LDW 2026, Carleton University

Testing Minimal Models of Highly-Predictive Dark Matter

Gordan Krnjaic
Fermilab & UChicago

+Han 2603.03444

+Berlin, Fieg, Trickle 2068.xxxxx

Overview

1. Classifying “highly predictive” models

2. Freeze-Out Production

3. Freeze-In Production

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What does “highly predictive” mean?

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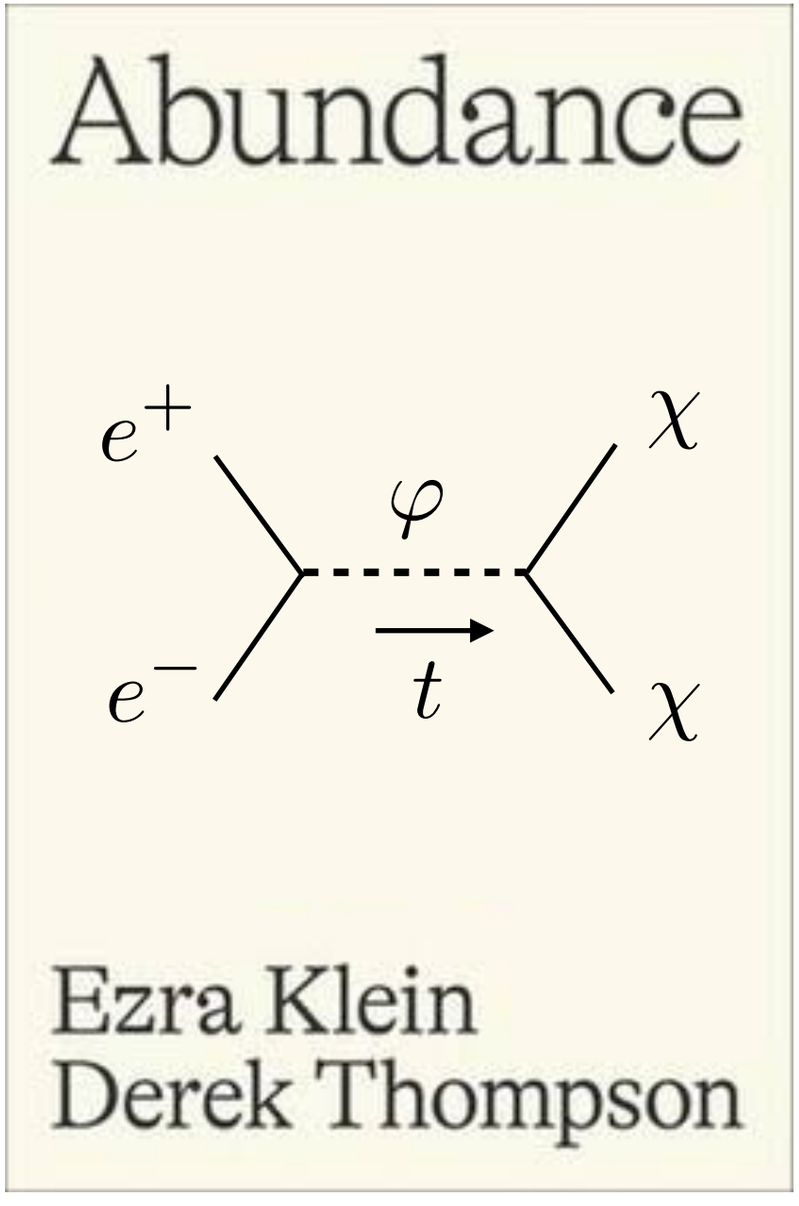

What does “highly predictive” mean?

Working definition: Abundance depends *only* on parameters that also govern observable quantities

$$\Omega_\chi = F(g_\chi, m_\chi, \cdots) \iff \Gamma_{\rm exp} = G(g_\chi, m_\chi, \cdots)$$

