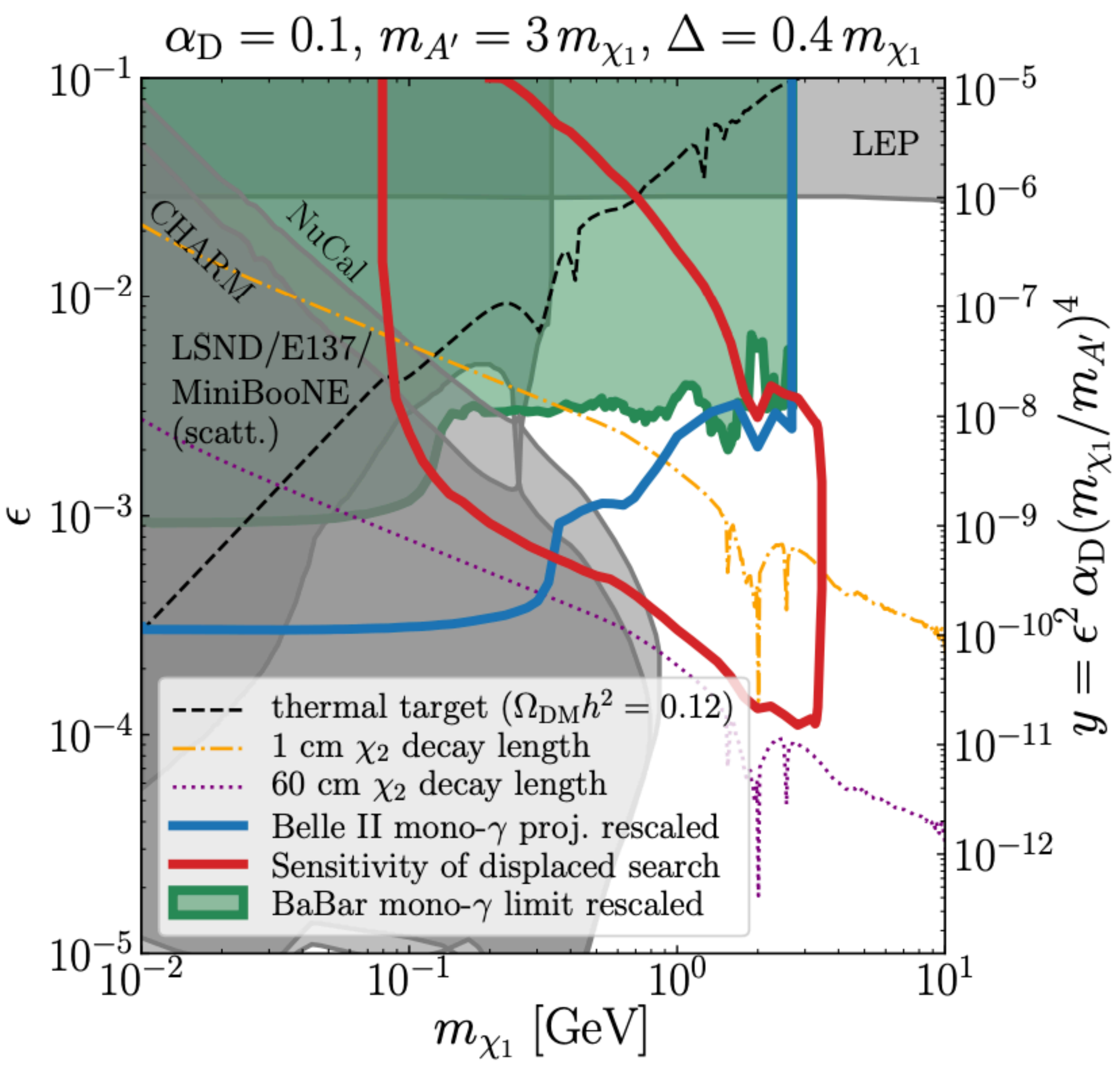
We choose benchmark points in [A. Abdullahi, MH, S. Pascoli, 2020], where anomalies in neutrino experiments, including the MiniBooNE excess, can be explained.

Future prospects

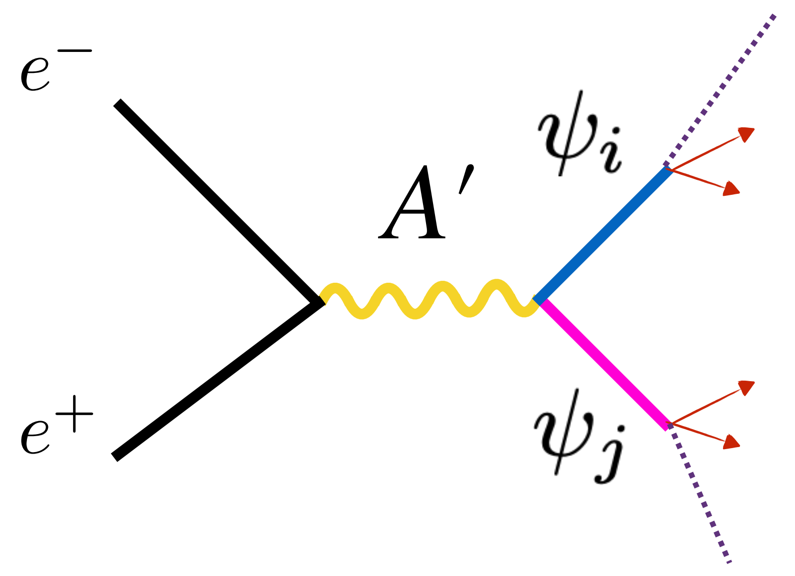
Fixed targets and neutrino experiments

Belle-II — displaced vertices

M. Duerr et al, arXiv:1911.03176



S-channel: 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.

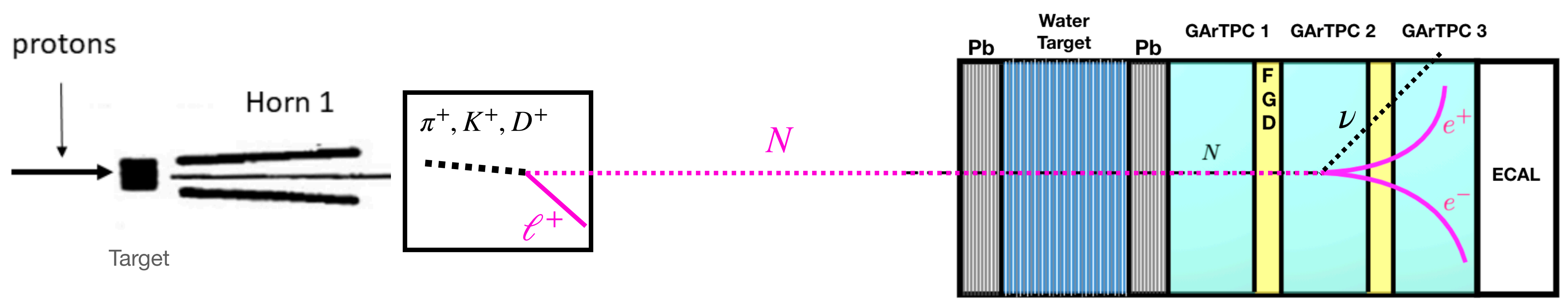
Dark Neutrino Sectors
Upscattering at the T2K near detector

