



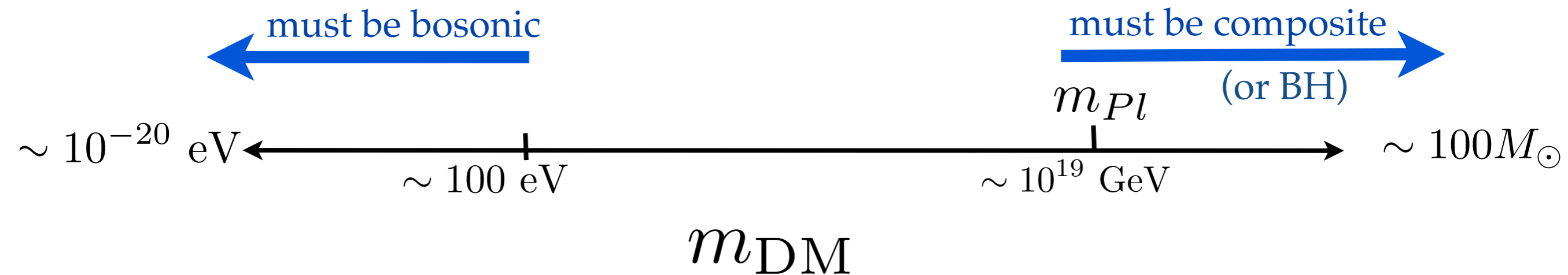
Theory Overview: Light DM @Accelerators

Gordan Krnjaic

Next Frontiers in the Search for Dark Matter

Galileo Galilei Institute Sept 24, 2019

What Clues Do We Have?



Huge space of allowed microscopic theories

Evidence only extends down to $\sim \text{kpc}$ (dwarf galaxy) scales

Theoretical guidance is essential

Need organizing principle for systematic progress

Overview

- 1) Why thermal DM?
- 2) Direct annihilation: thermal targets
- 3) “Hidden” annihilation: **visible decay searches**

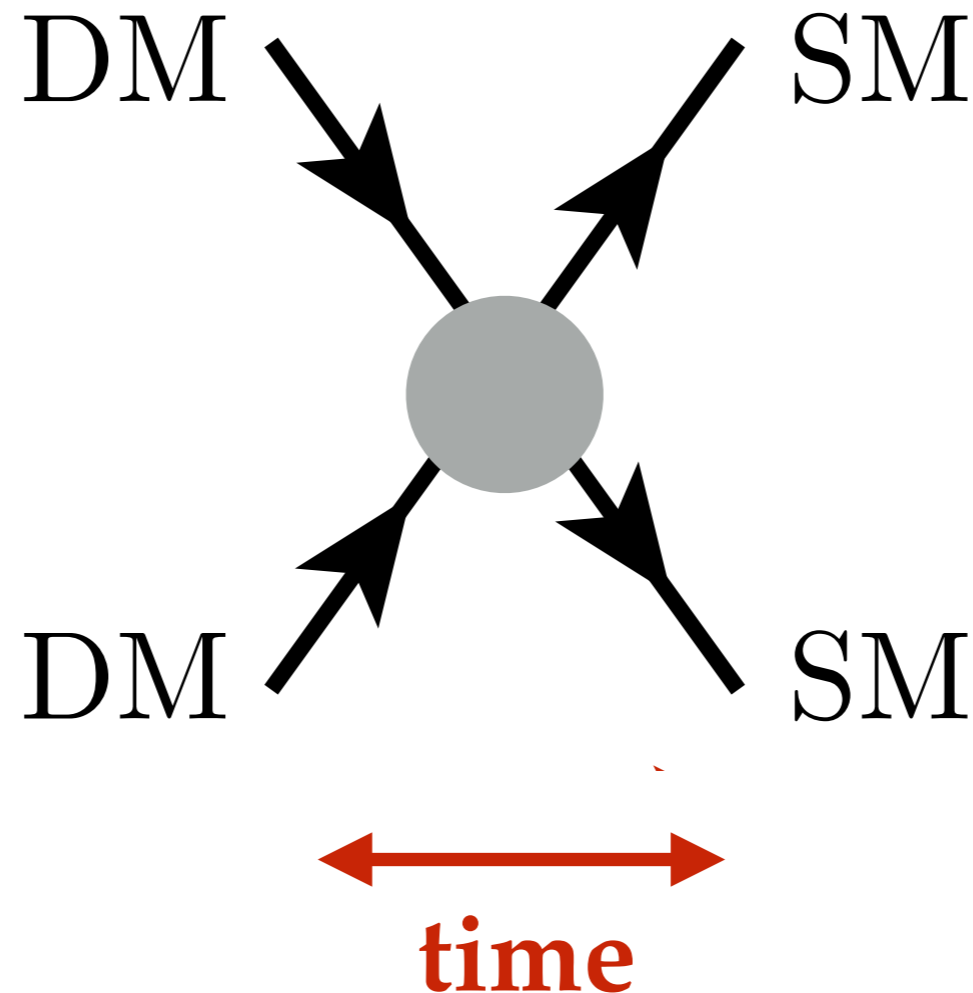
Overview

1) Why thermal DM?

2) Direct annihilation: thermal targets

3) “Hidden” annihilation: **visible decay searches**

Was DM ever in equilibrium with SM?



Chemical equilibrium: equal production / annihilation rates

Was DM ever in equilibrium with SM?

NO



How was it populated?

Was DM ever in equilibrium with SM?

NO

How was it populated?

Initial conditions

Axion / ALP

WIMPzilla

Primordial BH

⋮

Rarely predictive

Was DM ever in equilibrium with SM?

NO

How was it populated?

Feeble coupling to us

Sterile Neutrino

Freeze In

•
•
•

Very hard to test

[few known examples, see Thomas Hambye's talk]

Was DM ever in equilibrium with SM?

YES

$$n_\chi \sim n_\gamma \sim T^3$$

Where did its density go?

Was DM ever in equilibrium with SM?

YES

$$n_\chi \sim n_\gamma \sim T^3$$

Where did its density go?

Nowhere

Equilibrium predicts DM mass

$$m_\chi \sim 10 \text{ eV}$$

Too hot to handle LSS
(see Aurel Schneider's talk)

Was DM ever in equilibrium with SM?

YES

$$n_\chi \sim n_\gamma \sim T^3$$

Where did its density go?

Stable dark states

Heavy

Too much DM

Light

$$N_{\text{eff}} > 3$$

Requires nonstandard cosmology

Was DM ever in equilibrium with SM?

YES

$$n_\chi \sim n_\gamma \sim T^3$$

Where did its density go?

Visible matter

Was DM ever in equilibrium with SM?

YES

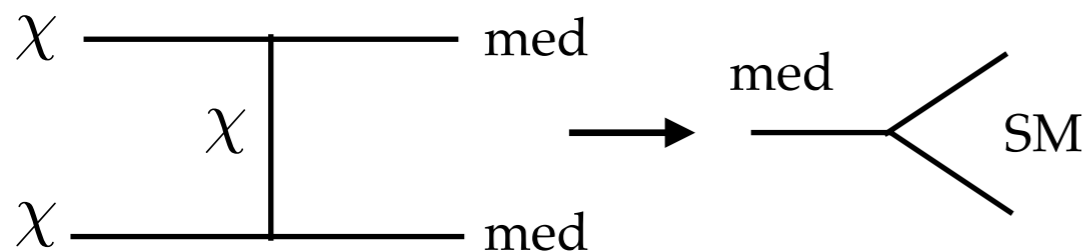
$$n_\chi \sim n_\gamma \sim T^3$$

Where did its density go?

Visible matter

$$m_\chi > m_{\text{med}}$$

Hidden Annihilation



Two step process

e.g. Secluded, SIMP, ELDER...

Motivates new force searches

Was DM ever in equilibrium with SM?

YES

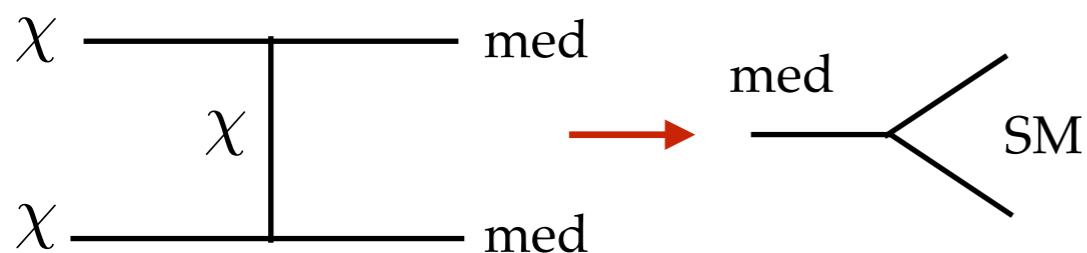
$$n_\chi \sim n_\gamma \sim T^3$$

Where did its density go?

Visible matter

$$m_\chi > m_{\text{med}}$$

Hidden Annihilation

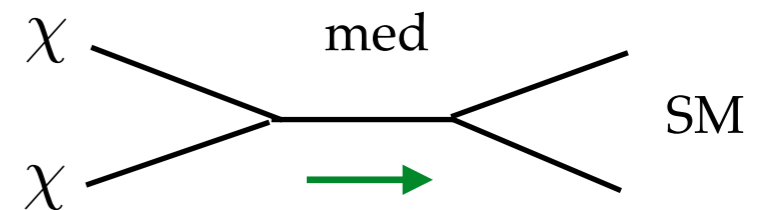


Two step process

e.g. Secluded, SIMP, ELDER...
Motivates new force searches

$$m_\chi < m_{\text{med}}$$

Direct Annihilation



One step process

Density set by SM coupling
Clear experimental targets

Q: What's so great about equilibrium?

A: Generic and easily achieved

Compare interaction rate
to expansion rate

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{\Lambda^2} (\bar{\chi} \gamma^\mu \chi) (\bar{f} \gamma_\mu f)$$

$$H \sim n \sigma v \quad \Rightarrow \quad \frac{T^2}{m_{Pl}} \sim \frac{g^2 T^5}{\Lambda^4} \Big|_{T=m_\chi}$$

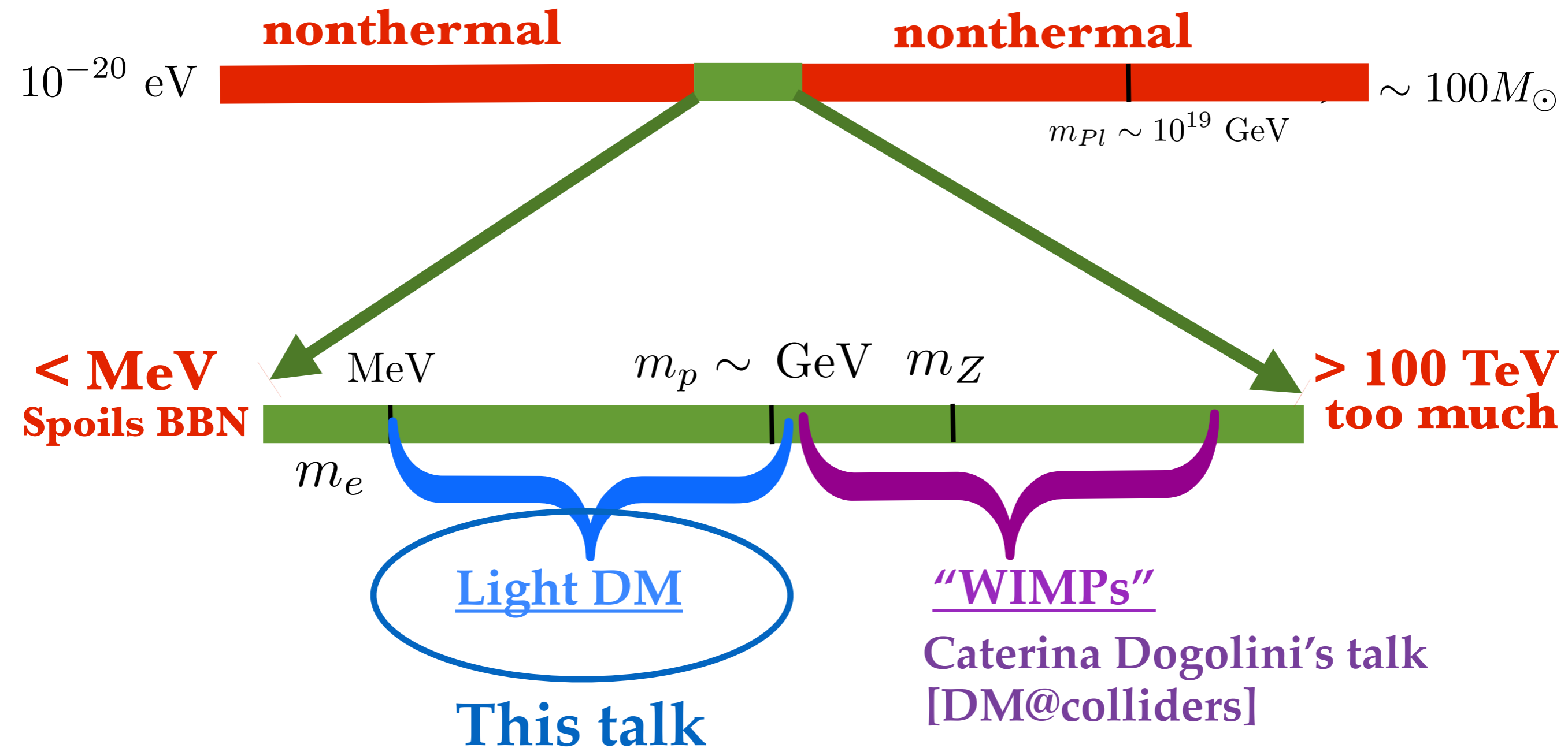
Equilibrium condition

$$g \gtrsim 10^{-8} \left(\frac{\Lambda}{10 \text{ GeV}} \right)^2 \left(\frac{\text{GeV}}{m_\chi} \right)^{3/2}$$

All* DM testable @ accelerators was once in equilibrium

Q: What's so great about equilibrium?

A: Narrows Viable Mass Range (!)



Light DM vs. WIMPs : General Issues

LDM must be neutral under SM

Else would have been discovered @ LEP / Tevatron / LHC...

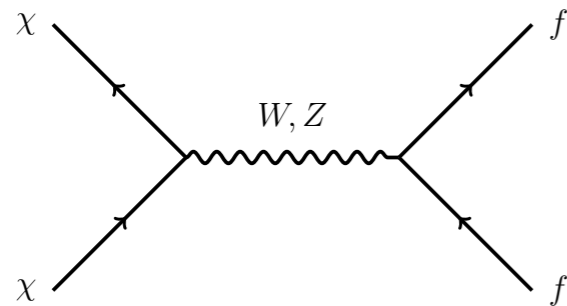
Light DM vs. WIMPs : General Issues

LDM must be neutral under SM

Else would have been discovered @ LEP / Tevatron / LHC...

LDM requires light new mediators

Overproduced without additional light, neutral “mediators”



$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29} \text{cm}^3 \text{s}^{-1} \left(\frac{m_\chi}{\text{GeV}} \right)^2$$

Lee/Weinberg '79

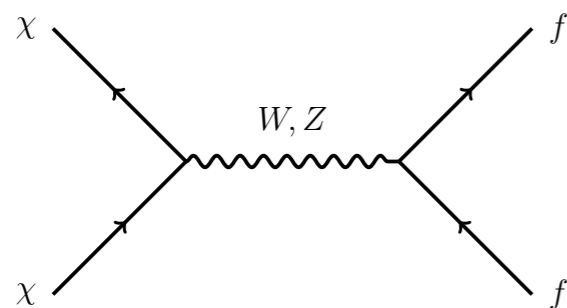
Light DM vs. WIMPs : General Issues

LDM must be neutral under SM

Else would have been discovered @ LEP / Tevatron / LHC...