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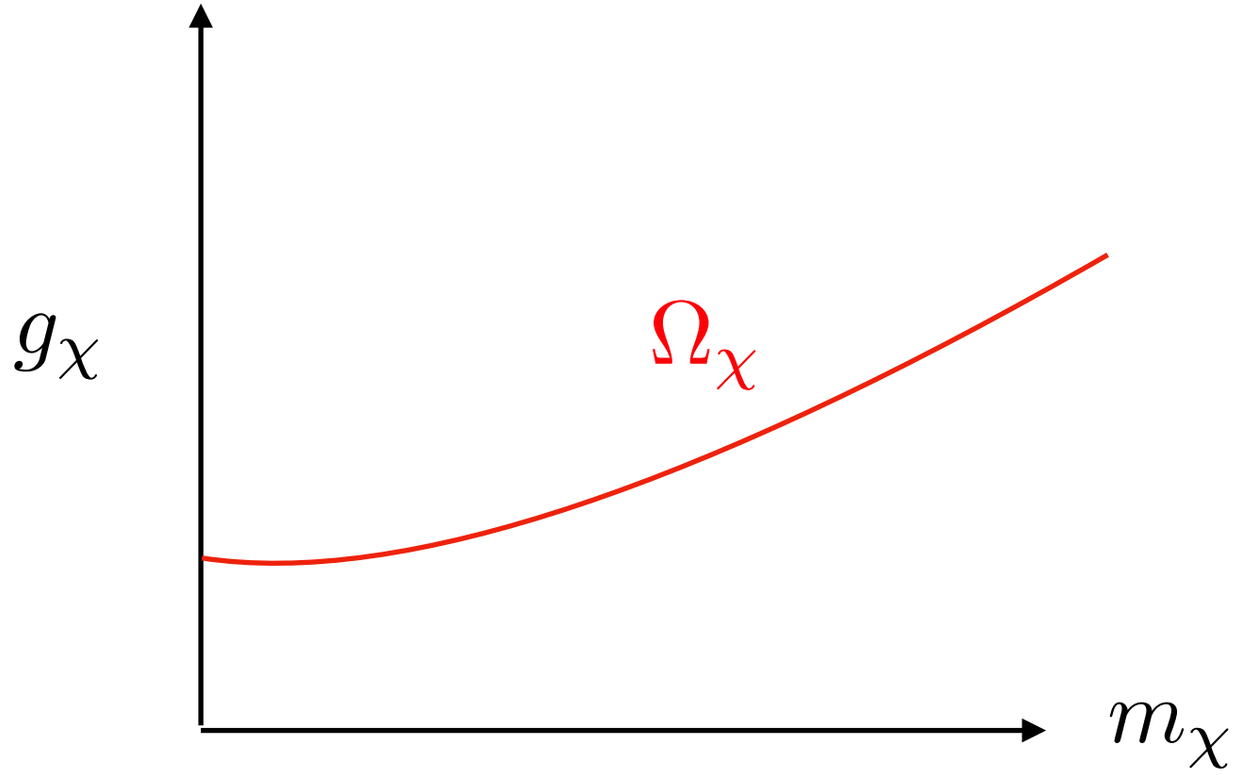

Sharp targets for discovery or falsification

What does “highly predictive” mean?

Working definition: DM abundance depends *only* on parameters that also govern observable quantities