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:



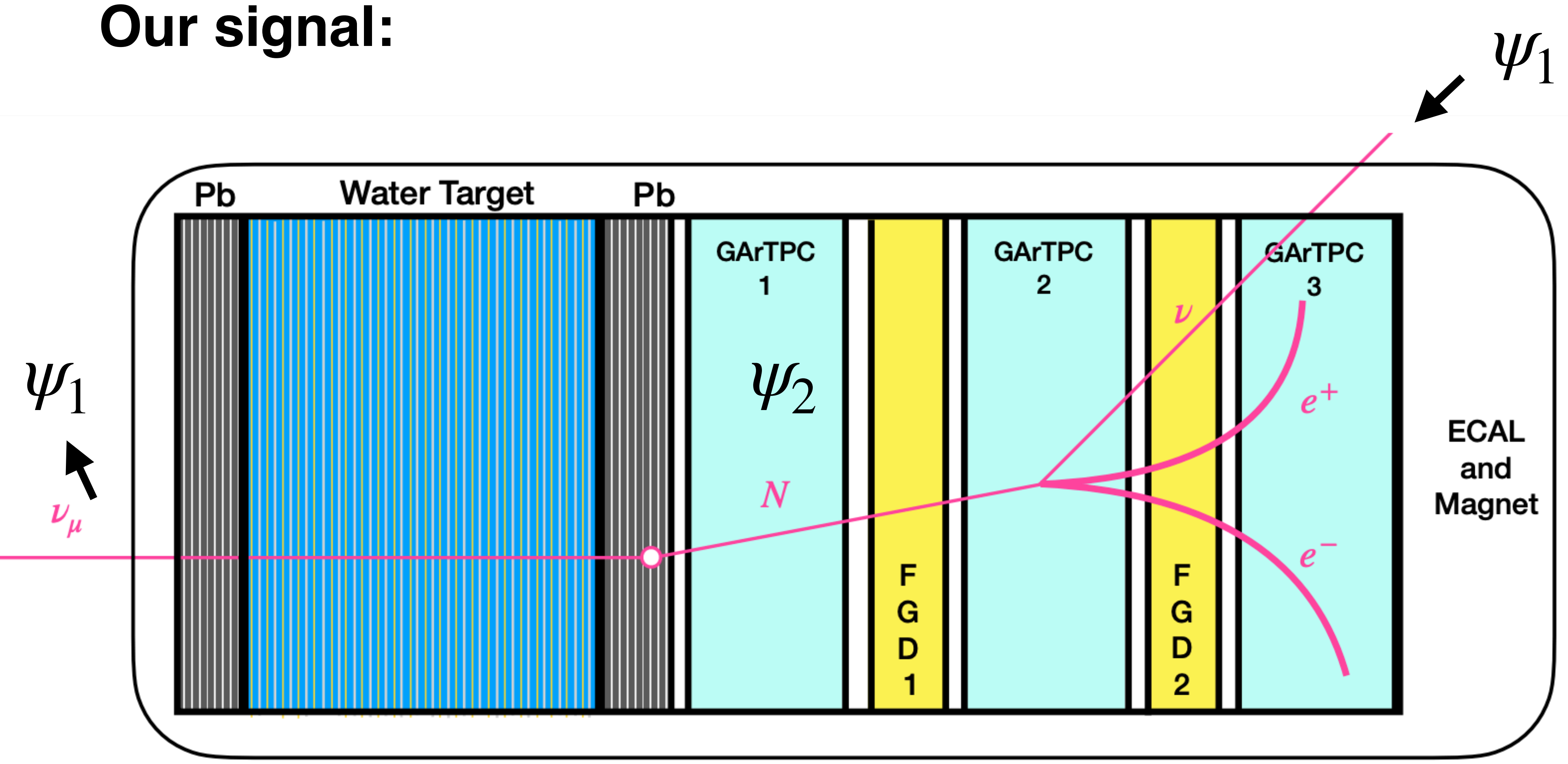
+ Heavy **lead** plates

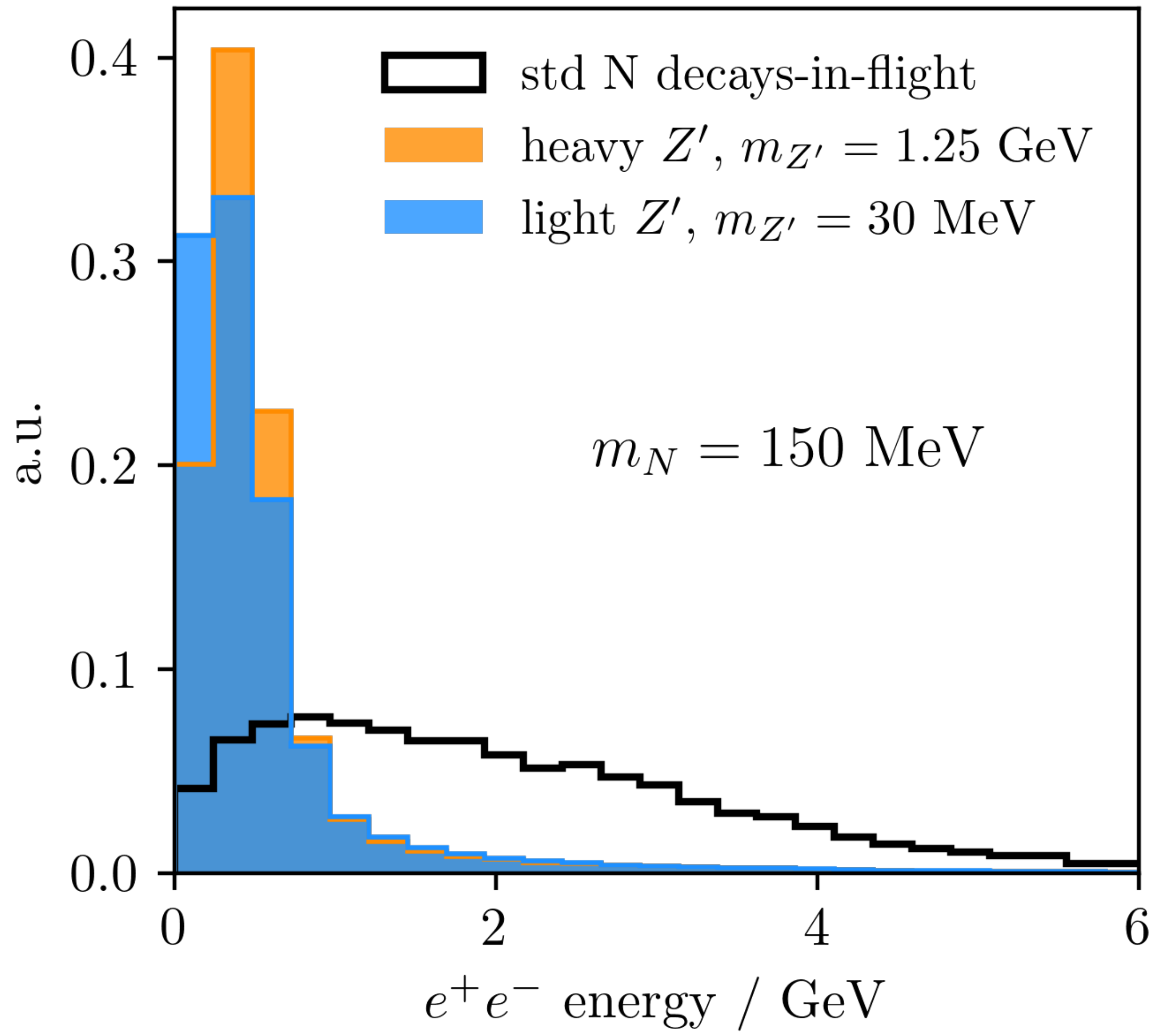