LDM requires light new mediators

Overproduced without additional light, neutral “mediators”



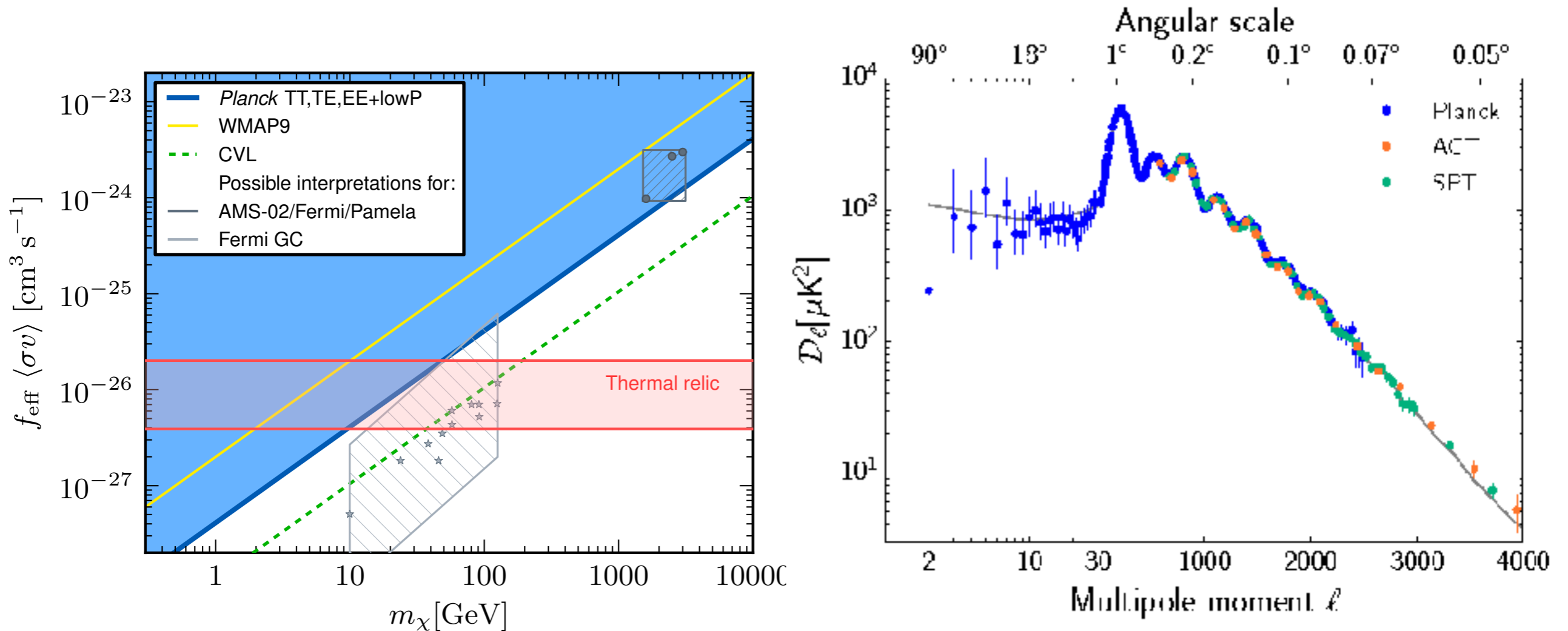
$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29} \text{cm}^3 \text{s}^{-1} \left(\frac{m_\chi}{\text{GeV}} \right)^2$$

Lee/Weinberg '79

LDM interactions renormalizable at accelerator energies

Else rate too small — greatly simplifies space of possible theories

Light DM vs. WIMPs : CMB Bounds



Planck Collaboration 1502.01589

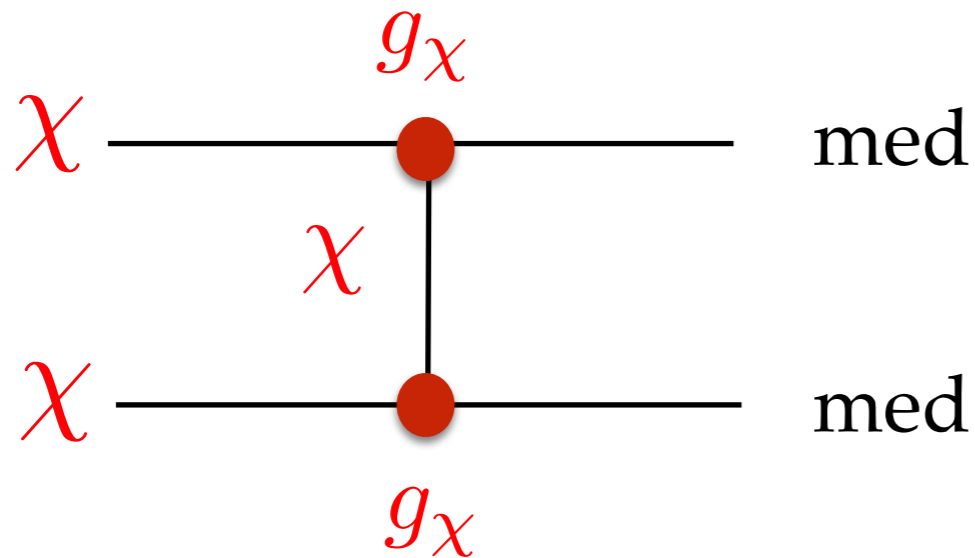
Rare out-of-equilibrium annihilation ionizes hydrogen @ CMB
CMB photons pass through extra plasma = bad

Rules out **s-wave** relic cross section for $\text{DM} < 10 \text{ GeV}$
No indirect detection for viable models!

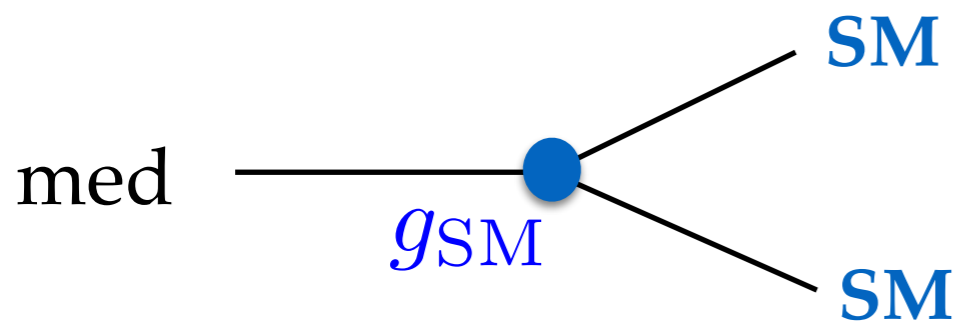
Who's Heavier: DM or Mediator?

Hidden Annihilation

$$m_\chi > m_{\text{med}}$$



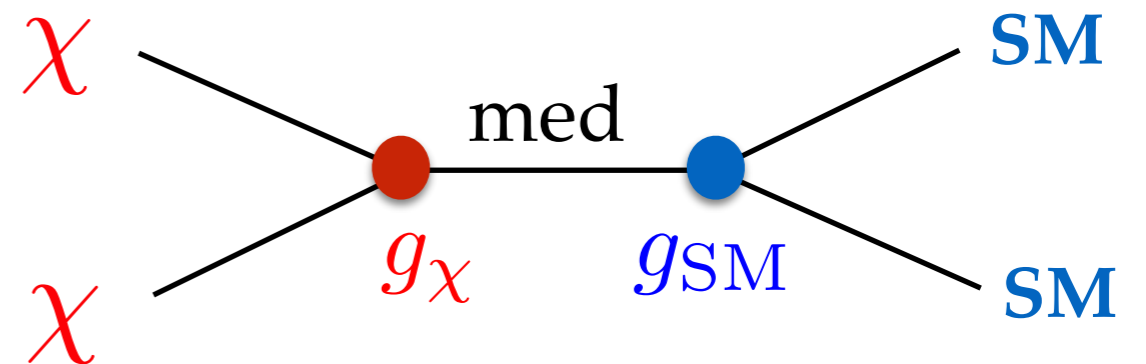
Abundance set by g_χ
No clear experimental target



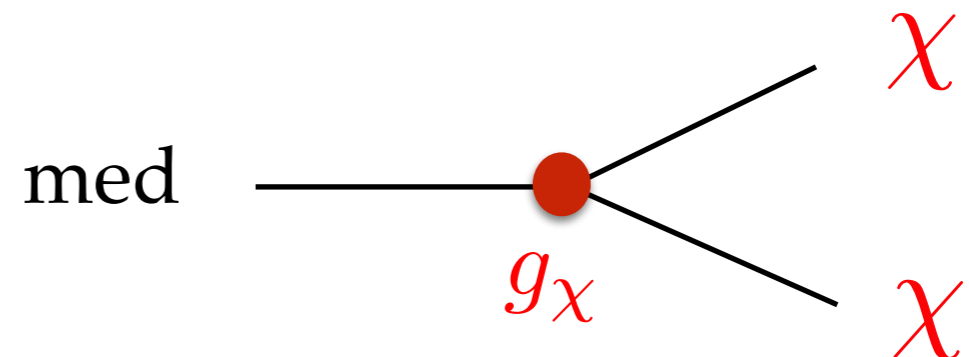
Mediator decays to **SM**

Direct Annihilation

$$m_\chi < m_{\text{med}}$$



Abundance depends on g_{SM}
Predictive thermal targets



Mediator decays to **DM**

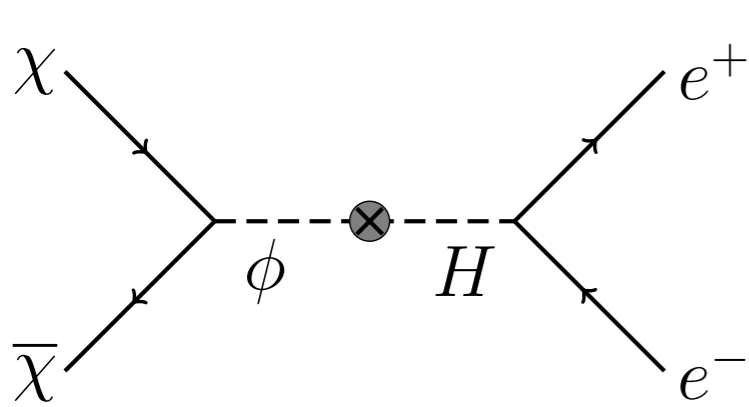
Overview

1) Why thermal DM?

2) **Direct annihilation: thermal targets**  **Theory**
Searches

3) “Hidden” annihilation: **visible decay searches**

What kind of mediator for **direct annihilation**? $m_\chi < m_{\text{med}}$

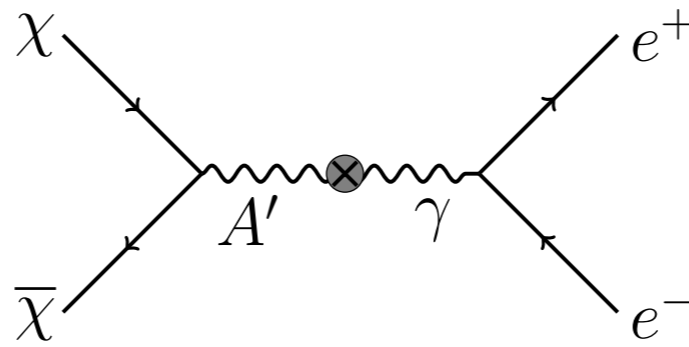


$$\epsilon \phi H^\dagger H$$

Neutral scalar
Mass mix w Higgs

$$\rightarrow \epsilon \phi \frac{m_f}{v} \bar{f} f$$

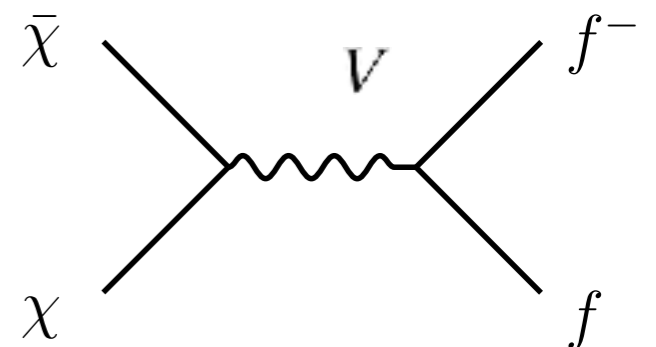
after EWSB



$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$

Dark photon A'
Kinetic mixing w/ γ

$$\rightarrow \epsilon A' J_{\text{EM}}^\mu$$



$$V_\mu J_{\text{SM}}^\mu$$

Gauge known global
quantum number

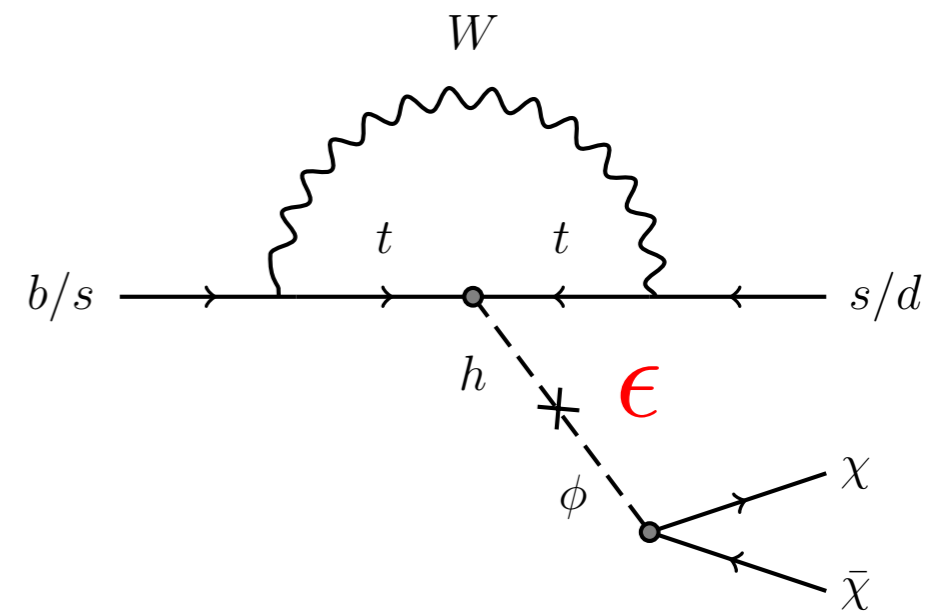
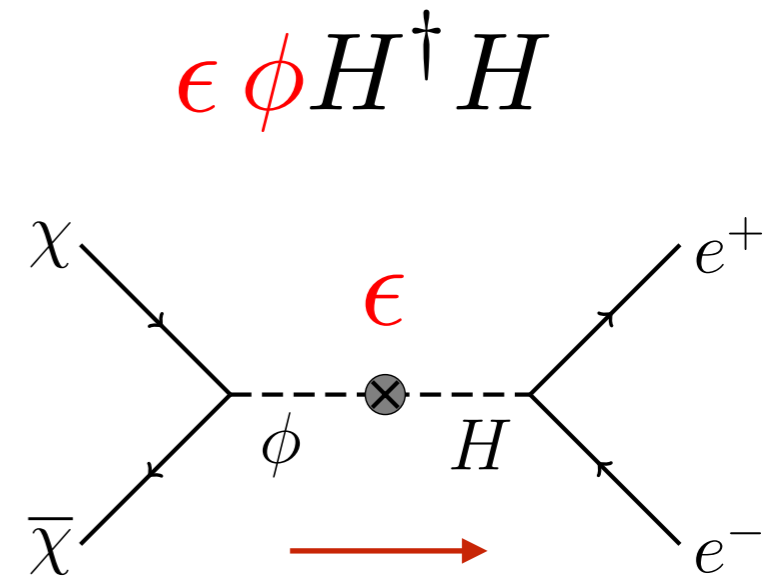
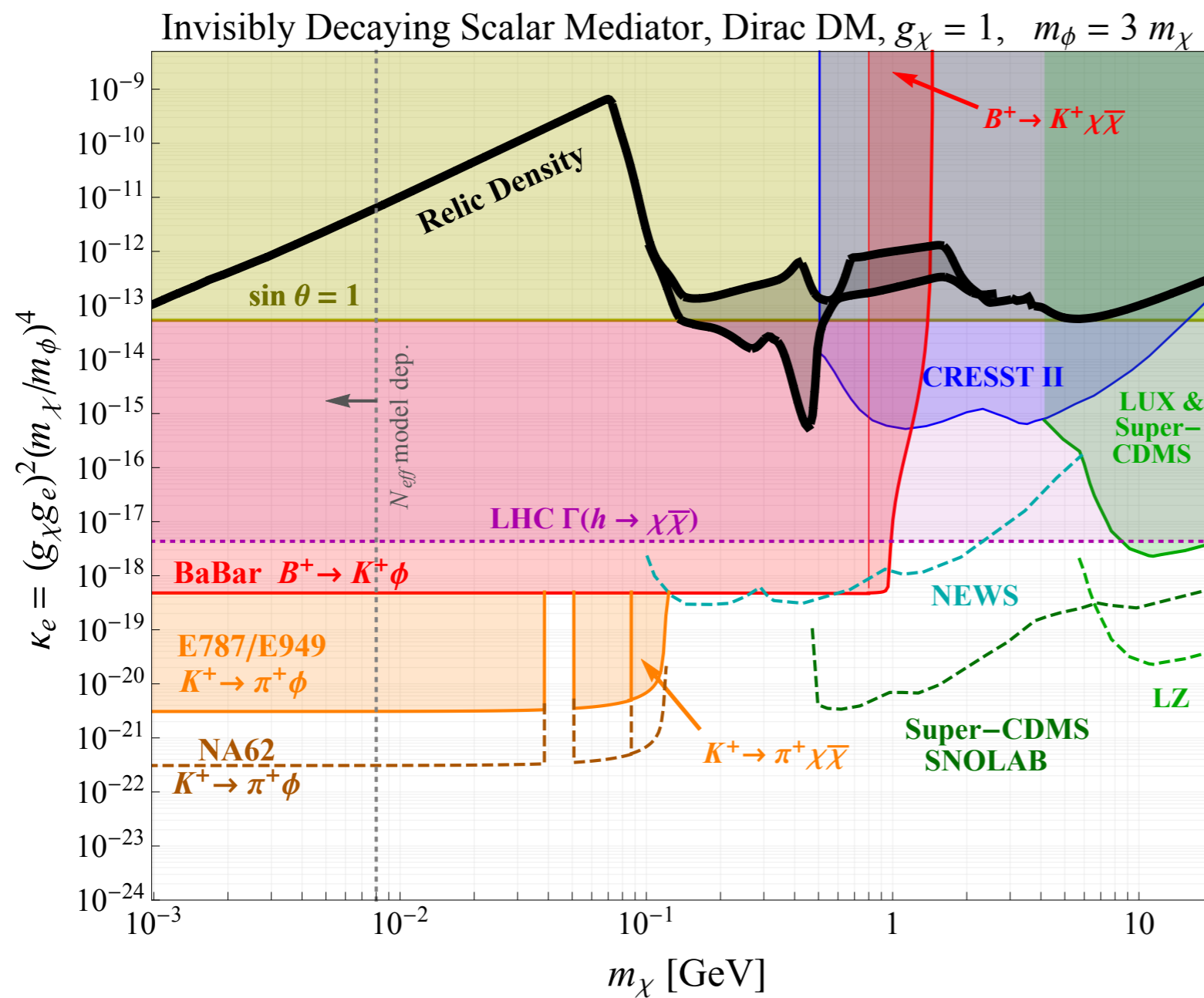
$$U(1)_{B-3L_i}$$

$$U(1)_{B-L}$$

$$U(1)_{L_i-L_j}$$

Complete list of renormalizable, anomaly-free options

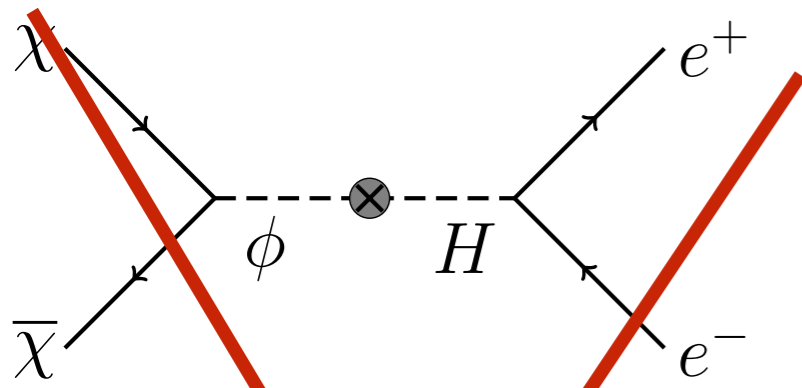
Scalar-mediated **direct-annihilation** ruled out!