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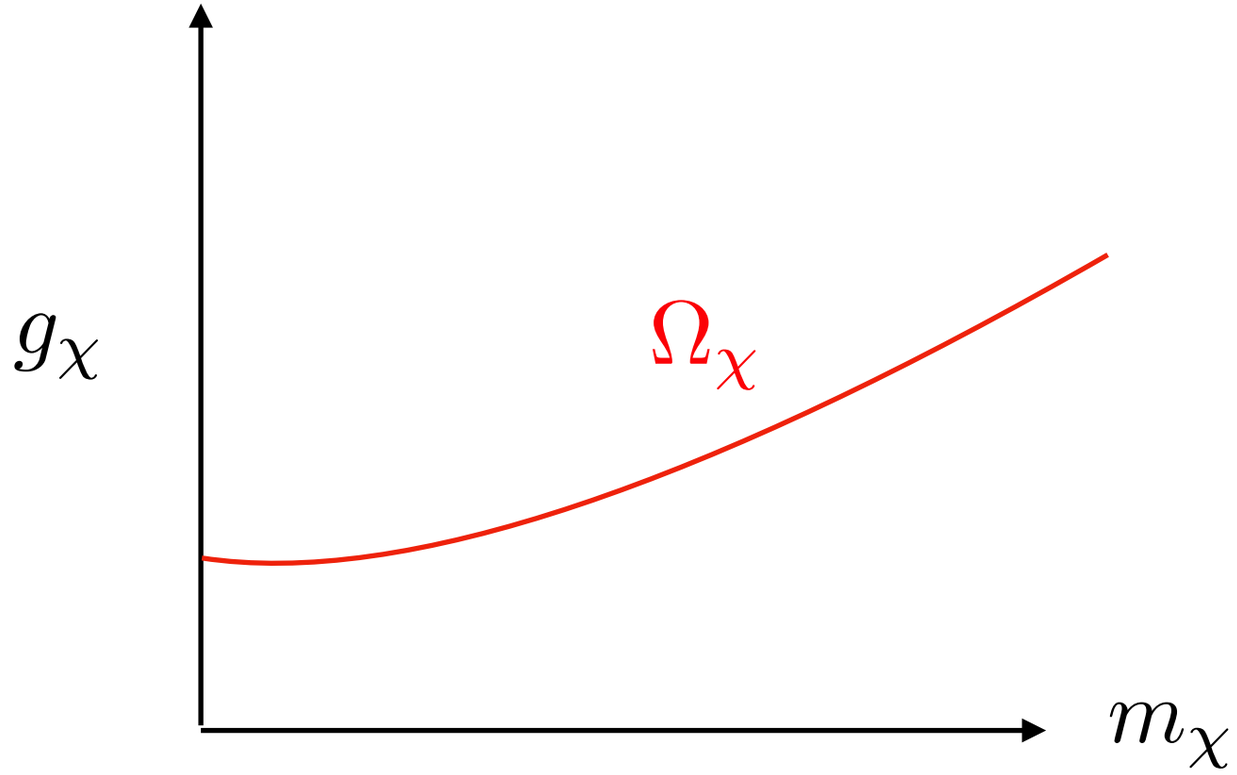
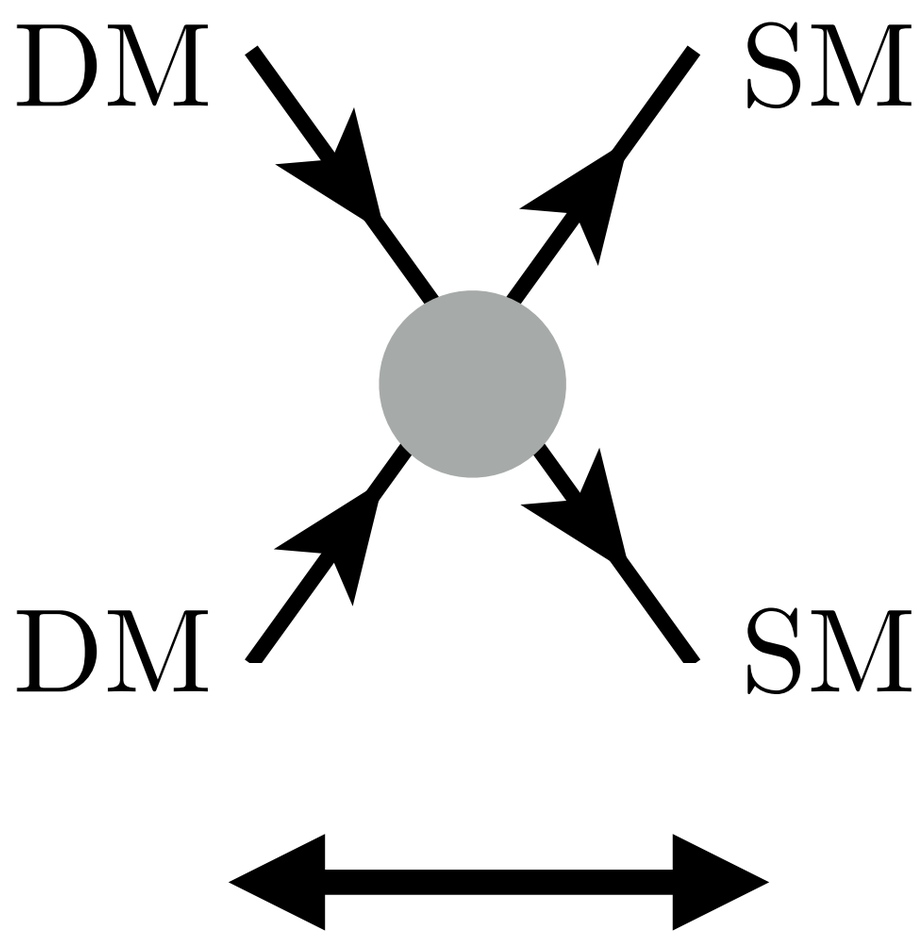


How to systematically identify & test these models?

Was DM ever in equilibrium with SM?



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 / Axion-like

Primordial Black Hole

Inflationary fluctuations

WIMPzillas

⋮

Generically* not "highly predictive"

Many well-motivated models,
but abundance depends on unknown
UV physics (inflation, reheating etc)

*post-inflatonary QCD axion DM is **extremely** predictive

Was DM ever in equilibrium with SM?

NO

How was it populated?

Freeze In Mechanism

Can be "highly predictive"

if the same couplings set production & detection rates

$$n_\chi(T_{\rm RH}) = 0 \quad , \quad \Gamma_{\rm SM\to\chi} < H$$

Dodelson, Widrow 9303287

Hall, Jedamzik, March-Russell, West 0911.1120

Was DM ever in equilibrium with SM?

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

Where did its density go?

$$n_i^{\rm eq} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \propto T^3 \qquad (T \gg m)$$

DM starts in chemical equilibrium with SM, then freezes out

Was DM ever in equilibrium with SM?

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

Where did its density go?