+ Gaseous Argon modules

+ 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)

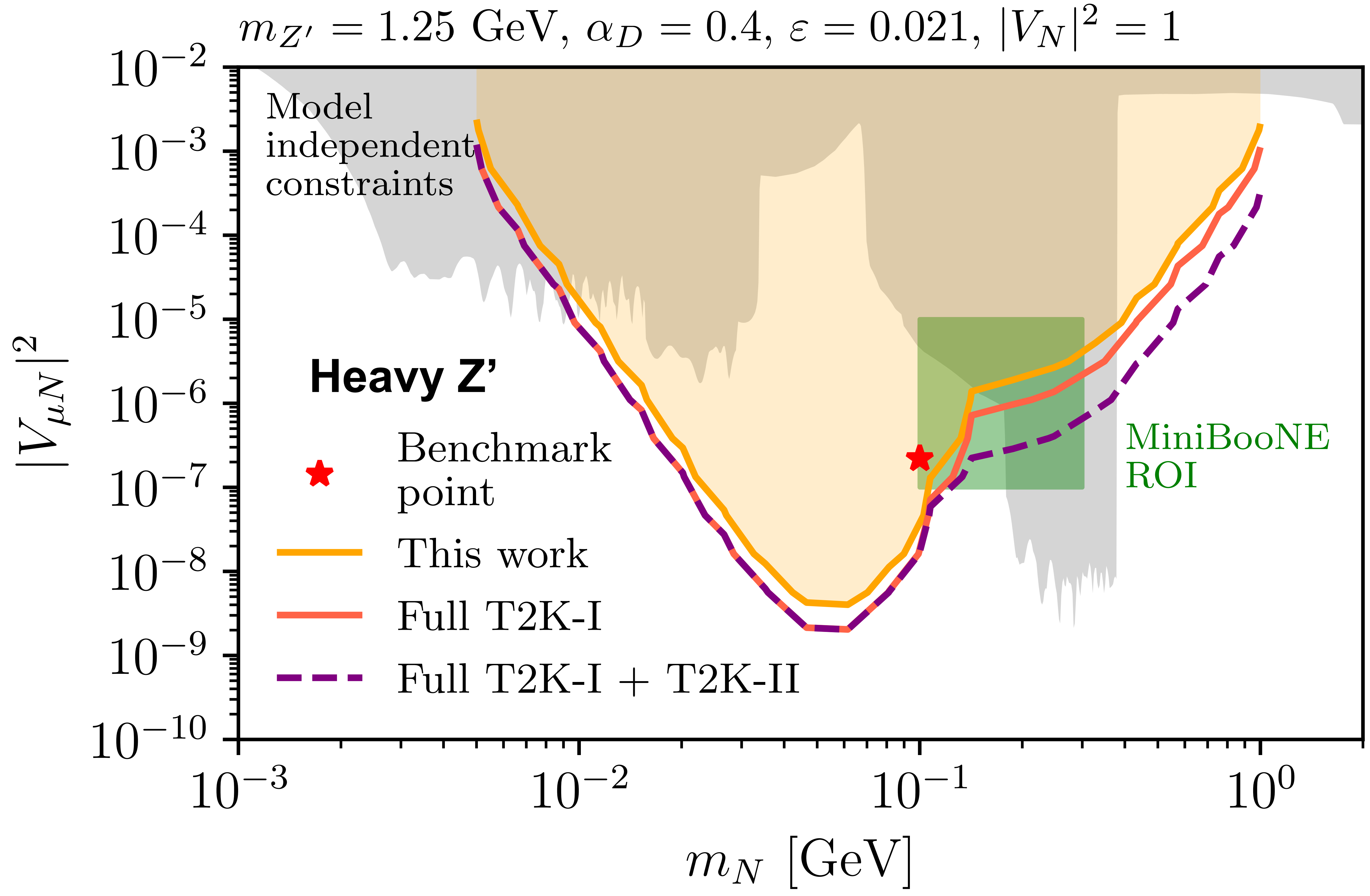
Our upscattering signal is different, mostly in energy (colors).