Exclusion independent of DM candidate

GK 1512.04119

What kind of mediator for **direct annihilation**?

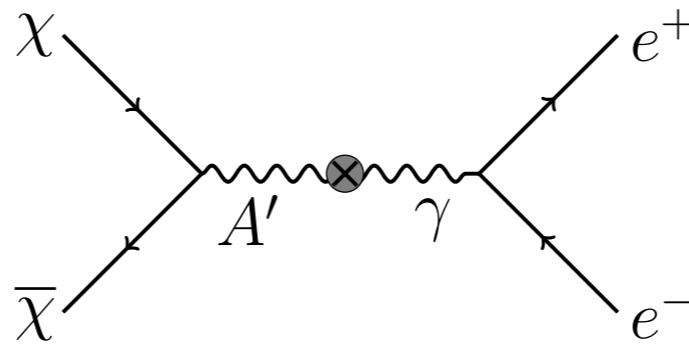


$$\epsilon \phi H^\dagger H$$

Neutral scalar
Mass mixing w Higgs

$$\rightarrow \epsilon \phi \frac{m_f}{v} \bar{f} f$$

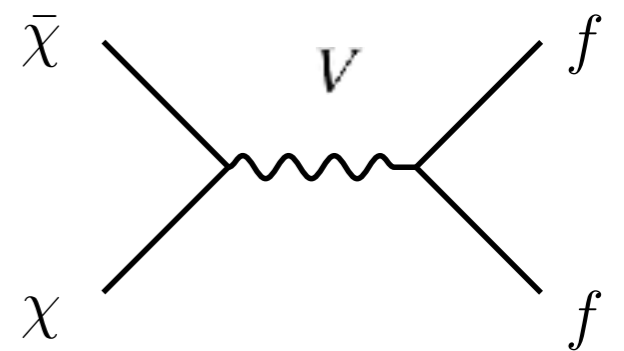
Direct annihilation
Ruled out



$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$

Dark photon A'
Kinetic mixing w γ

$$\rightarrow \epsilon A' J_{\text{EM}}^\mu$$



$$V_\mu J_{\text{SM}}^\mu$$

Gauge known global
quantum number

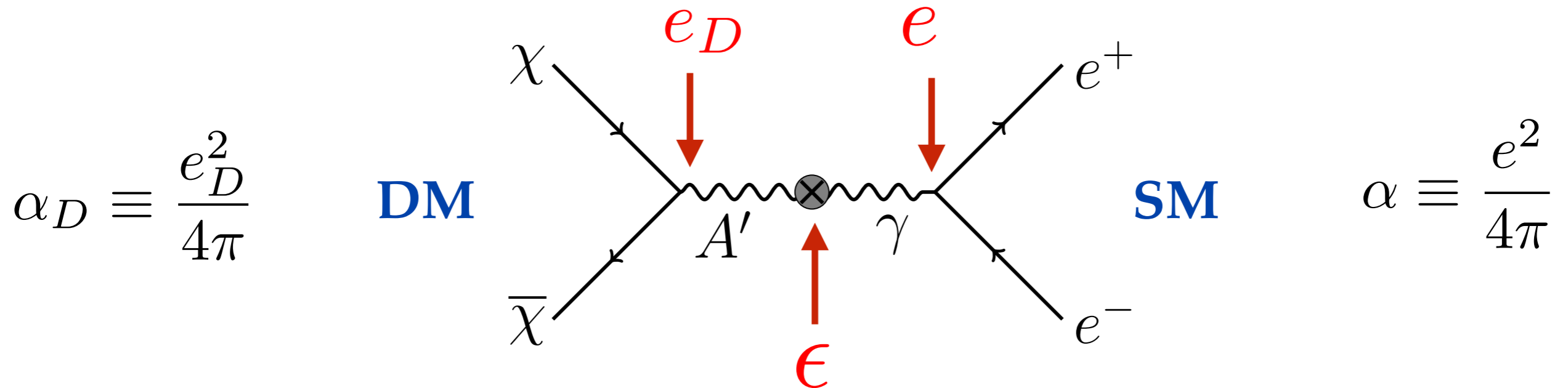
$$U(1)_{B-3L_i}$$

$$U(1)_{B-L}$$

$$U(1)_{L_i-L_j}$$

Similar pheno, different details/bounds

Representative Model: Dark Photon Mediator A'



Critical freeze out value of y for each DM candidate

$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2} \qquad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}} \right)^4$$

Direct annihilation $m_{A'} > m_\chi$

Unitarity $\alpha_D \lesssim 1$

\Rightarrow Minimum SM coupling ϵ required for thermal freeze out

Finite list of CMB-safe DM candidates

$$\mathcal{L} \supset g_D A'_\mu J^\mu_\chi$$

$$J^\mu_\chi = \begin{cases} \bar{\chi} \gamma^\mu \chi & \text{Asym. Dirac} \\ \bar{\chi}_1 \gamma^\mu \chi_2 & \text{Pseudo-Dirac} \\ \frac{1}{2} \bar{\chi} \gamma^\mu \gamma^5 \chi & \text{Majorana} \\ i \chi^* \partial_\mu \chi & \text{Scalar} \end{cases}$$

$\bar{\chi}$ all annihilate away pre-CMB
 no more **annihilation** partners

Heavier χ_2 decays pre-CMB
 no more **coannihilation** partners

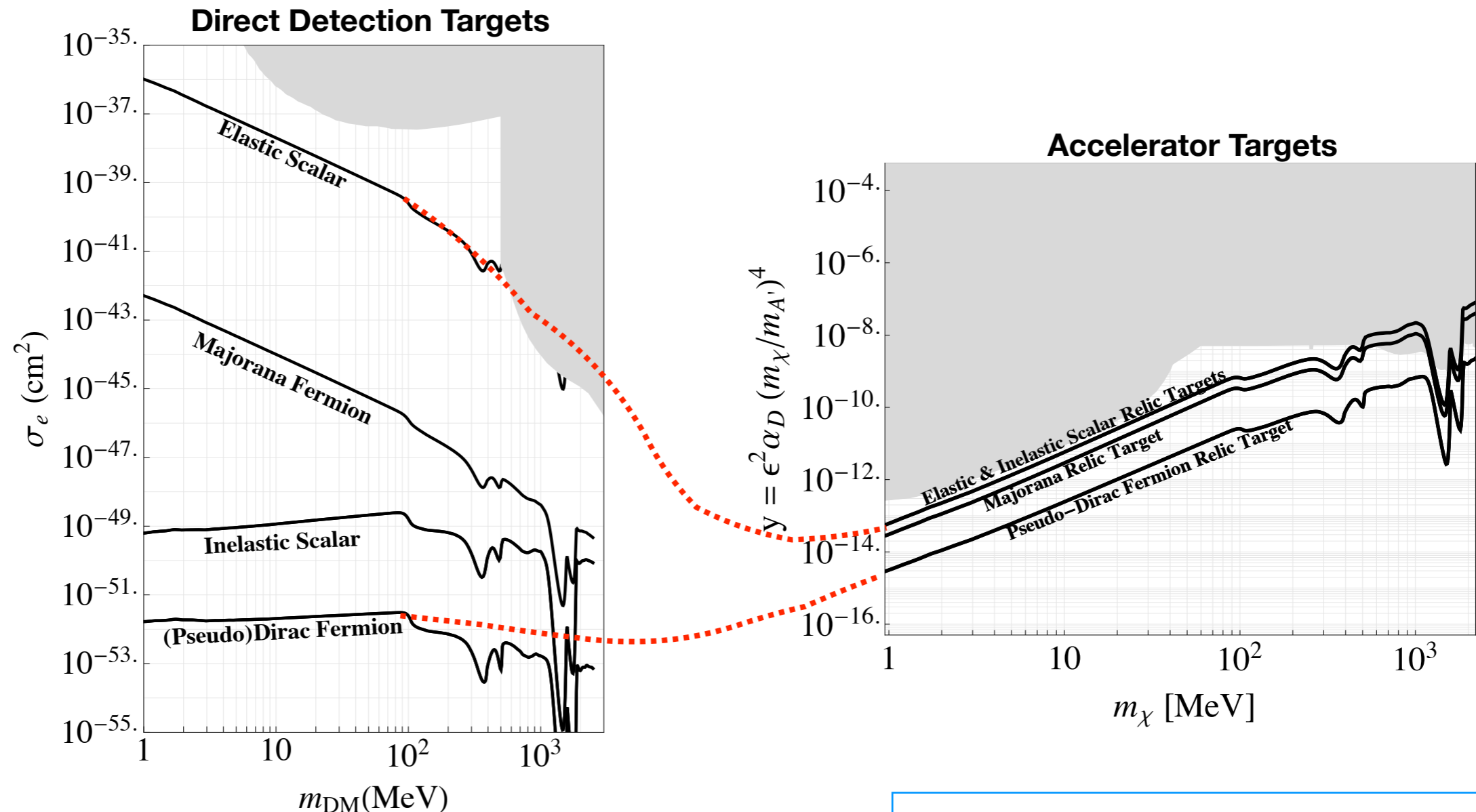
$\sigma v \propto v^2$ velocity redshifts
 tiny annihilation rate at CMB

Safe models require either:

P-wave annihilation
 Scalar or Majorana

Different DM population @ CMB
 Asymmetric Dirac or Pseudo-Dirac

Why Accelerators? Accessible Thermal Targets



non-relativistic cross sections can
be loop- or velocity- suppressed

Relativistic freeze-out kinematics

Calculable dark matter rate

No astrophysical uncertainties

Thermal targets within reach

Overview

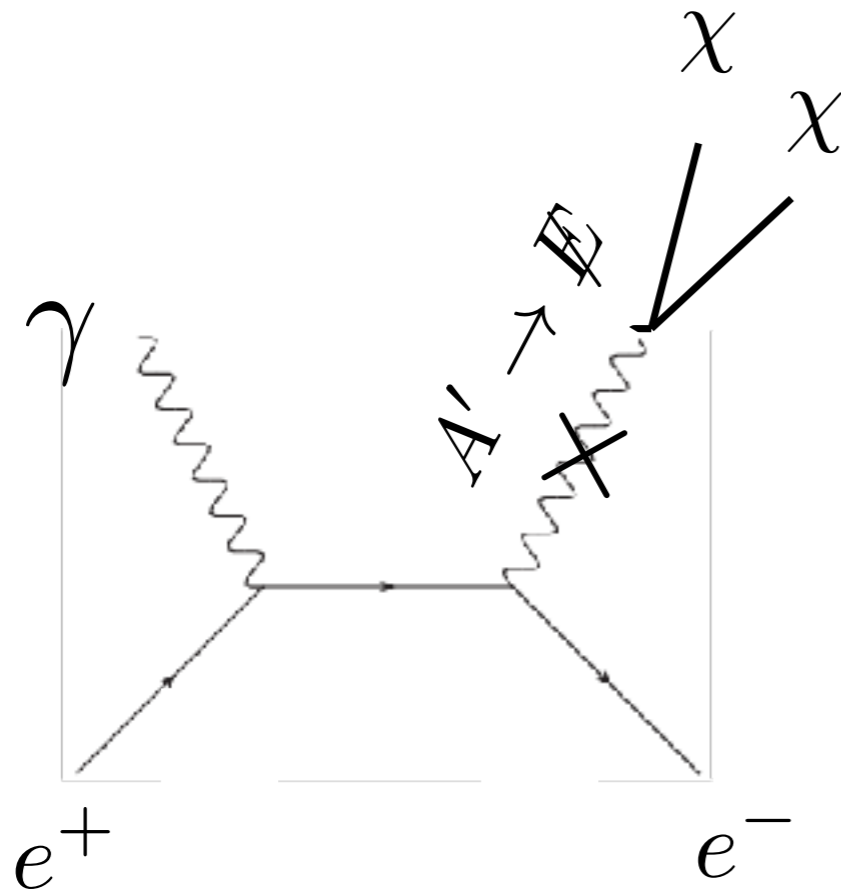
1) Why thermal DM?

2) **Direct annihilation: thermal targets**  **Theory**
Searches

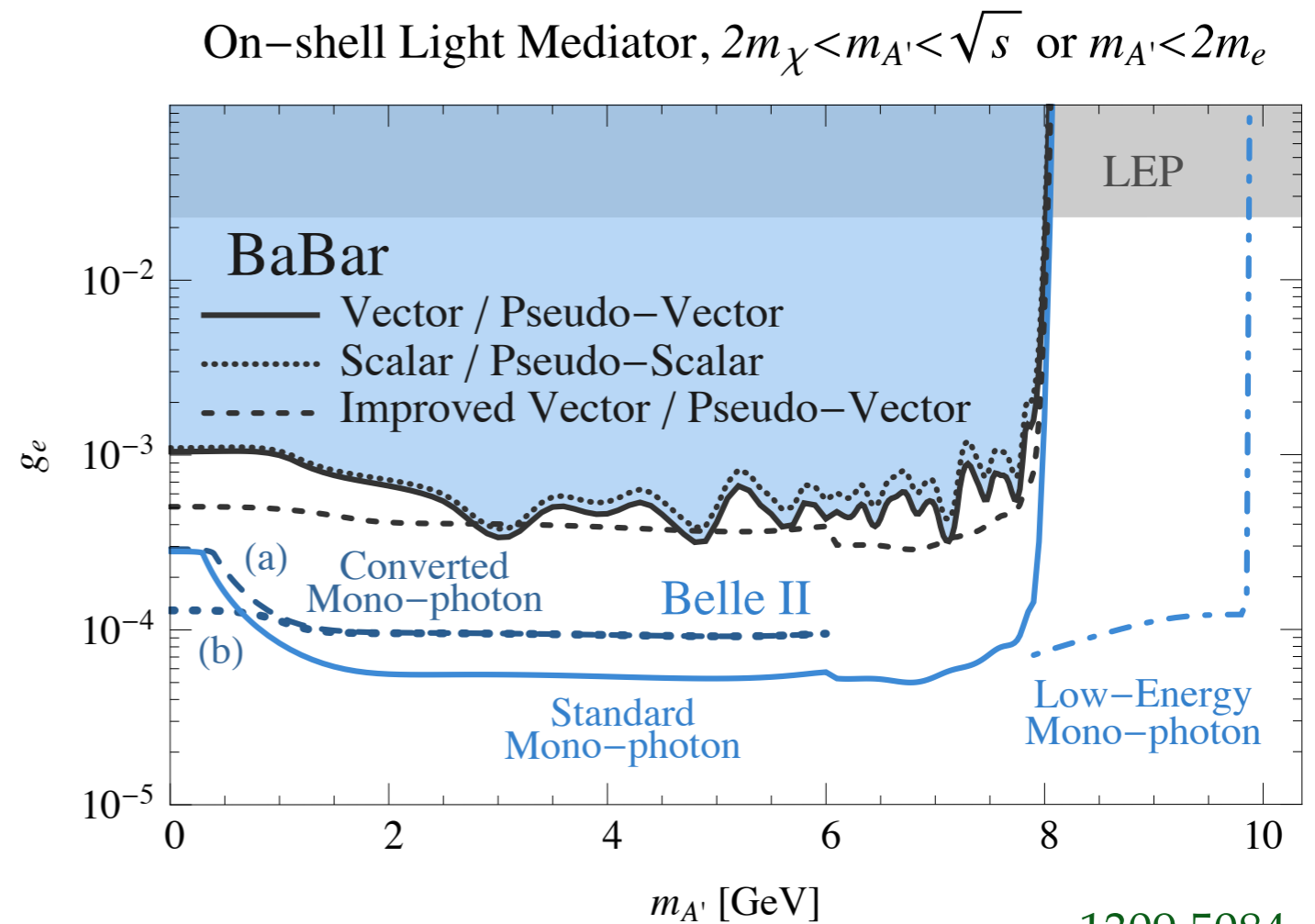
3) “Hidden” annihilation: **visible decay searches**