Stayed big

We have measured $\rho_\chi \sim m_\chi n_\gamma \sim \mathrm{keV\,cm^{-3}}$

Mass must be $\Longrightarrow$ $m_\chi \sim 10\,\mathrm{eV}$

Too hot for large scale structure

Can't freeze out as relativistic species,
needs to be heavier and transfer its entropy

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 stuff

$\sum \Omega_{\rm dark} > \Omega_{\rm DM}$

Light

$N_{\rm eff} > 3$ spoils

CMB/BBN/LSS

Requires nonstandard cosmology

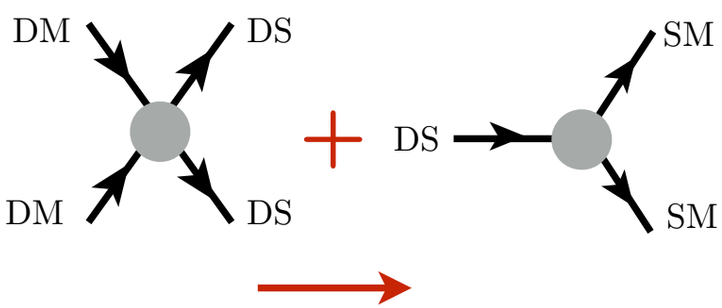
Was DM ever in equilibrium with SM?

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

Where did its density go?

Visible matter

Secluded Annihilation



Visibly decaying dark state (DS)

Pospelov, Ritz, Voloshin 0711.4866

Not "highly predictive"

Observables depend only on mediator-SM coupling

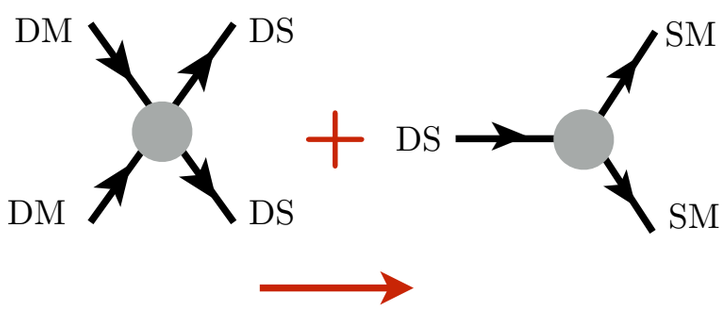
Was DM ever in equilibrium with SM?

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

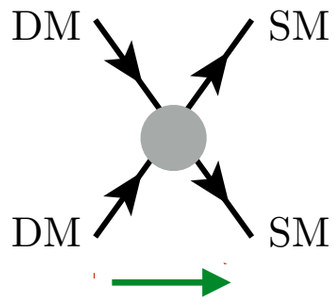
Where did its density go?

Visible matter

Secluded Annihilation



Direct Annihilation



Generically "highly predictive"

Same couplings set production & detection rates

Overview

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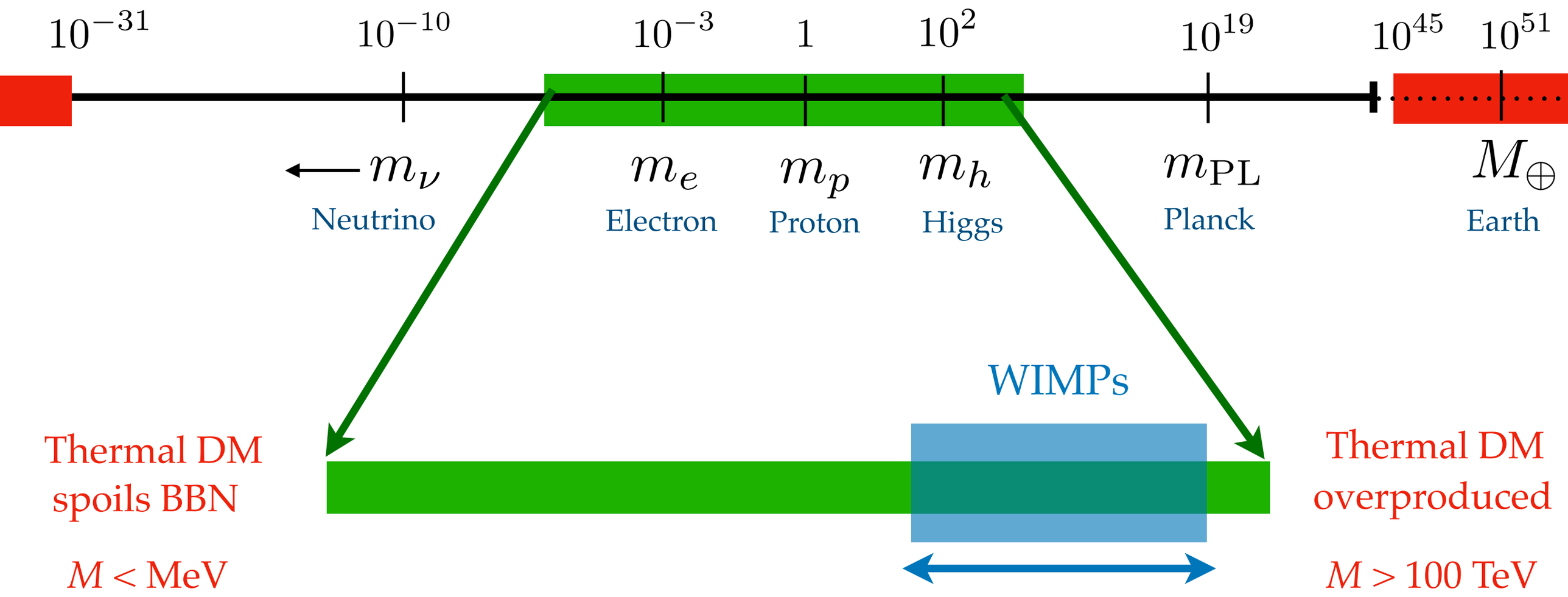
Thermal Freeze Out