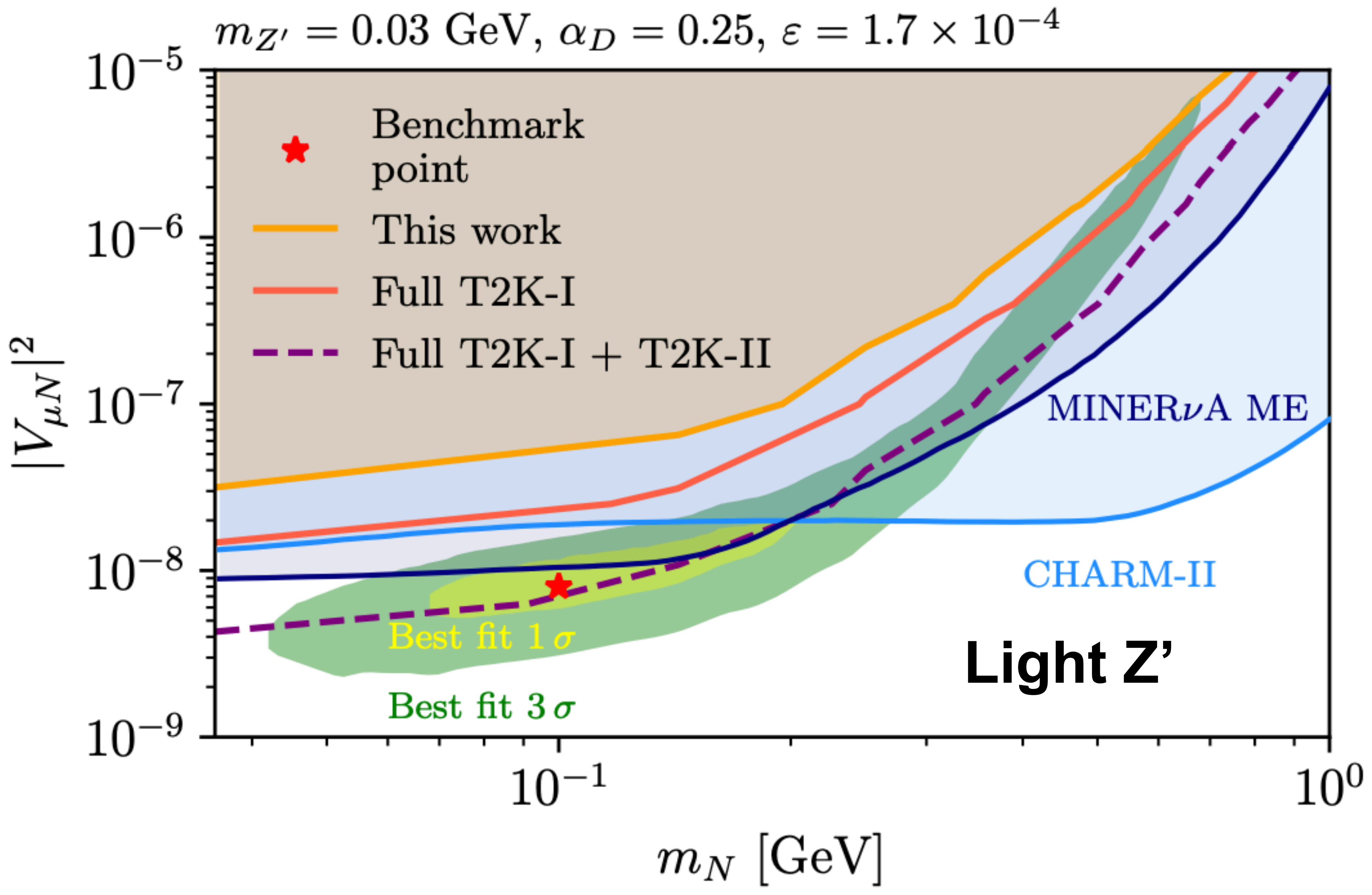
Dark Neutrino Sectors
Upscattering at the T2K near detector

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





* Unfortunately, no MiniBooNE fit is available yet.

Models with $c\tau_N^0/m_N > 1\,\mathrm{cm/GeV}$

Is in tension with T2K data,

Otherwise, rate in GArTPC is too low.

DarkNews-Generator

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

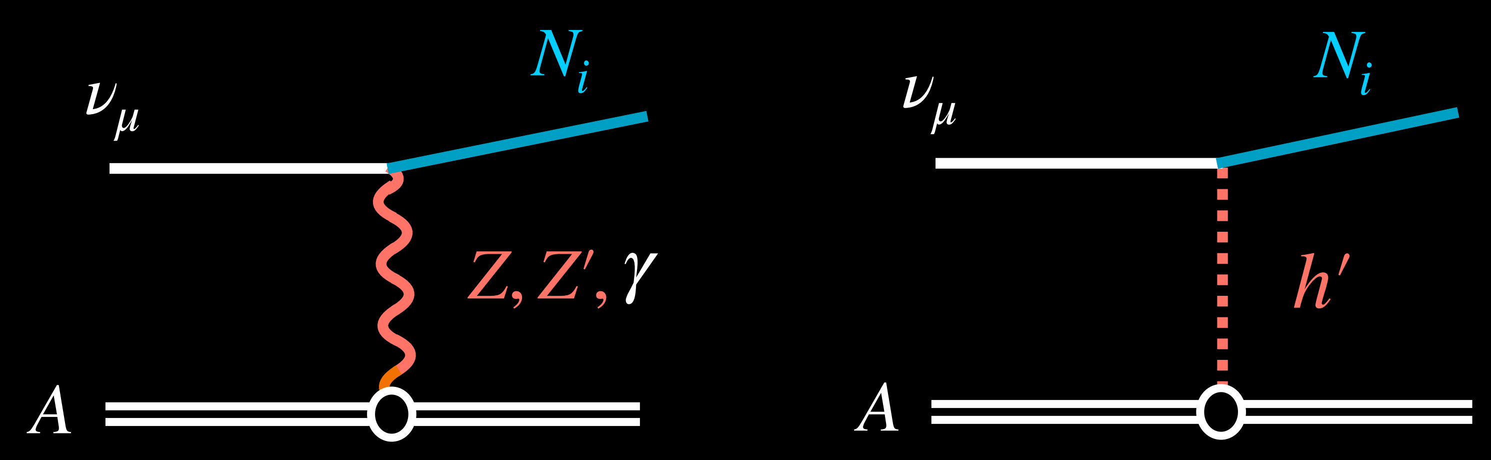
`DarkNews` is a lightweight MC generator for new physics in neutrino-nucleus scattering. Including vector, scalar, and dipole mediators in upscattering processes to up to 3 HNLs.

`pip install DarkNews`

Modeling several processes for GeV-scale accelerator experiments:

Scattering:

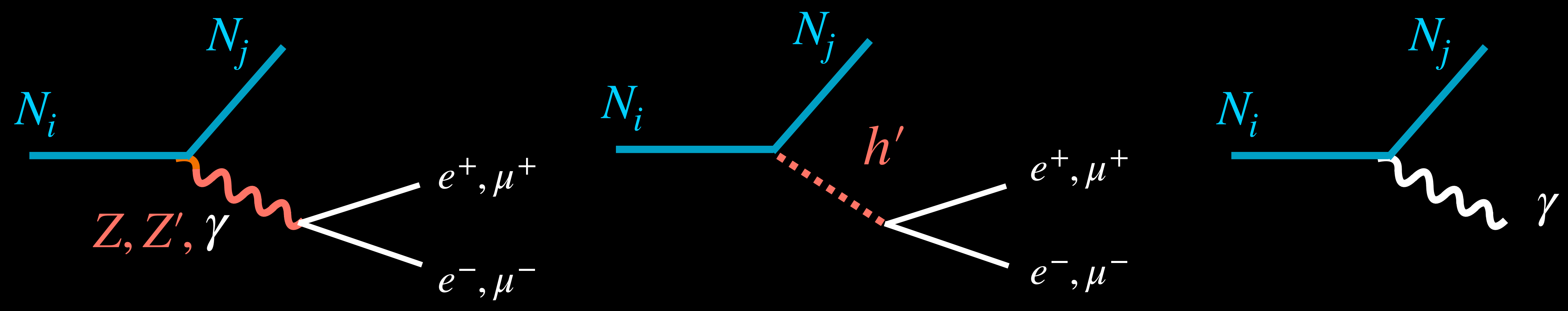
$\nu A \to N A$
(Coherent & QE peak)



Helicity conserving or flipping upscattering $\nu \to N$

HNL decay:

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



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

Conclusions

A semi-visible dark photon with $m_{A'} \sim 1$ GeV and $\varepsilon \sim 10^{-2}$ is easy to look for, but so far, not directly targeted by current searches.