B-Factory Strategy

Mono photon missing energy bump search: BABAR, Belle II



$$m_{A'}^2 = (p_\gamma - p_{e^+} - p_{e^-})^2$$



1309.5084

CM energy known ~ 10 GeV

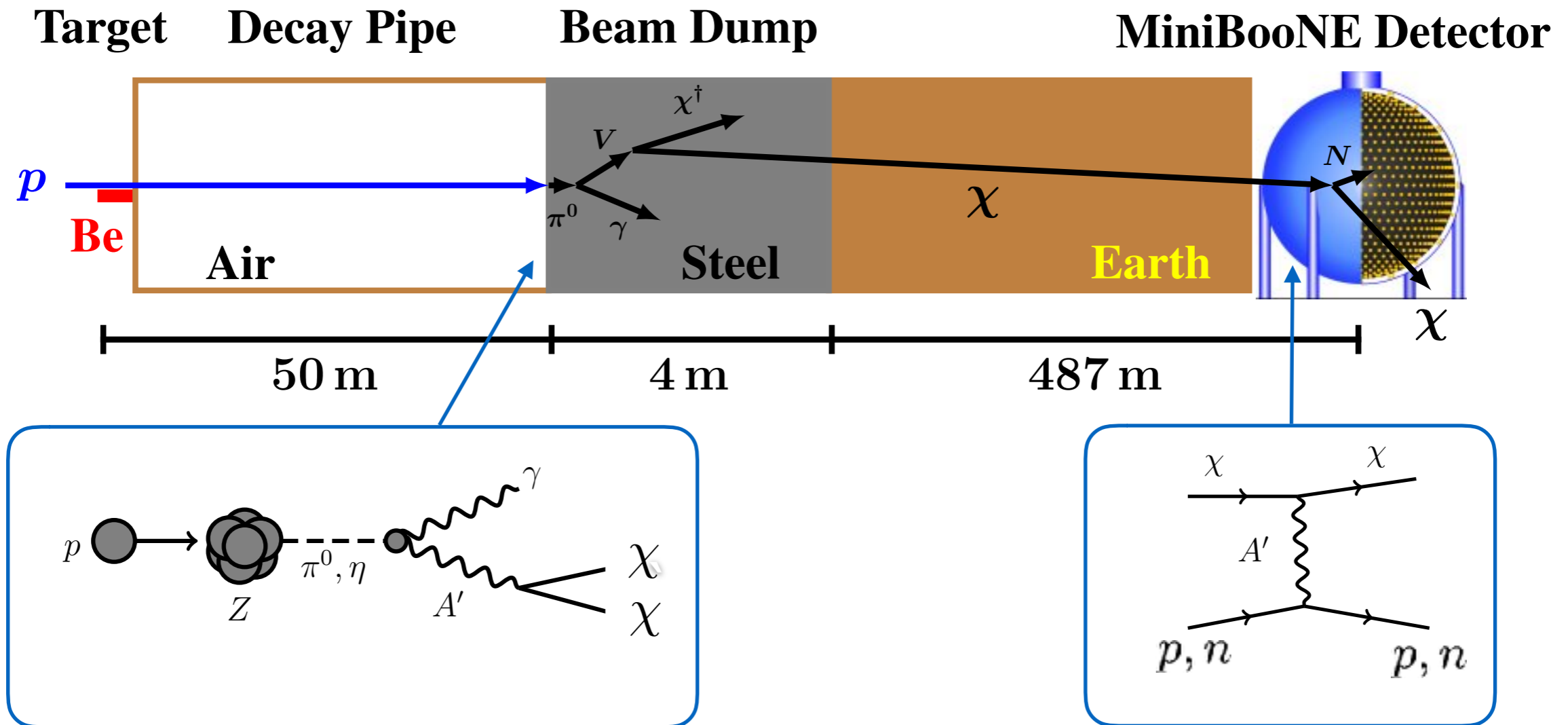
Izaguirre, GK, Schuster, Toro 1307.6554

Essig, Mardon, Papucci, Volansky Zhong 1309.5084

BABAR Collaboration arXiv:1702.03327

Proton Beam Dumps

“Relativistic direct detection” Existing bounds from LSND, MiniBooNE



Step 1: Make relativistic DM in target

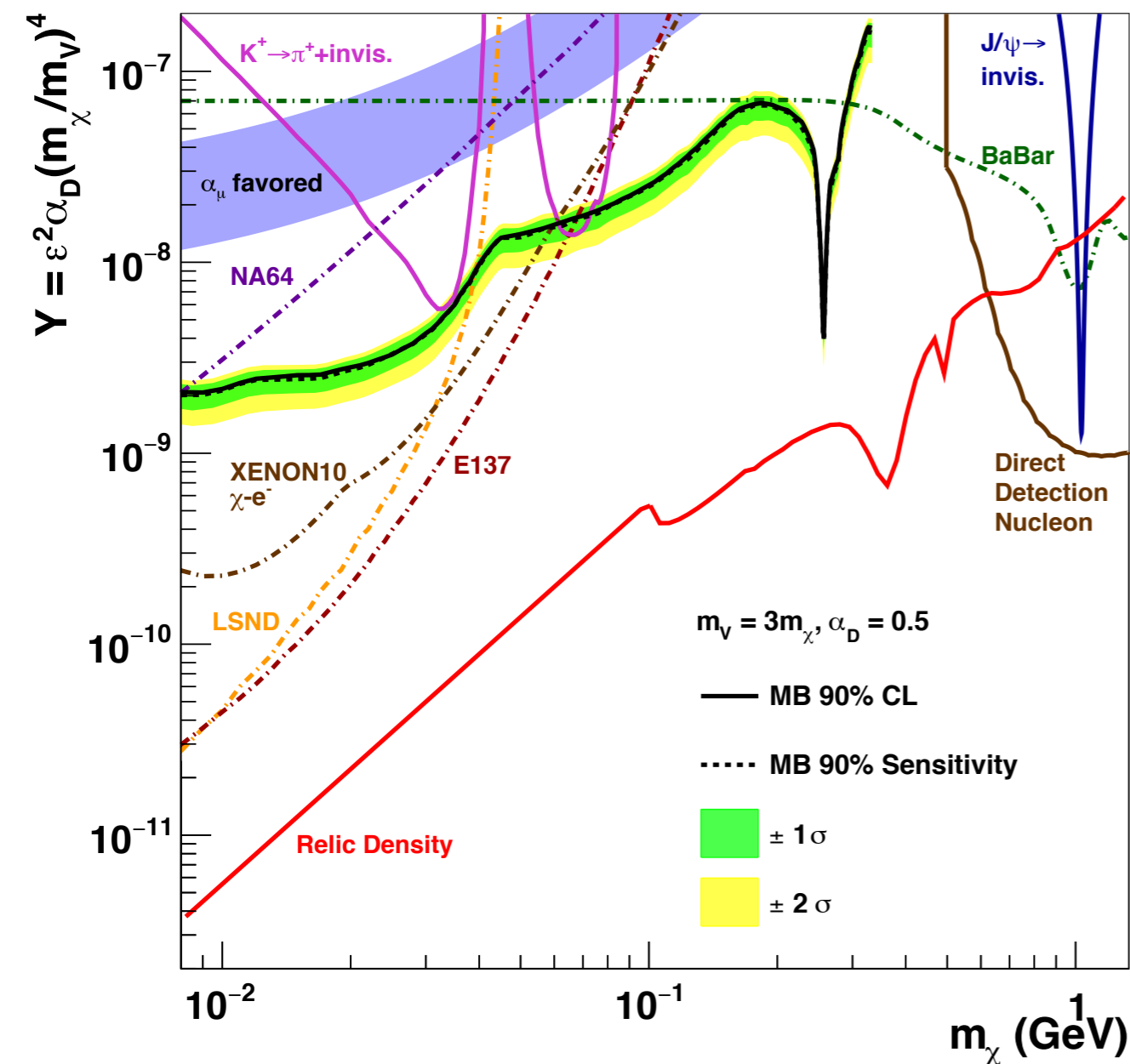
Step 2: DM scatters in detector

Batell, Pospelov, Ritz 0903.0363
 deNiverville, Pospelov, Ritz 1107.4580
 Izaguirre, GK, Schuster, Toro 1307.6554

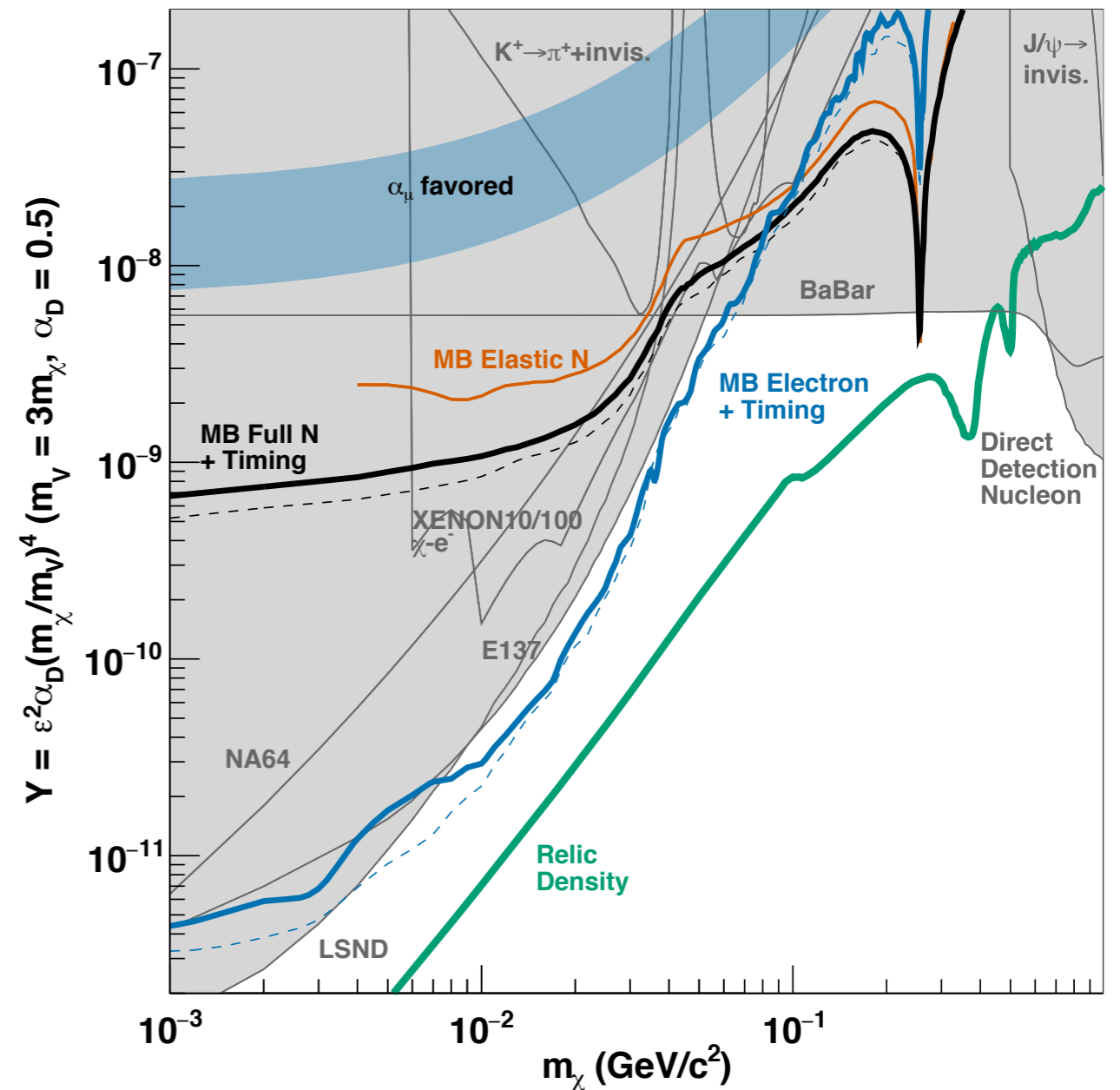
$$[\text{production}] \times [\text{detection}] \propto \epsilon^4$$

Proton Beam Dumps

Latest results from MinBooNE 2018. First dedicated search for LDM



MiniBooNE Collaboration Phys. Rev. Lett. 118 (2017)

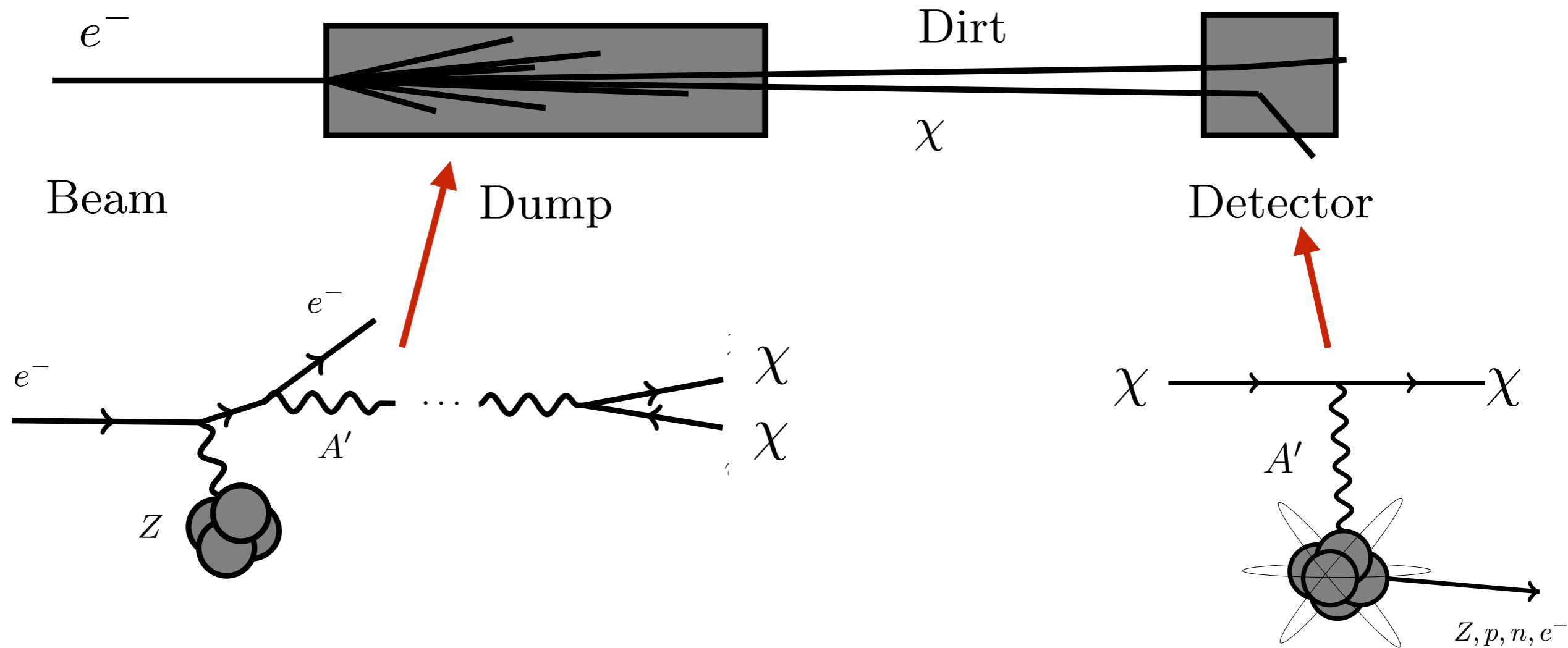


MiniBooNE Collaboration 1807.06137

See Xiaoyong Chu's talk

Electron Beam Dumps

Place simple detector behind existing beam dumps (JLab/SLAC...)



Step 1: Make relativistic DM in target

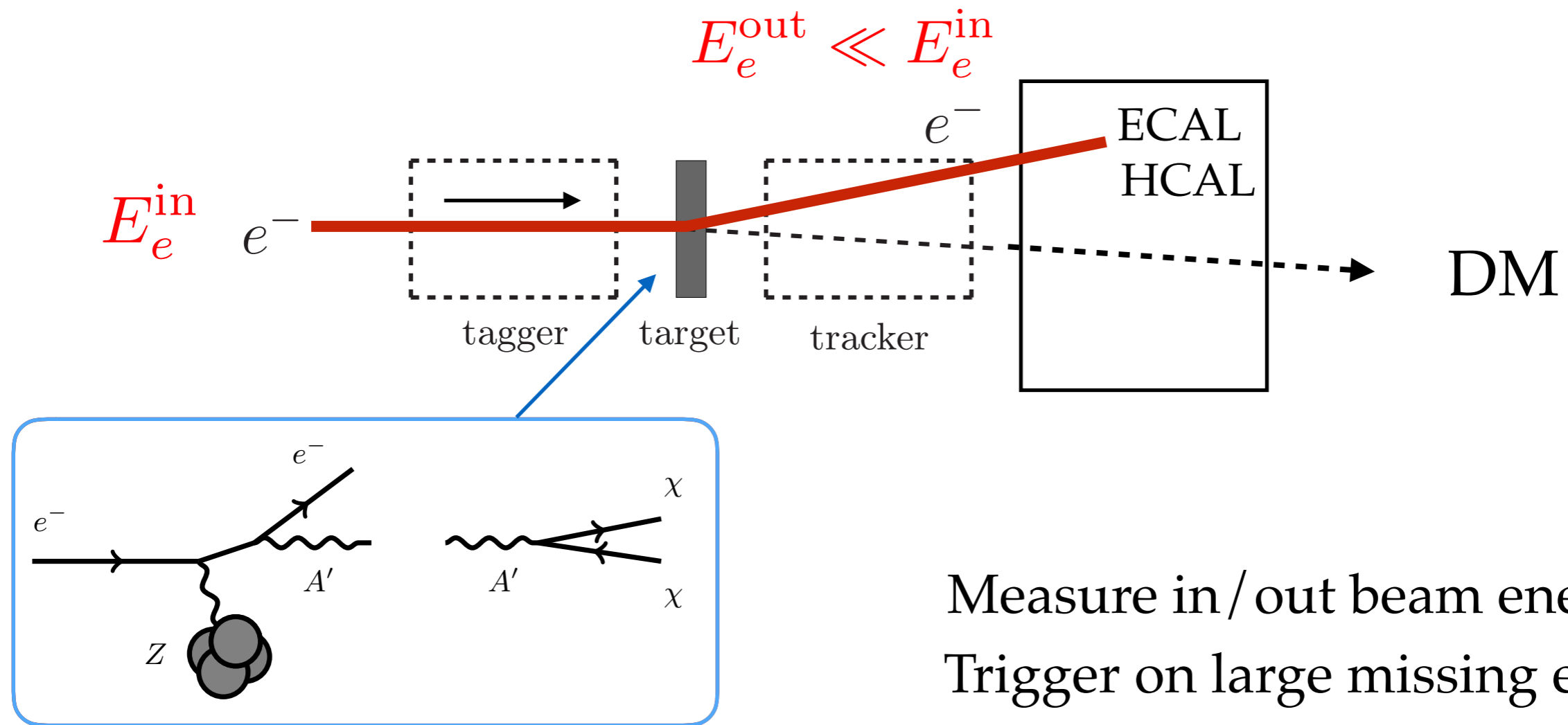
Step 2: DM scatters in detector

Izaguirre, GK, Schuster, Toro 1307.6554
 Batell, Essig, Zurjuron 1406.2698
 BDX Collaboration 1406.3028

$$[\text{production}] \times [\text{detection}] \propto \epsilon^4$$

Missing Momentum Strategy

Signal is the **electron or muon beam** itself: LDMX, NA64, M³
If DM is produced, beam loses large energy fraction