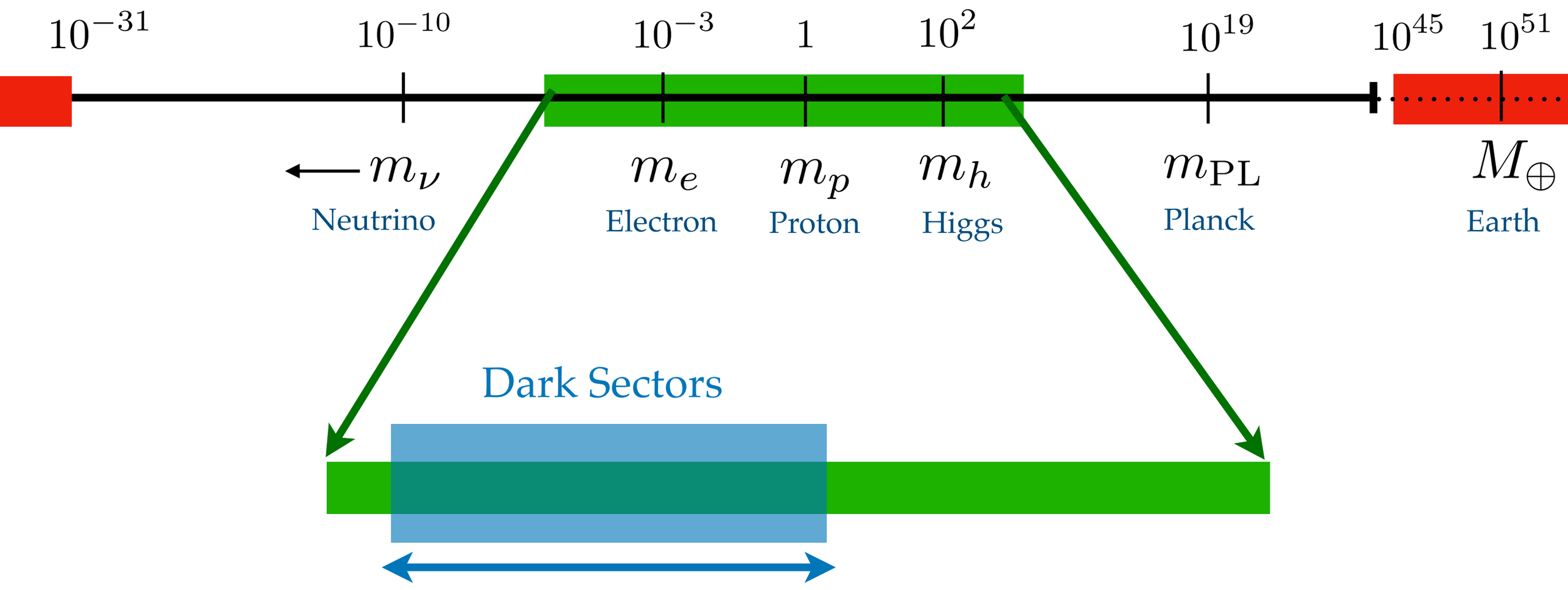


WIMPs: weak force mediates DM annihilation

Probe with direct/indirect detection, collider production

Well motivated, but null results after ~ 30 years of searches

Thermal Freeze Out < GeV

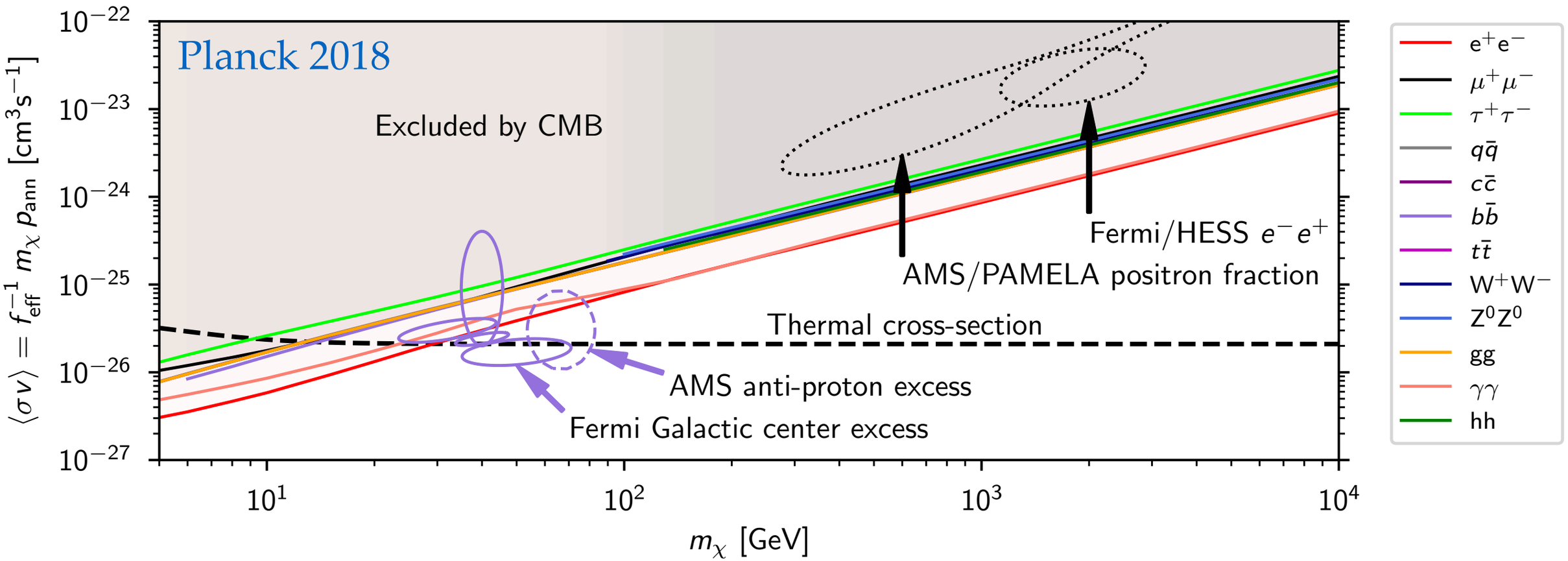


Need renormalizable **new forces** to mediate DM annihilation