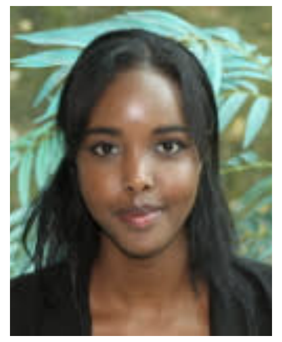
Interesting solution to the $(g-2)_\mu$ puzzle and can also have connections to the anomalies in the neutrino short-baseline program.

Thank you

The 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. 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 dig much deeper into parameter space.

Collaborators:



Asli Abdullahi
Fermilab

Daniele Massaro
Uni of Bologna

Silvia Pascoli
Uni of Bologna

Back-up slides

Dark forces contributing to $(g\text{-}2)_\mu$

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

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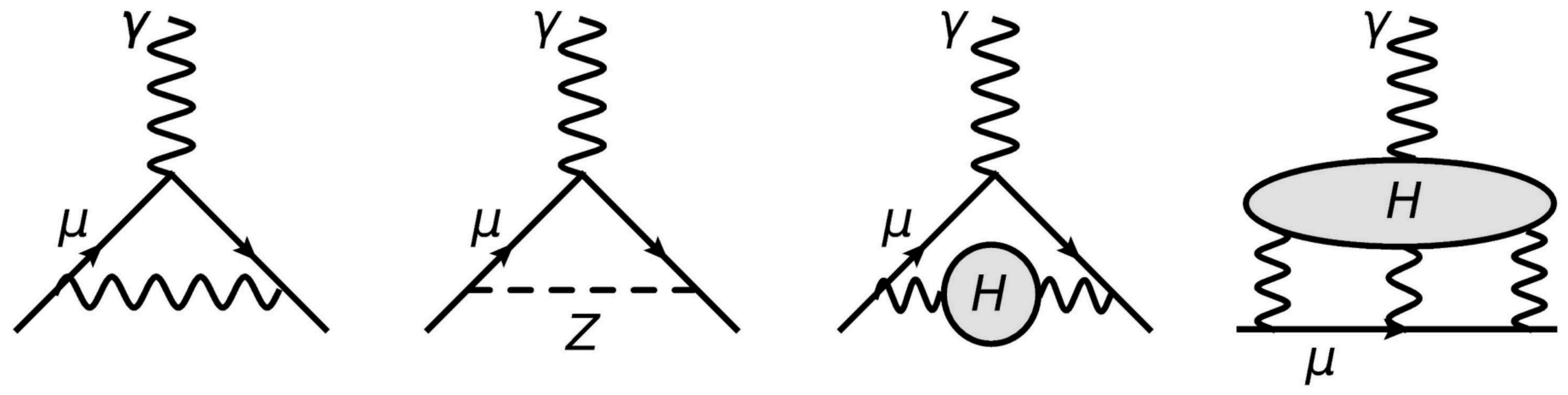
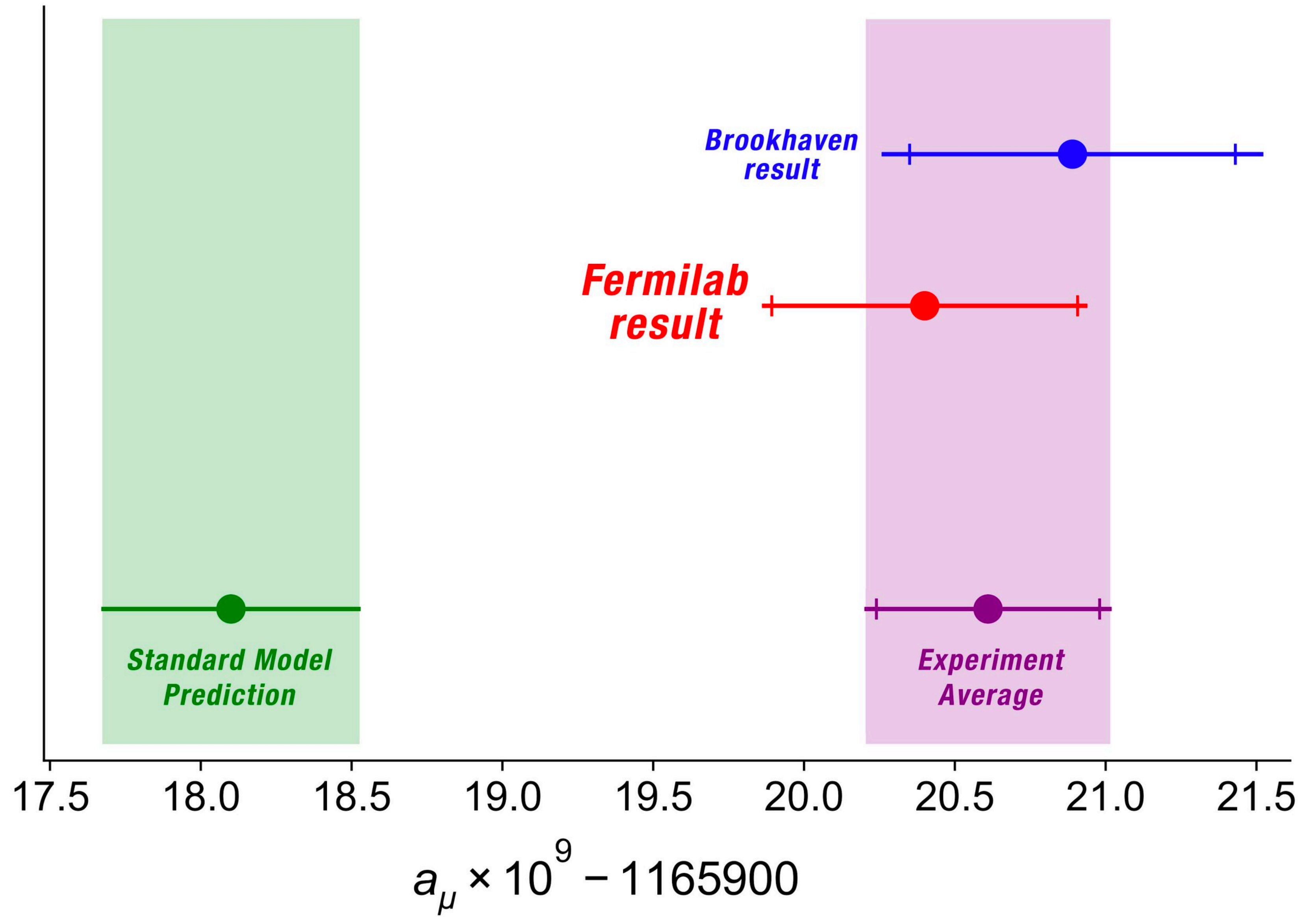




$$a_\mu^{\rm EXP} = 116592061(41) \times 10^{-11}$$

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).