Measure in / out beam energy
Trigger on large missing energy
Veto all other SM activity

Izaguirre, GK, Schuster, Toro 1411.1404

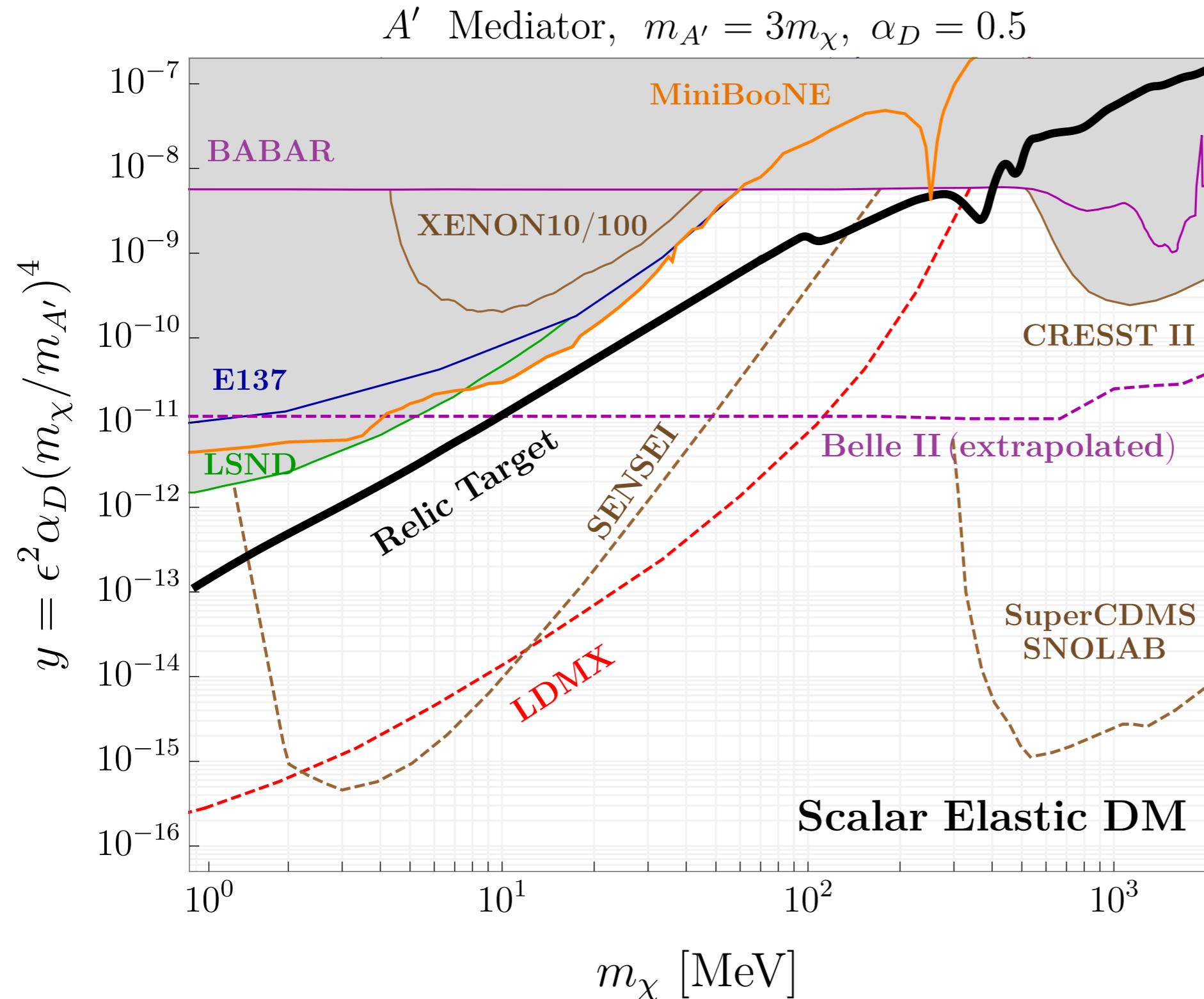
Gninenko, Krasnikov, et al 1604.08432

NA64 Collaboration 1610.02988

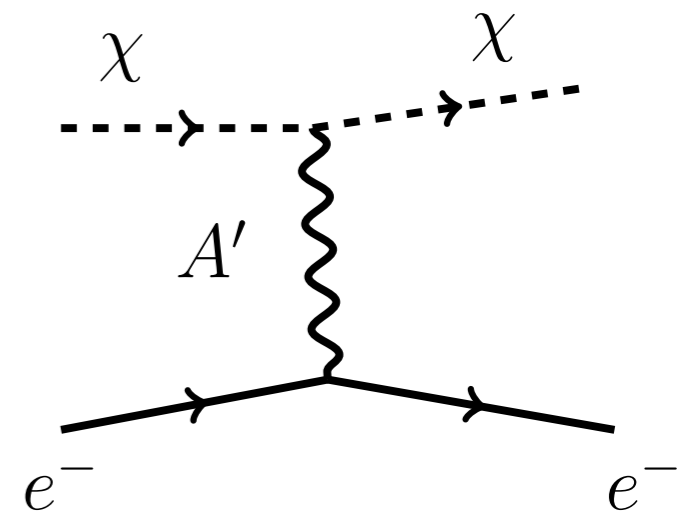
LDMX Collaboration 1808.05219

See Andrea Celentano's talk

Comprehensive Coverage: Dark Photon Mediator A'



Spin-0 Scalar DM

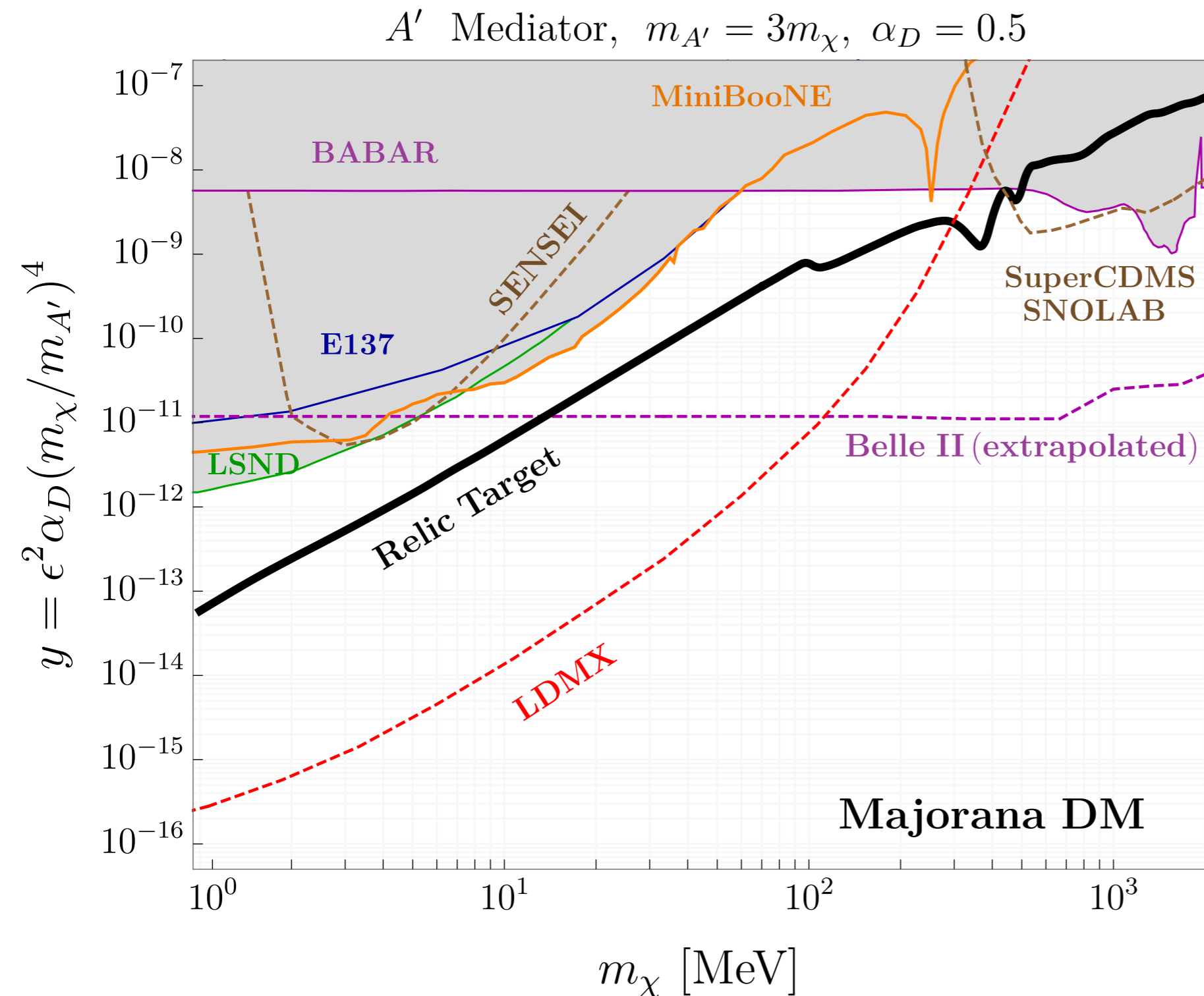


$$A'_\mu \chi^* \partial_\mu \chi$$

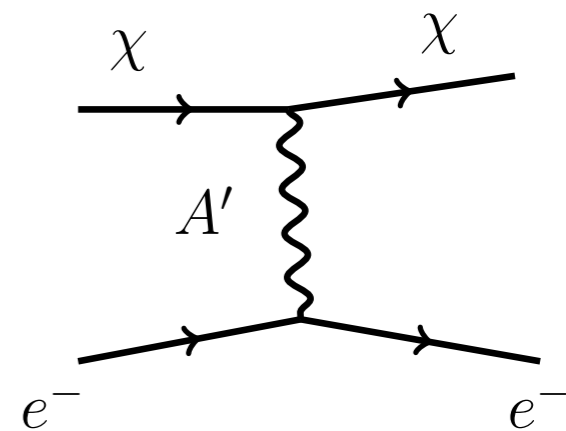
CMB safe

Direct annihilation
p-wave suppressed
at recombination

Comprehensive Coverage: Dark Photon Mediator A'



Spin-1/2 Majorana DM

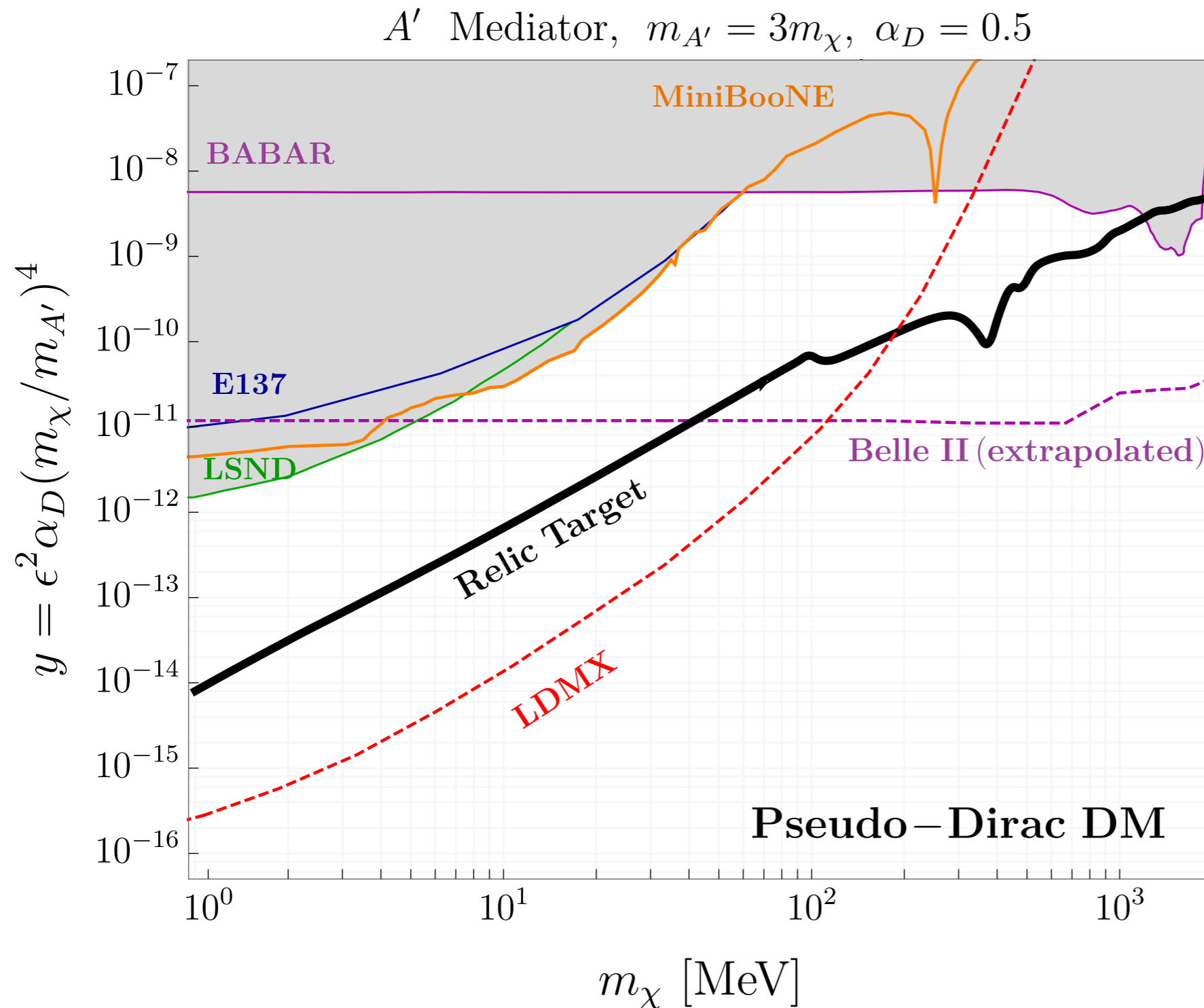


$$A'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

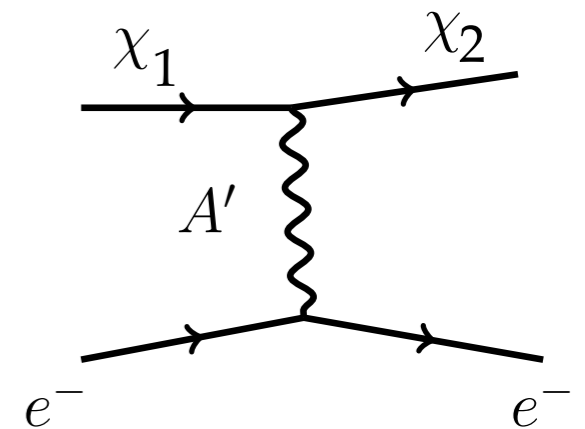
CMB safe

Direct annihilation
p-wave suppressed
at recombination

Comprehensive Coverage: Dark Photon Mediator A'