Weak force is too weak: $\sigma v \sim \dfrac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\dfrac{m_\chi}{\mathrm{GeV}}\right)^2$

Lee, Weinberg 1979

CMB limits provide organizing principle



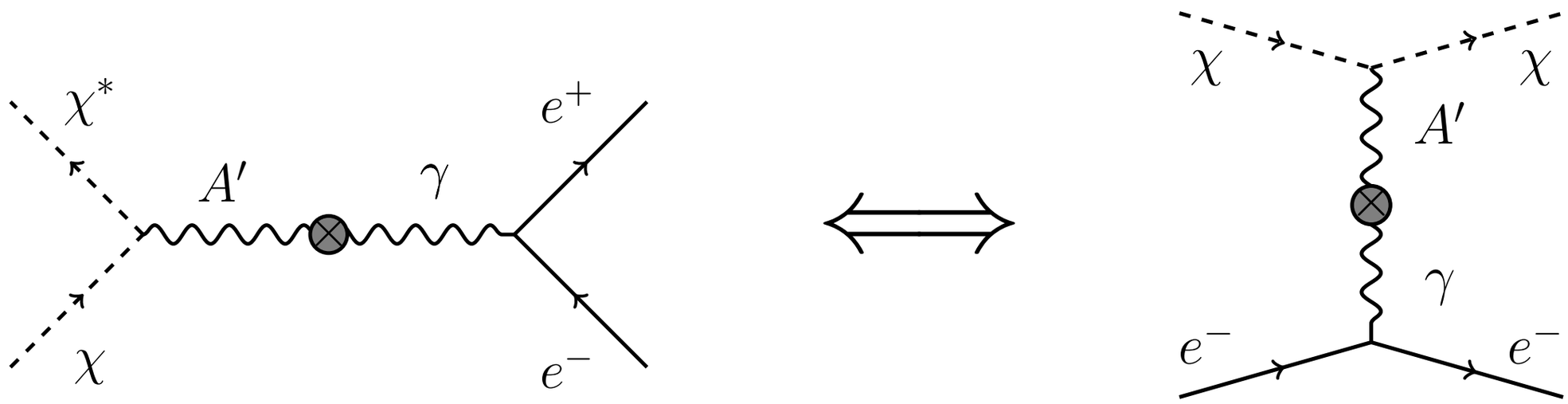
Rare annihilation for z < 1100 spoils CMB anisotropies

Rules out s-wave annihilation for DM < O(10) GeV
No indirect-detection for viable < GeV models