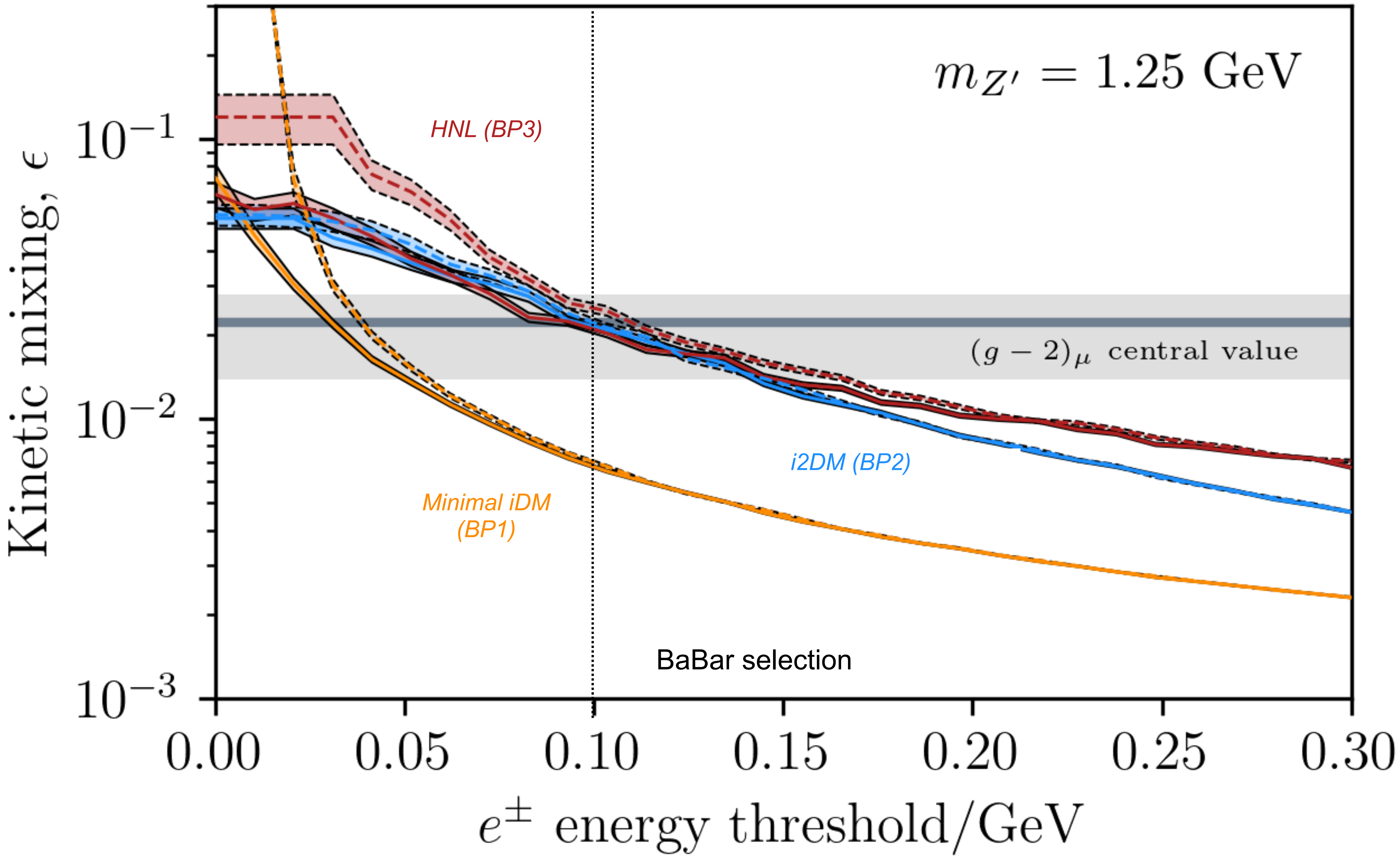
If theory predictions are indeed under control, then new physics must not be too far out of reac

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

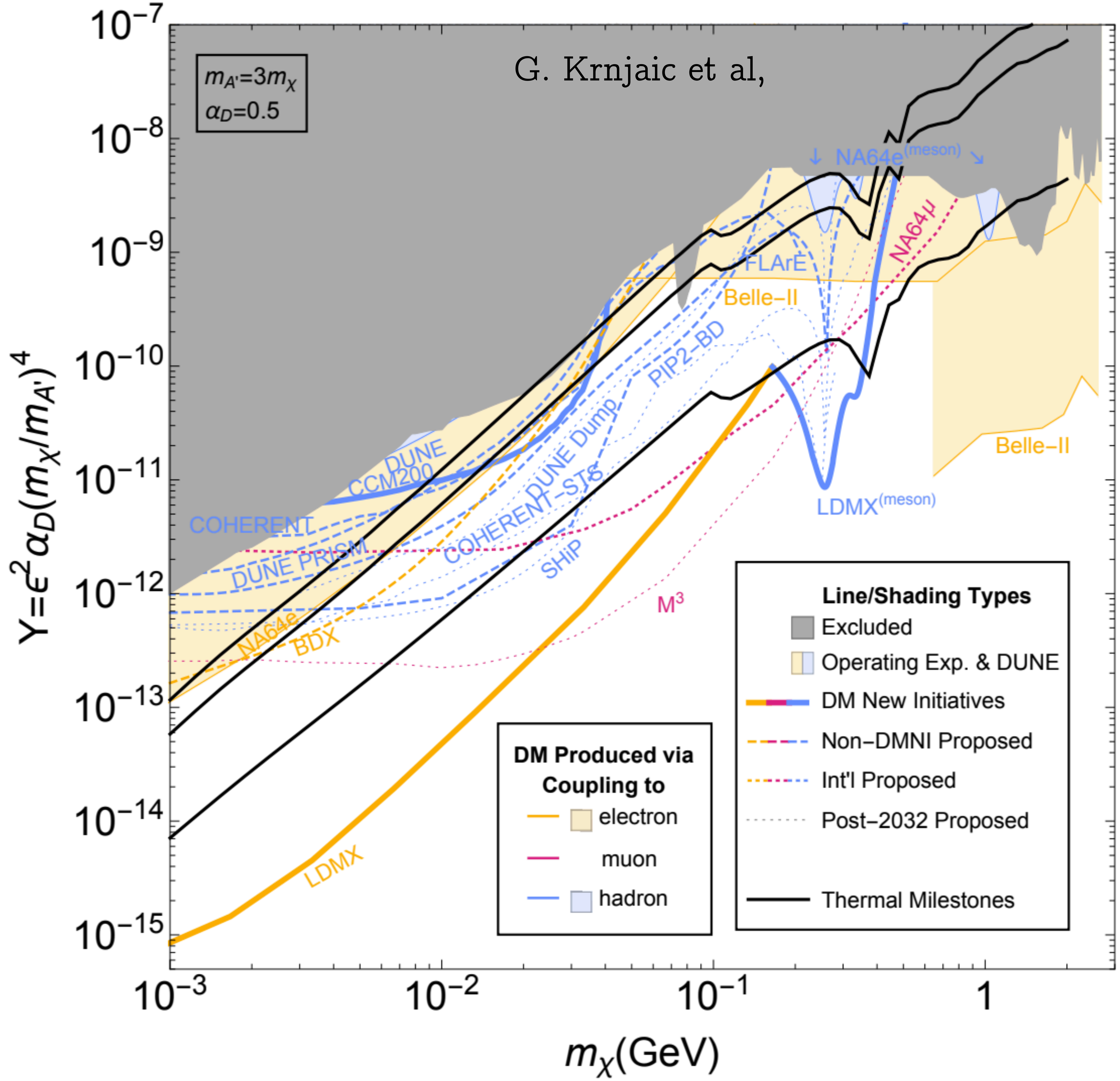
$$\frac{\Lambda}{g} \sim \text{ few 100s of GeV}$$