Pseudo-Dirac DM

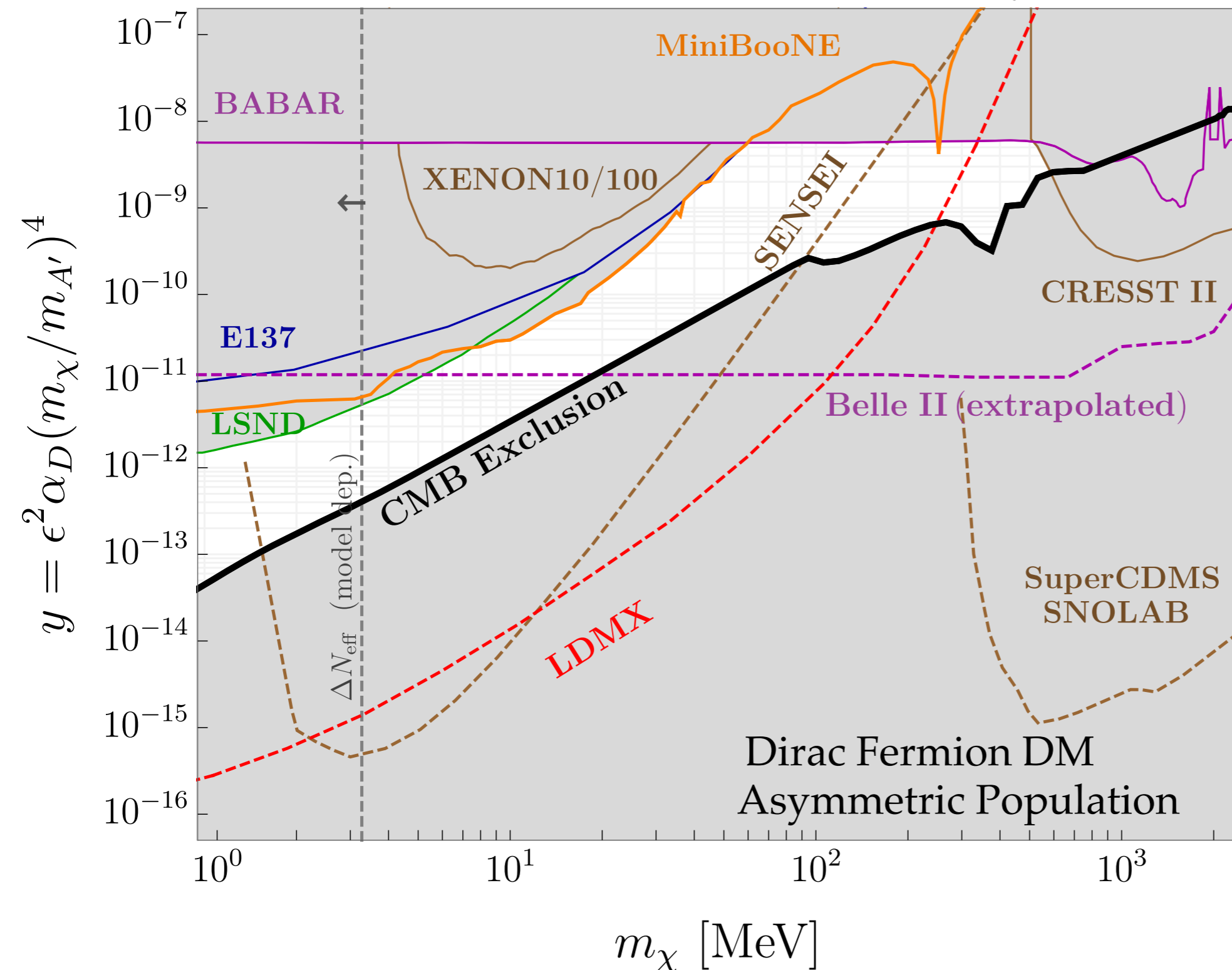


$$A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2$$

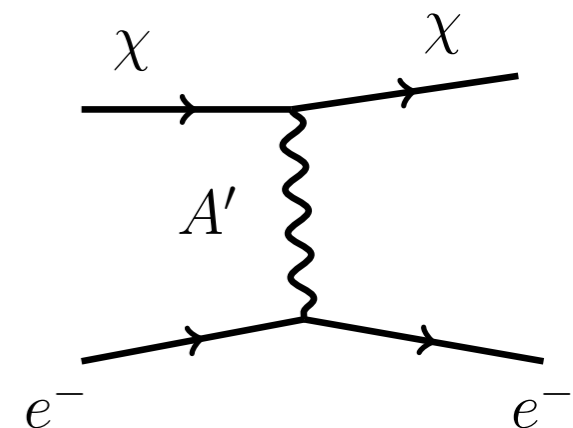
CMB safe
heavier partner χ_2
decays before
recombination

Comprehensive Coverage: Dark Photon Mediator A'

Asymmetric DM, A' Mediator, $m_{A'} = 3m_\chi$, $\alpha_D = 0.5$



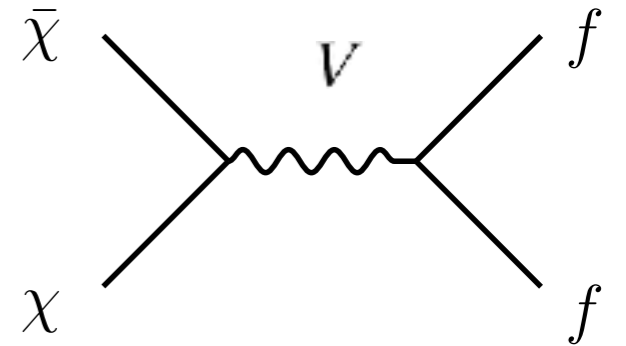
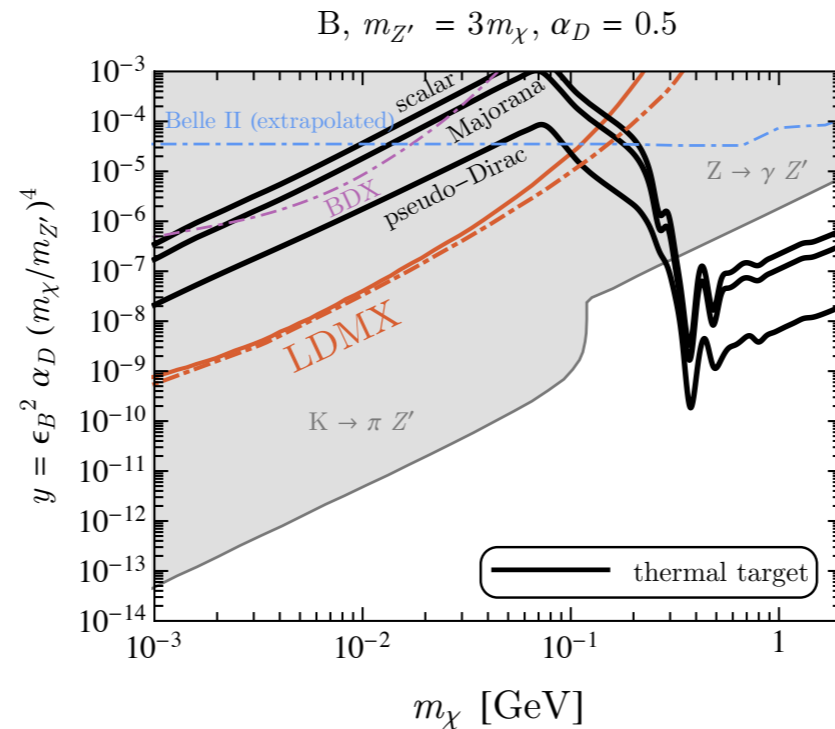
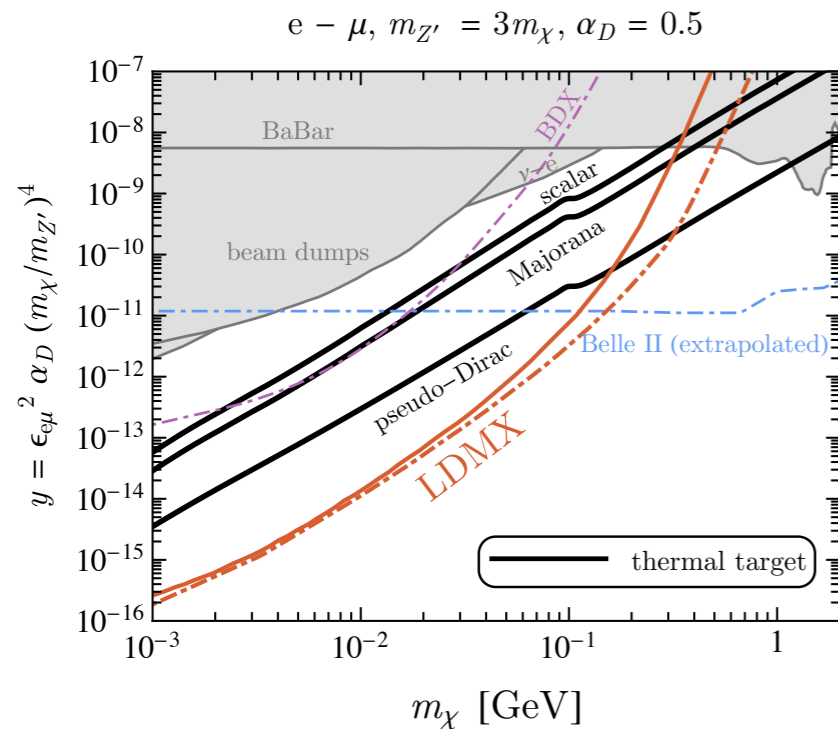
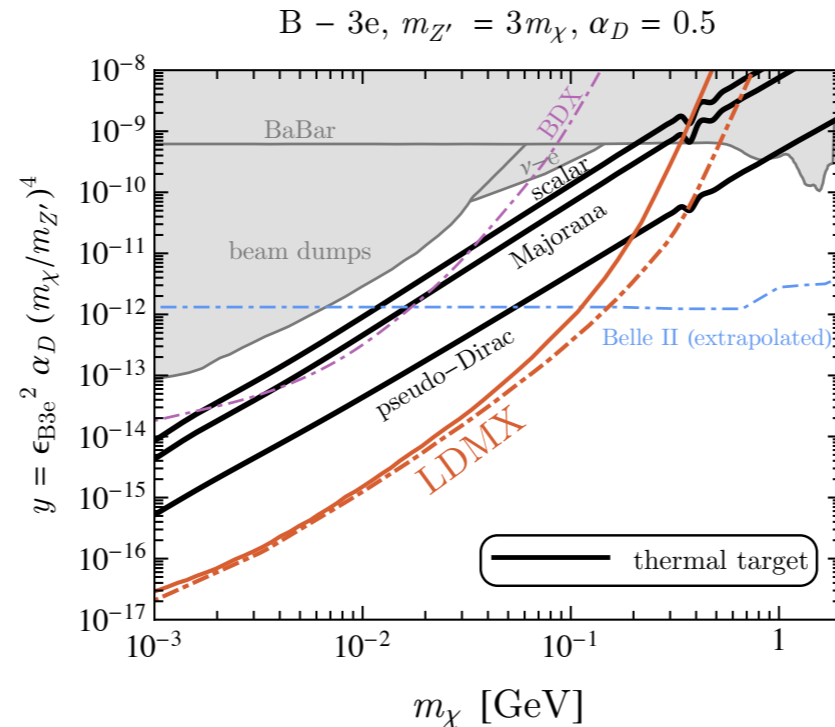
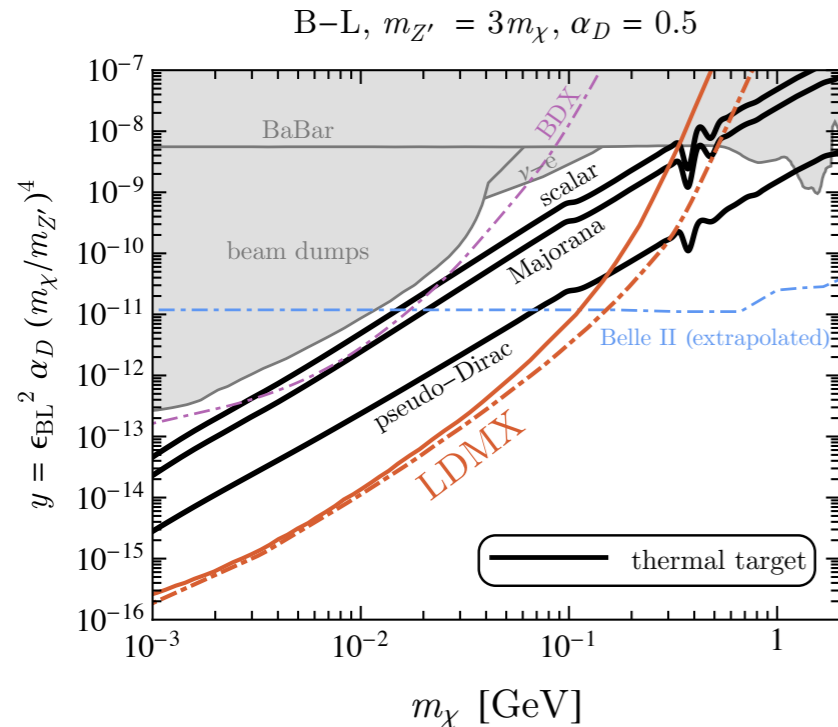
Dirac DM



$$A'_\mu \bar{\chi} \gamma^\mu \chi$$

CMB safe
antiparticles
gone before
recombination

What About Other Viable Mediators?



$$V_\mu J_{SM}^\mu$$

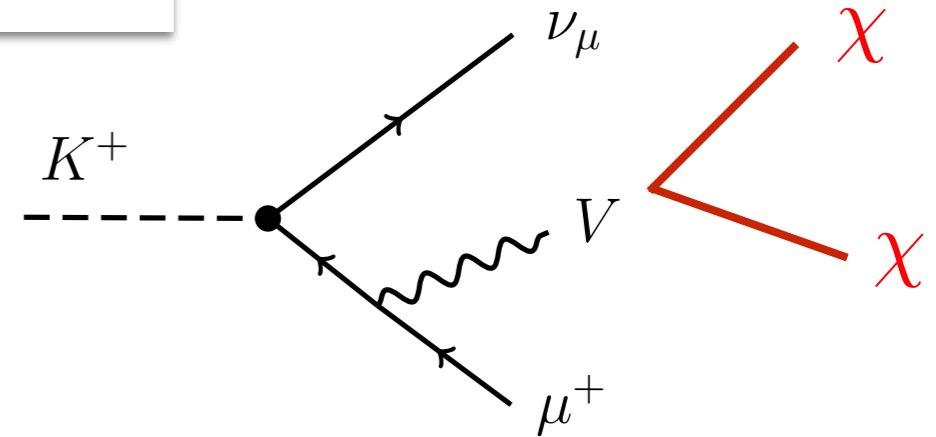
Gauge known global quantum number

$$U(1)_{B-3L_i}$$

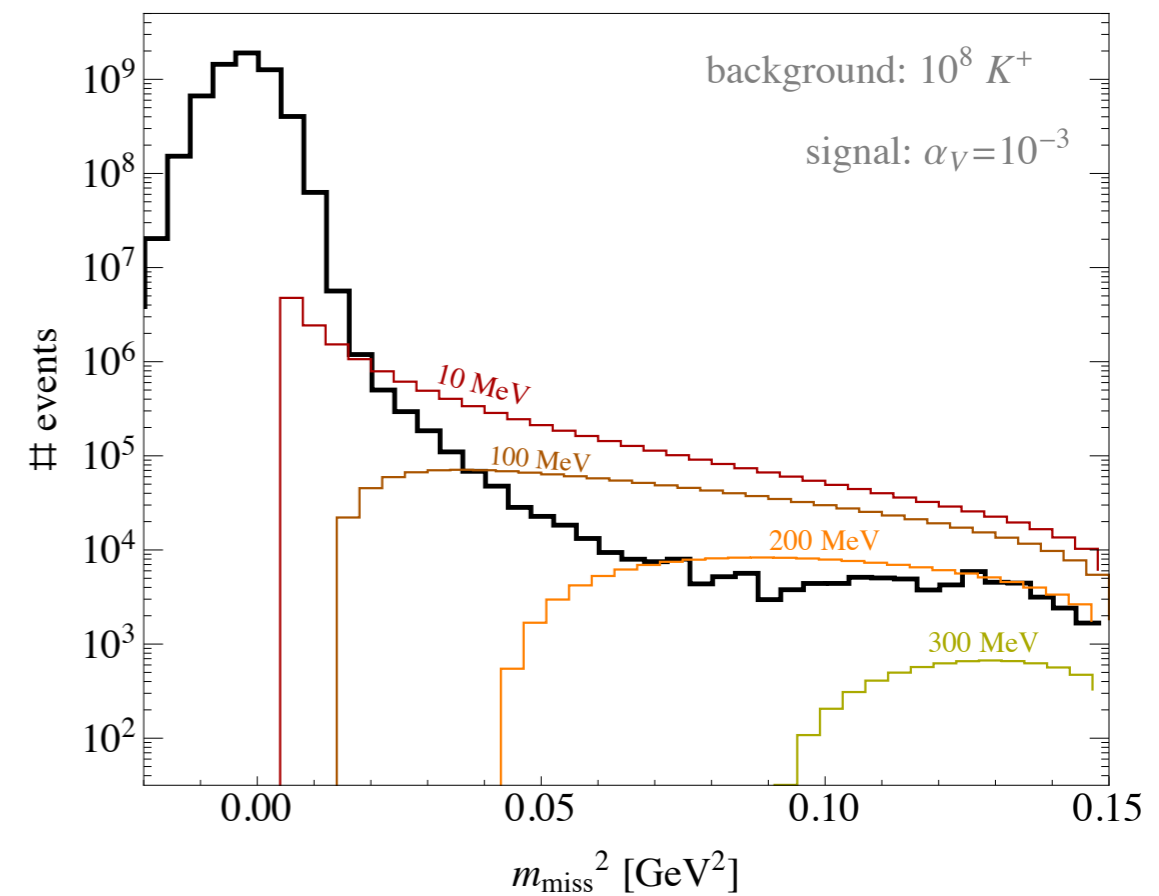
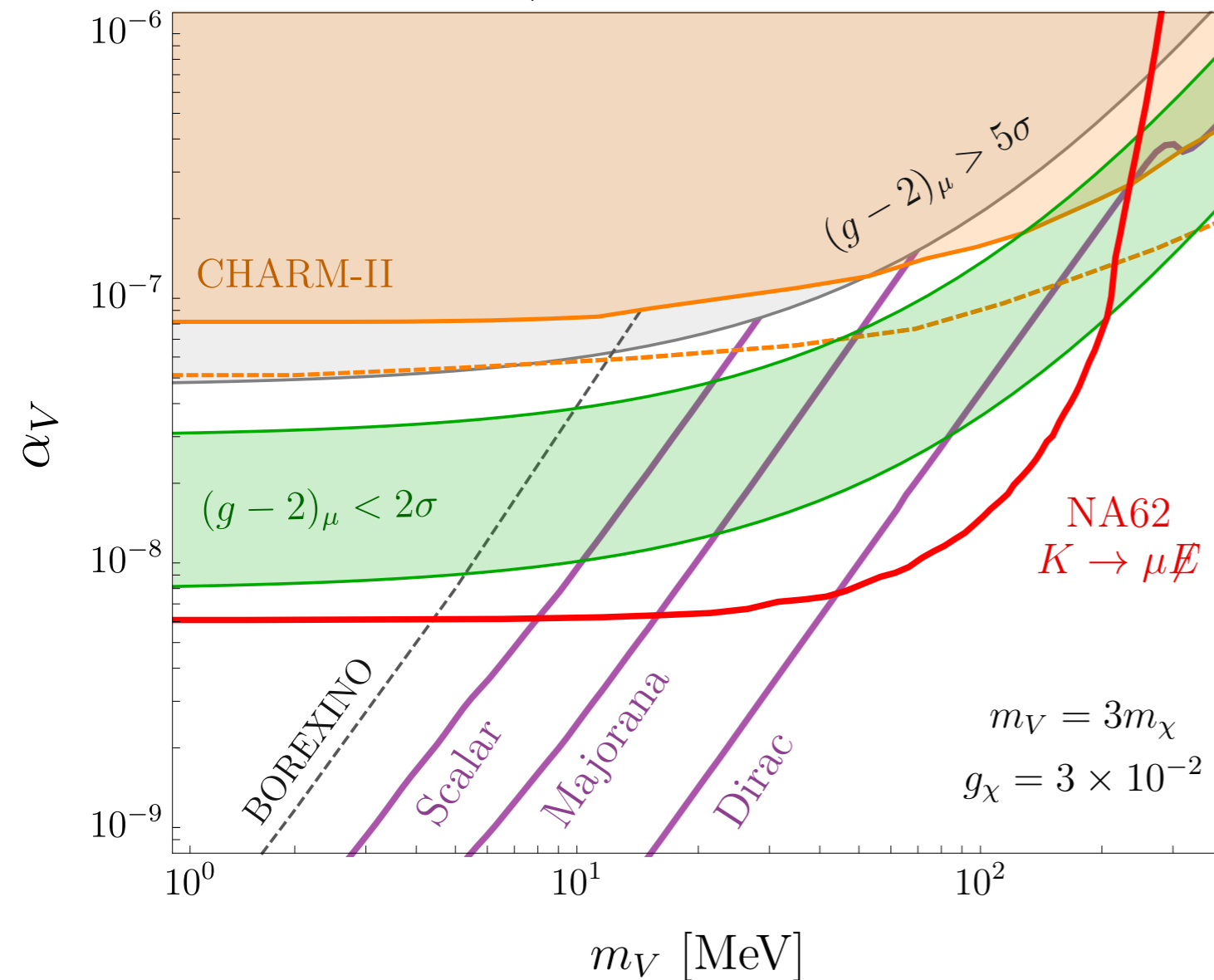
$$U(1)_{B-L}$$