Slatyer 1506.03812

Highly Predictive Freeze Out (< GeV)

$$m_A > m_\chi$$



Production

Detection

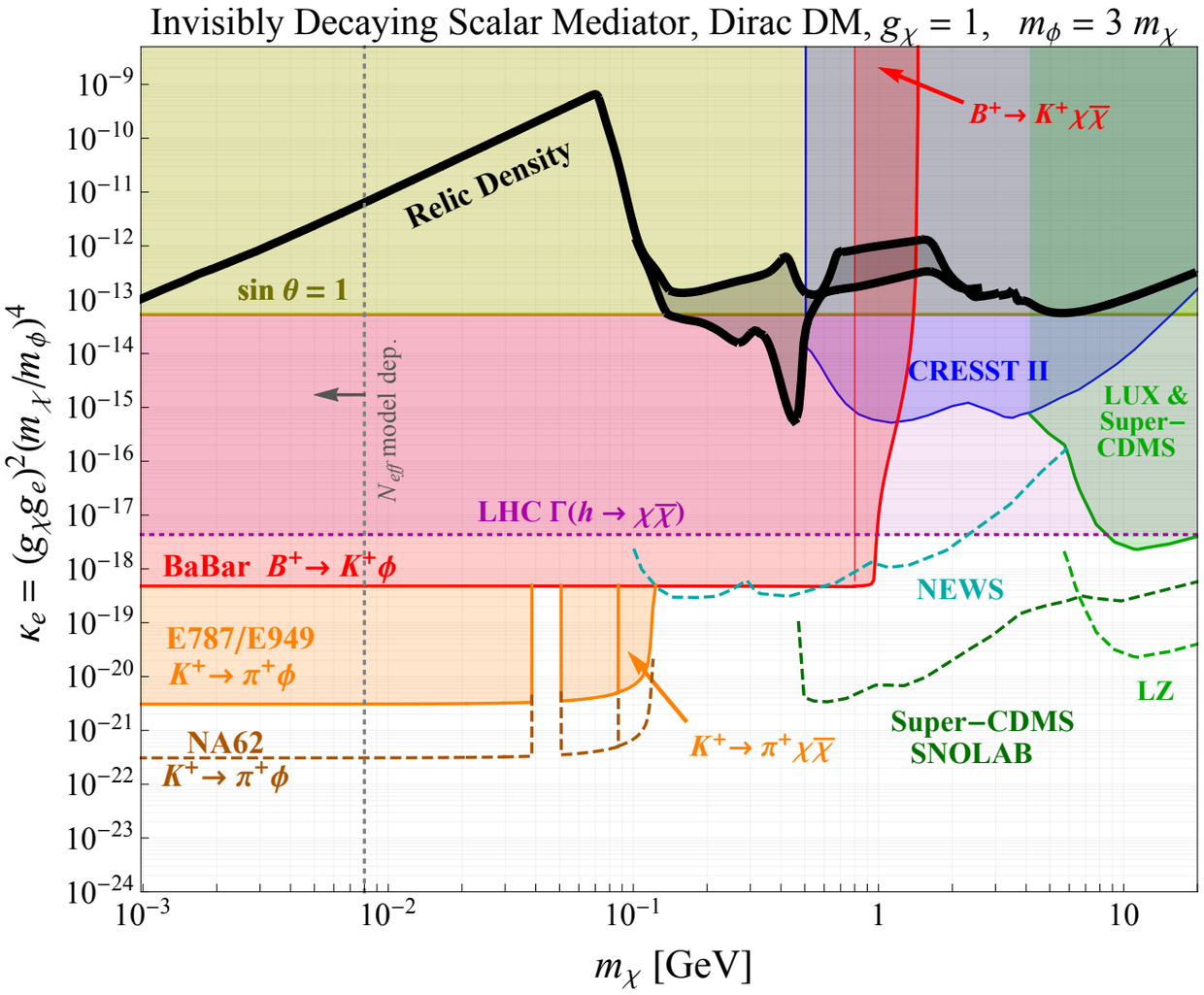
Finite list of renormalizable mediators

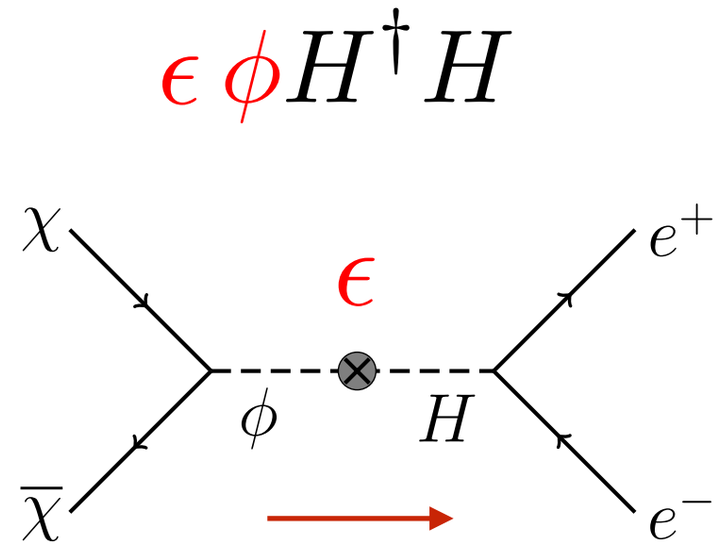
Spin-0: Higgs-mixed scalar, flavor-specific (pseudo)scalars