Signal characteristics

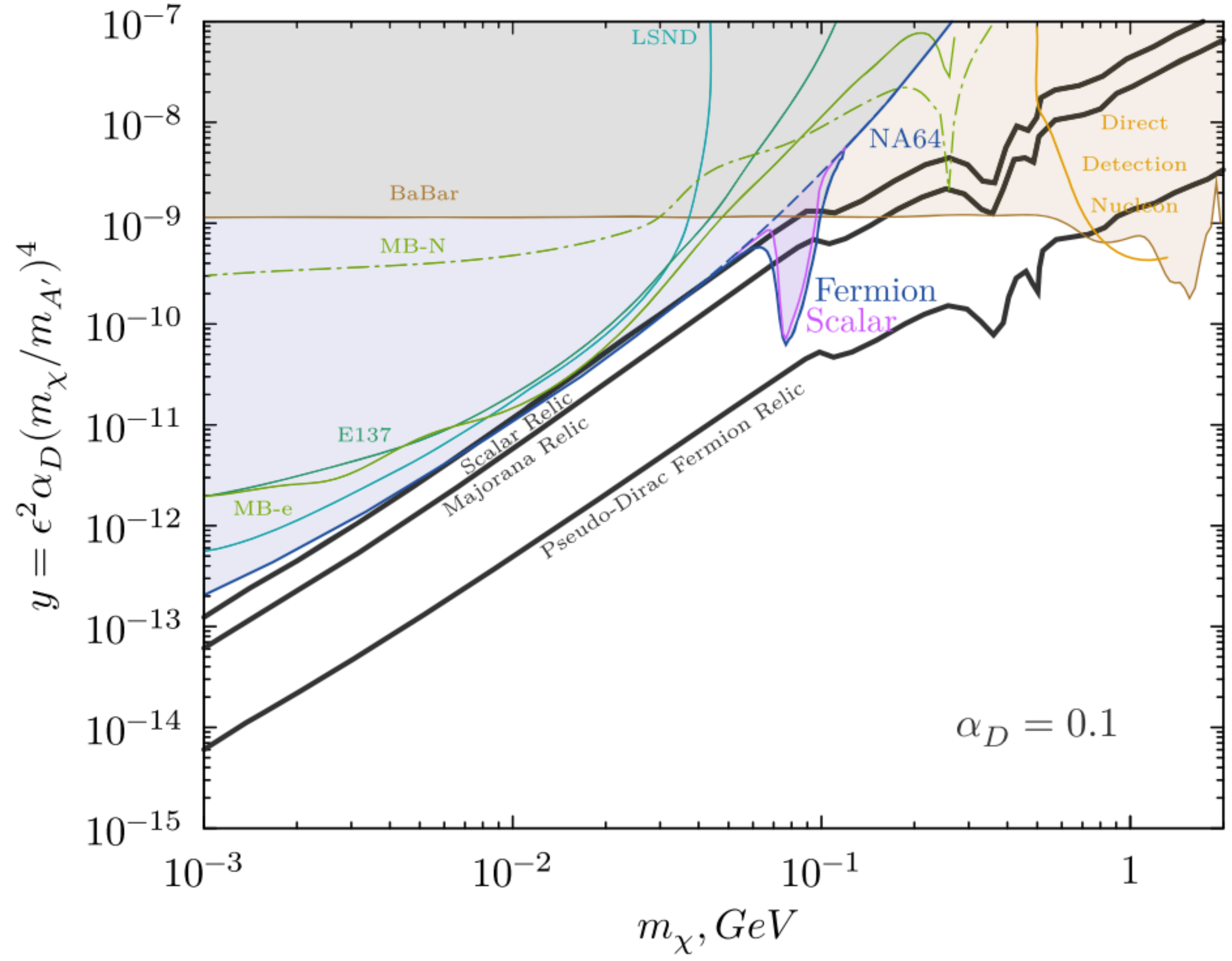
Dependence of the results on simulation assumptions