$$U(1)_{L_i-L_j}$$

Kaon Decay Strategy: NA62



Vector Model : $L_\mu - L_\tau$ Gauge Boson + Dark Matter



$$m_{\text{miss}}^2 = (P_X + P_{\nu_\mu})^2 = (P_K - P_\mu)^2$$

Reece, Wang 0904.1743

Ibe, Nakano, Suzuki 1611.08460

GK, Marques-Tavares, Koshuka, Redigolo 1902.07715

Was DM ever in equilibrium with SM?

YES

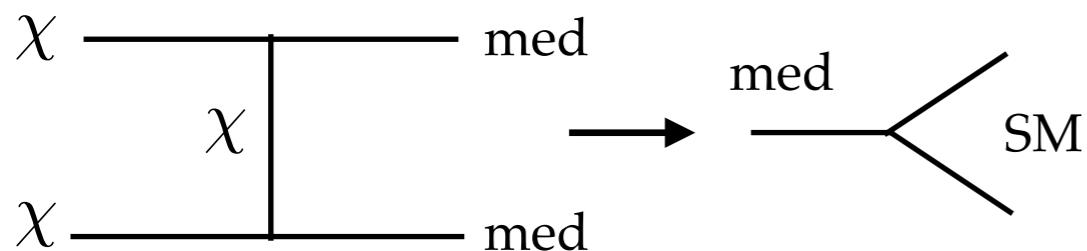
$$n_\chi \sim n_\gamma \sim T^3$$

Where did its density go?

Visible matter

$$m_\chi > m_{\text{med}}$$

Hidden Annihilation



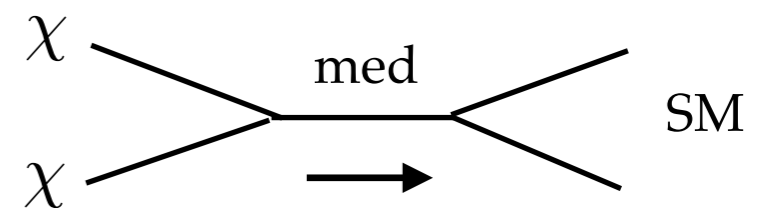
Two step process

Hard to test DM origin

Can discover mediator if lucky

$$m_\chi < m_{\text{med}}$$

Direct Annihilation

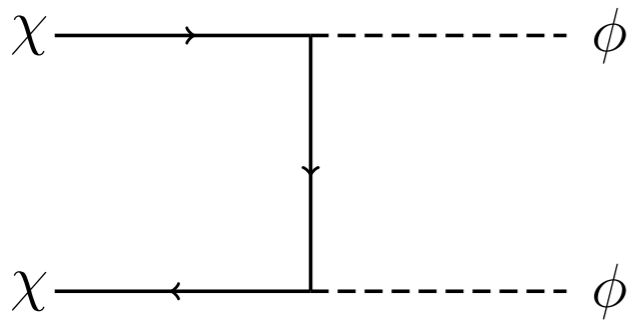


One step process

Density set by SM coupling

Clear experimental targets

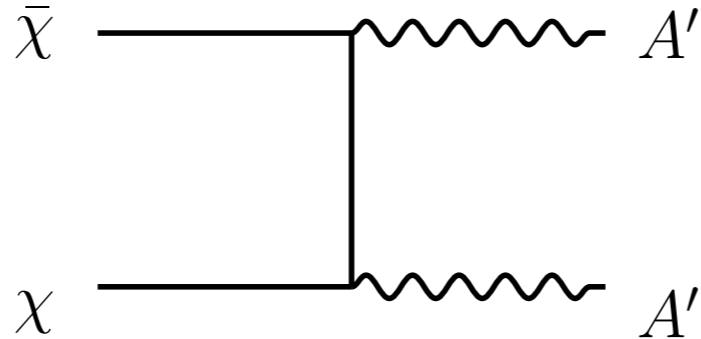
What kind of mediator for **hidden annihilation**? $m_\chi > m_{\text{med}}$



$$\epsilon \phi H^\dagger H$$

Neutral scalar
Mass mixing w Higgs

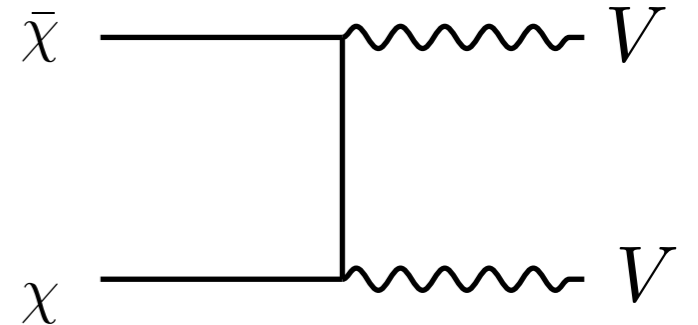
$$\rightarrow \epsilon \phi \frac{m_f}{v} \bar{f} f$$



$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$

Dark photon A'
Kinetic mixing w γ

$$\rightarrow \epsilon A' J_{\text{EM}}^\mu$$



$$V_\mu J_{\text{SM}}^\mu$$

Gauge known global
quantum number

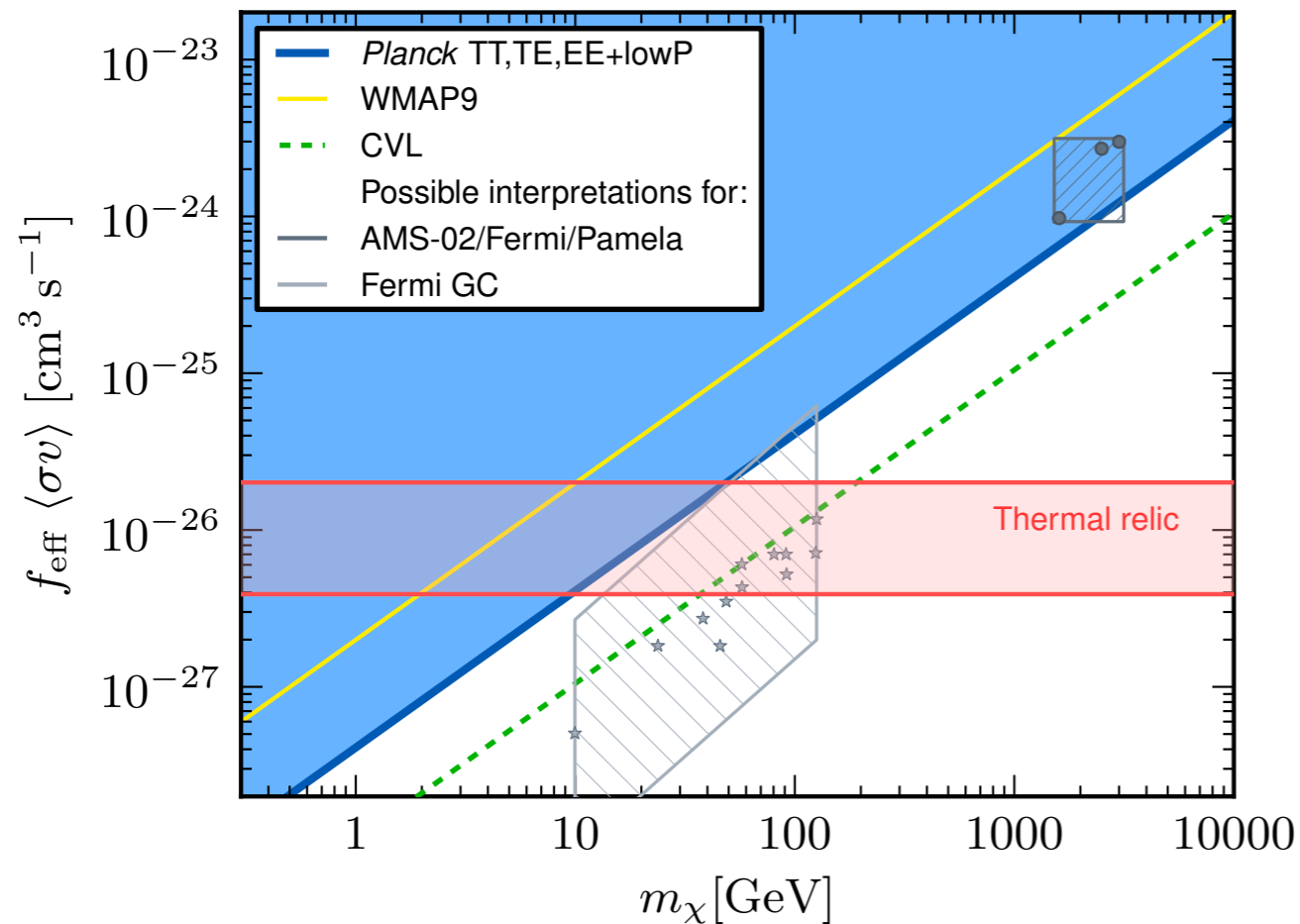
$$U(1)_{B-3L_i}$$

$$U(1)_{B-L}$$

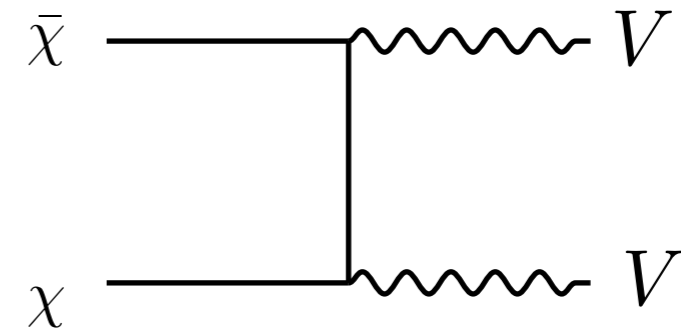
$$U(1)_{L_i-L_j}$$

Complete* list of renormalizable, anomaly-free options

CMB kills hidden annihilation to vectors



Planck Collaboration 1502.01589

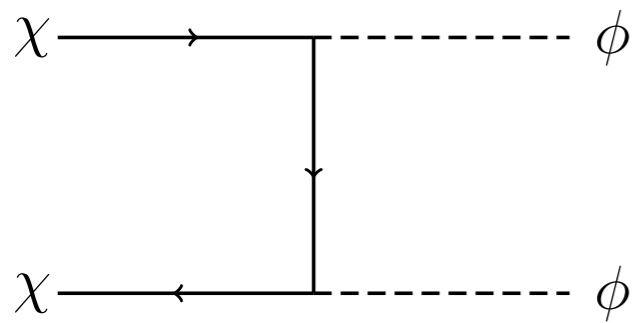


Annihilation to 2 vectors
always s-wave process
for all DM candidates

Danger!

Early universe equilibrium still possible if DM has
particle/antiparticle asymmetry

What kind of mediator for **hidden annihilation**? $m_\chi > m_{\text{med}}$

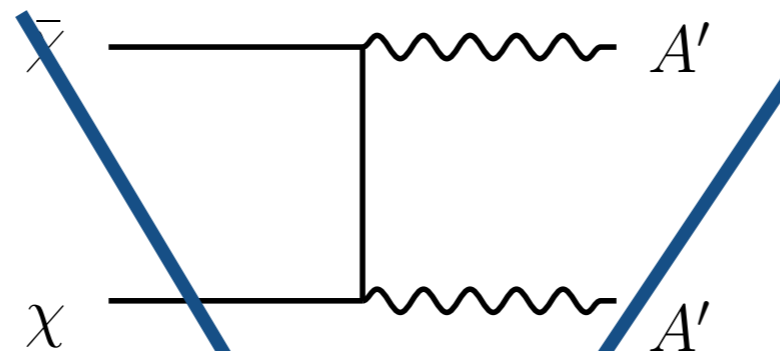


$$\epsilon \phi H^\dagger H$$

Neutral scalar
Mass mixing w Higgs

$$\rightarrow \epsilon \phi \frac{m_f}{v} \bar{f} f$$

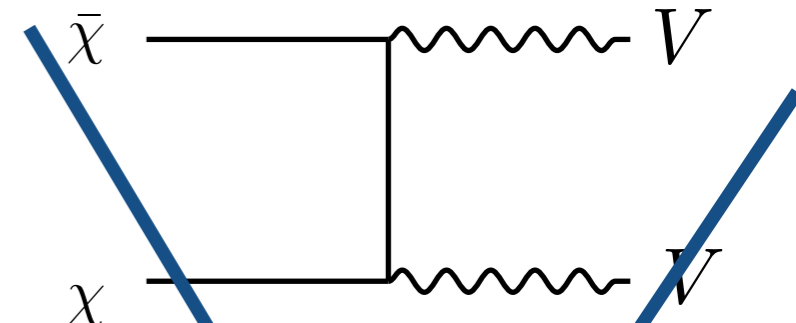
CMB safe
p-wave
(still no DM target)



$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$

Dark photon A'
Kinetic mixing w γ

$$\rightarrow \epsilon A' J_{\text{EM}}^\mu$$



$$V_\mu J_{\text{SM}}^\mu$$

Gauge known global
quantum number

$$U(1)_{B-3L}$$

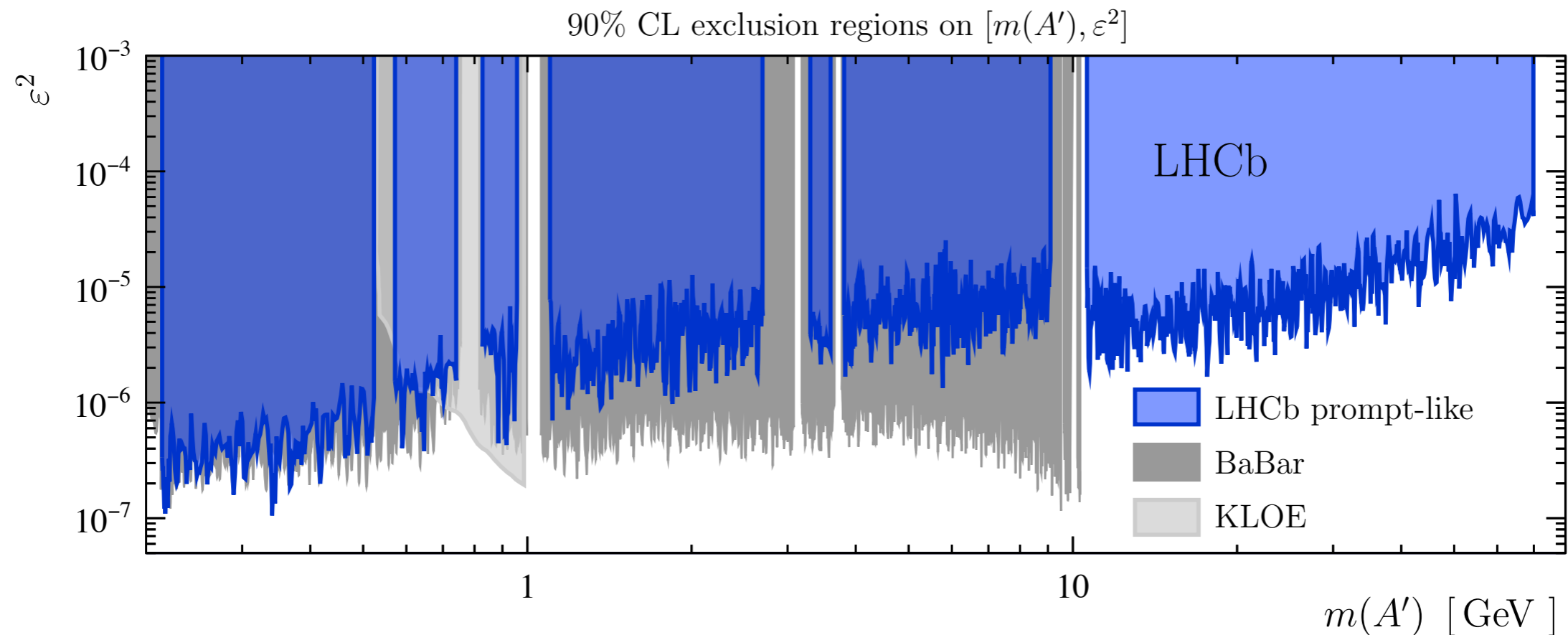
$$U(1)_{B-L}$$

$$U(1)_{L_i-L_j}$$

Ruled out except for V that decay to neutrinos

Collider strategy: prompt decays

Resonance searches for visible daughters: BABAR, Belle II, LHCb...