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

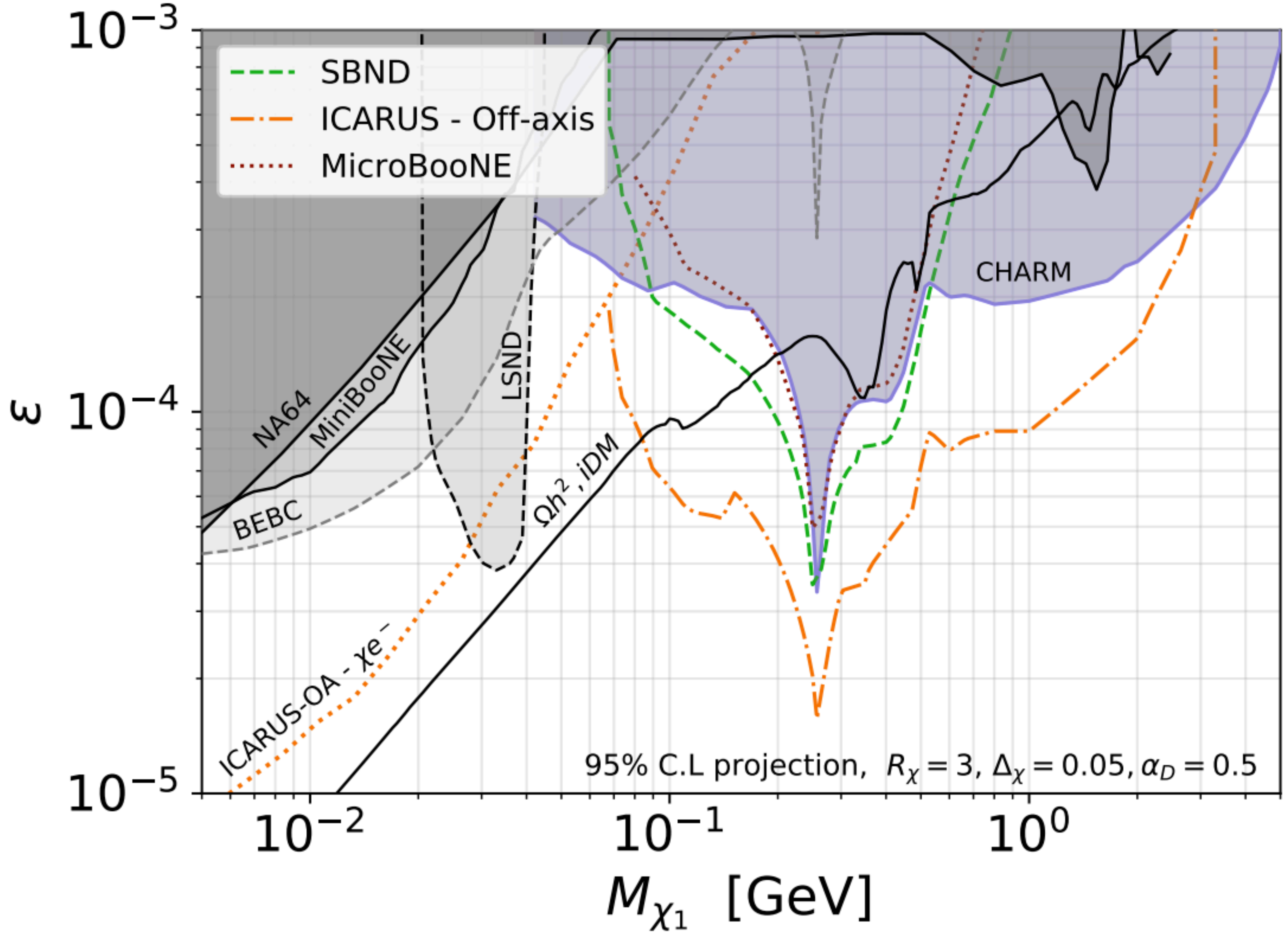


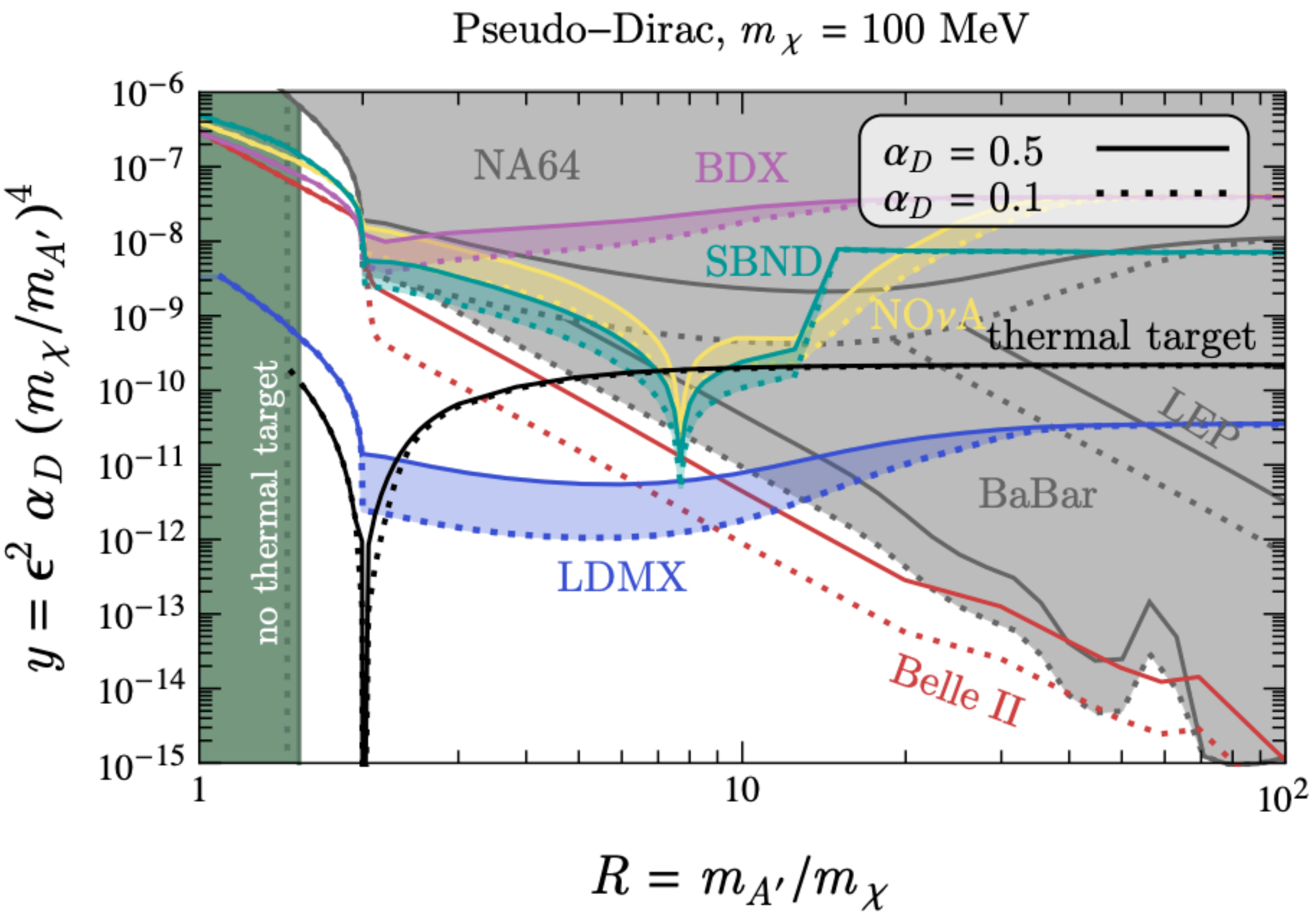
NA64 including resonant production.



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
$y = \epsilon^2 \alpha_D (m_\chi/m_{A'})^4$
$R = m_{A'}/m_\chi$