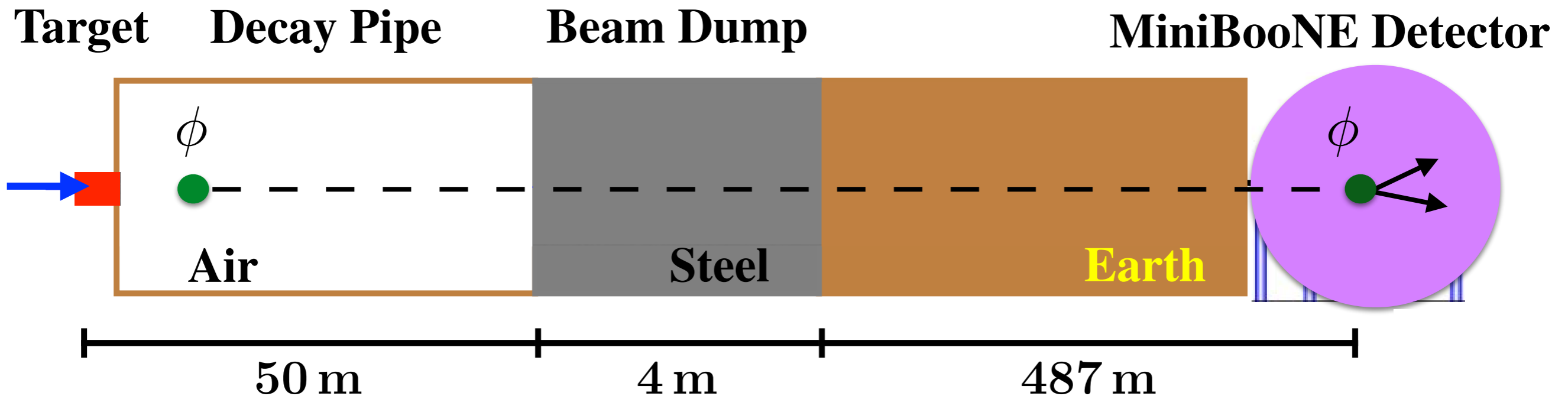
B-factories: continuum production

$$e^+e^- \rightarrow \gamma A' \rightarrow \gamma(e^+e^-)$$

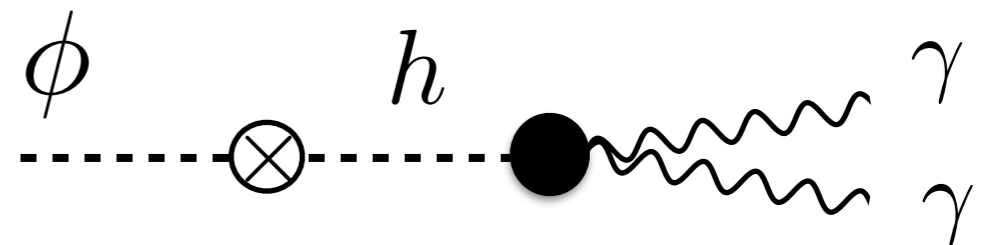
Colliders (also short-er baseline fixed targets)

$$K^+ \rightarrow \pi^+ A' \rightarrow \pi^+(e^+e^-)$$

Beam Dumps: LLP searches



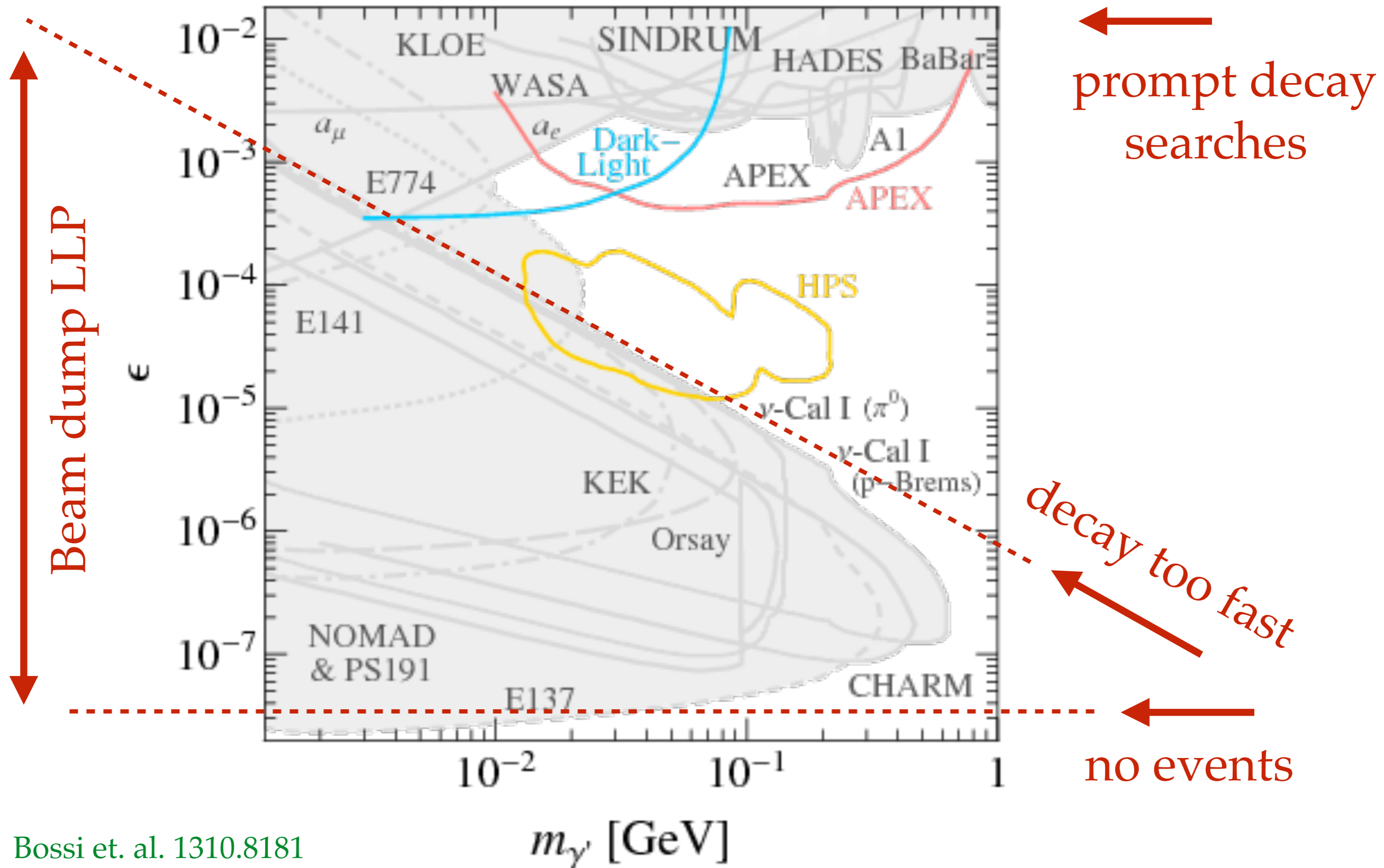
- 1) LLP produced in target
- 2) Passes through shielding
- 3) Decays in detector



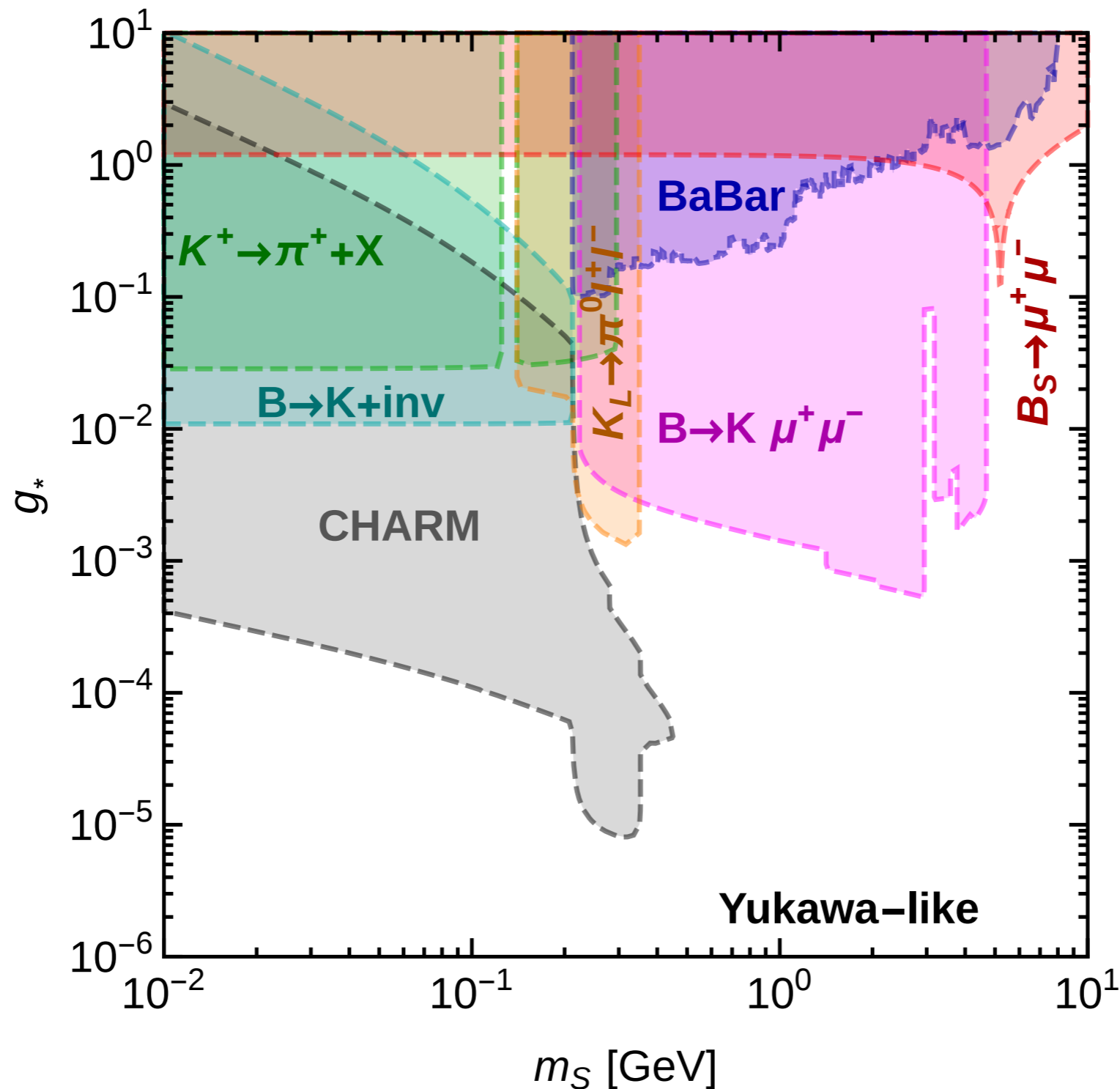
Even though this is motivated by hidden DM annihilation
same signature even if LLP is unrelated to DM

Visibly Decaying Vectors

$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$



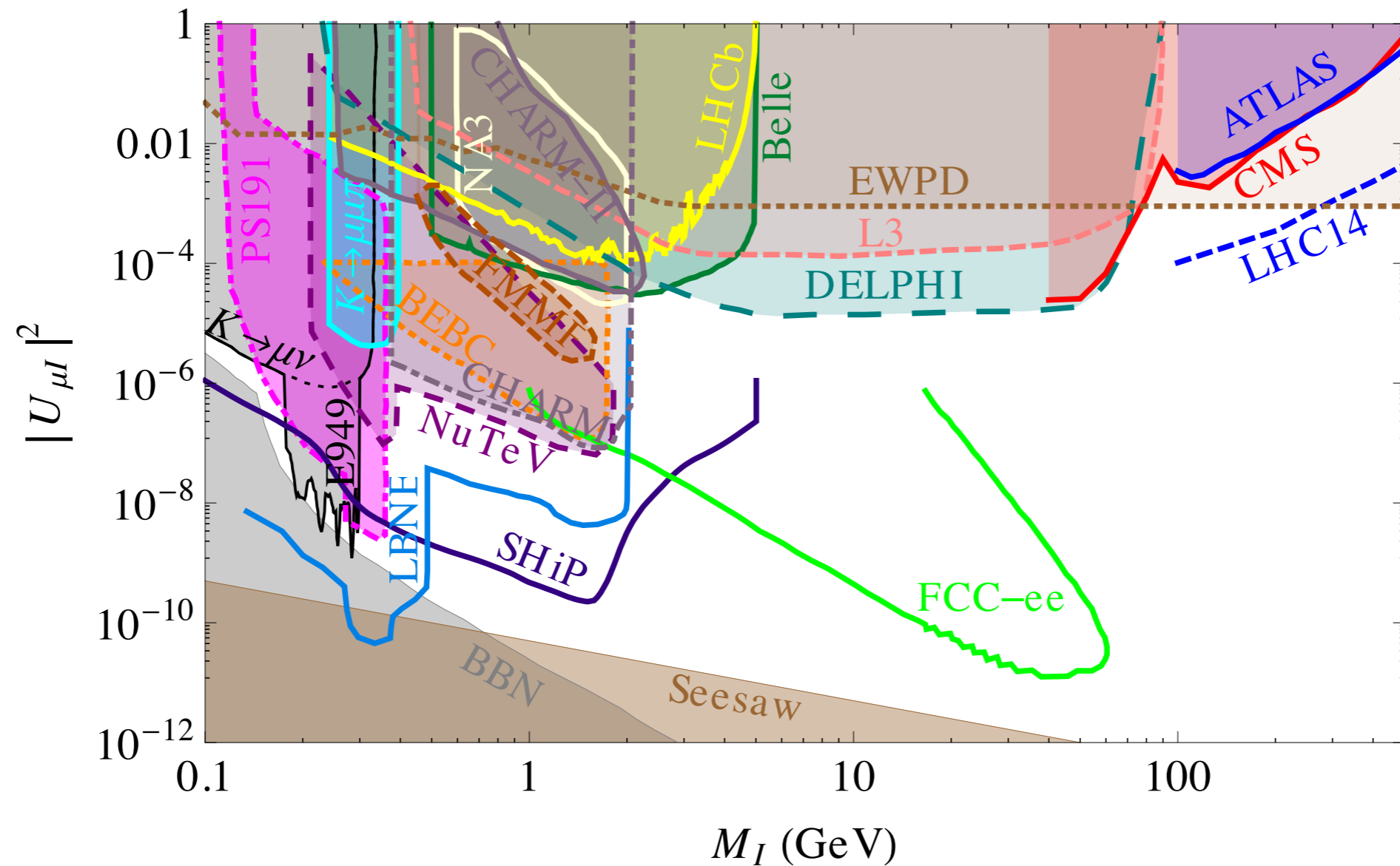
Beam Dumps: Scalar LLP Searches



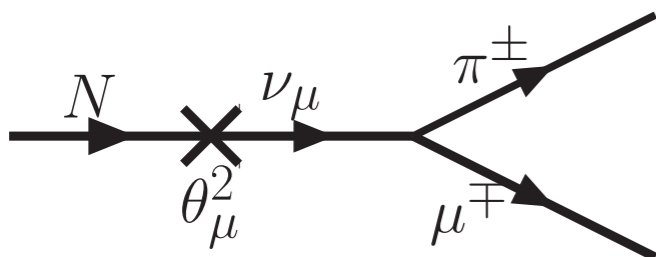
$$\epsilon \phi H^\dagger H$$

Similar param
space for ALPs

Heavy Neutral Leptons



$LH\bar{N}$



Fermion decay via neutrino mixing

Summary

A Modest Proposal $\Gamma(\text{DM} \leftrightarrow \text{SM}) > H$

Rate beats Hubble expansion at *some* point [easy to realize]

Thermodynamics Set Initial Condition $n_{\text{DM}} \sim T^3$

Insensitive to unknown high scales [inflation, baryogenesis...]

Predicts Min. Annihilation Rate $\sigma v \gtrsim 10^{-26} \text{cm}^3 \text{s}^{-1}$

Equilibrium overproduces DM, must deplete with non-gravitational force

Viable Window In Our Neighborhood

Coincidentally in broad vicinity of the electroweak scale

MeV $\sim m_e$

GeV $\sim m_p$

$m_{Z,h}$

$\sim 10\text{s TeV}$

ΔN_{eff}

LDM

“WIMPs”

$\Omega_\chi > \Omega_{\text{DM}}$

BBN

New Frontier of Hidden Sector Searches

MeV $\sim m_e$

GeV $\sim m_p$

$m_{Z,h}$

$\sim 10\text{s TeV}$

LDM

“WIMPs”

Missing Momentum

LDMX, NA64, M³

Beam Dumps:

BDX, MiniBooNE, MicroBooNE,
ICARUS, SBND, DUNE, JSNS2
REDTOP, Dark/SpinQuest, NOvA
SHiP, FerMINI, Stopped Pions...

Direct Detection

Indirect Detection

Collider Production

**New accelerator searches cover direct annihilation targets
+ Improve coverage for mediators in hidden annihilation forces**