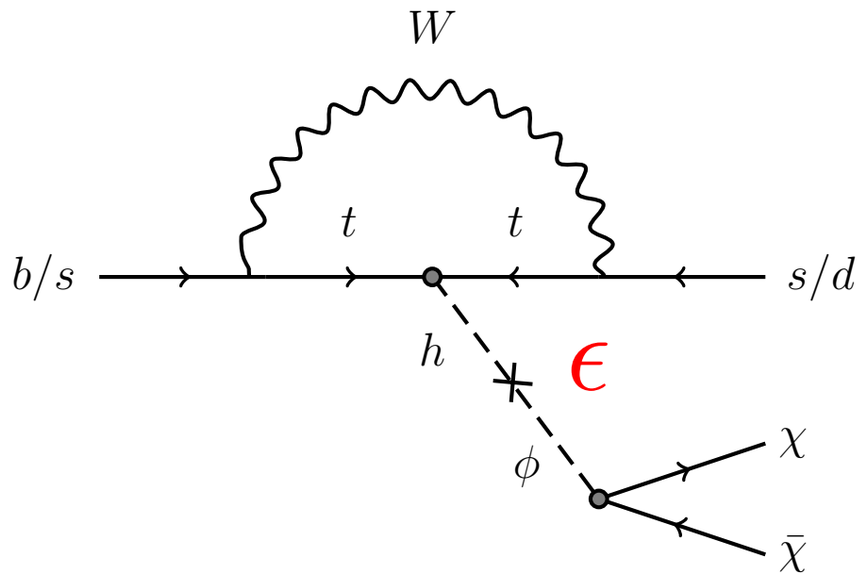
Spin-1: A' , $L_i - L_j$, $B - L$, $B - 3L_i \ldots$

Izaguirre, GK, Schuster, Toro 1505.00011

Higgs-mixed meditator ruled out







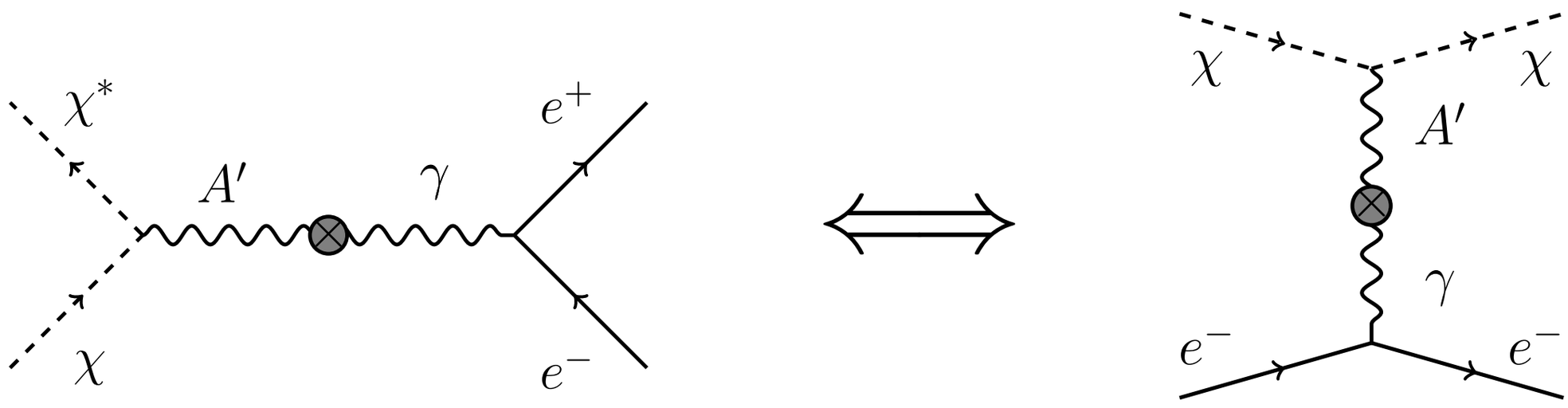
Conclusion independent of DM candidate

Similar conclusions for pseudo-scalar mediators

GK:1512.04119

Highly Predictive Freeze Out (< GeV)

$m_A > m_\chi$



Finite list of renormalizable mediators

~~**Spin-0:** Higgs-mixed scalar, flavor specific (pseudo) scalars~~

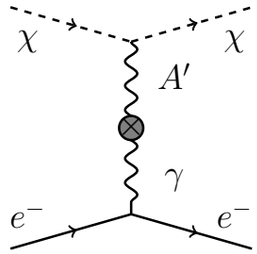
Spin-1: $A'\ ,\ L_i - L_j\ ,\ B-L\ ,\ B-3L_i \ldots$

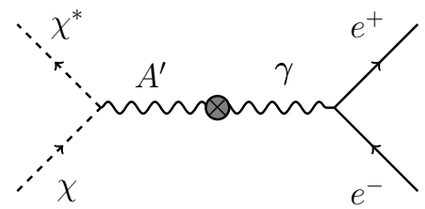
Finite list of DM candidates

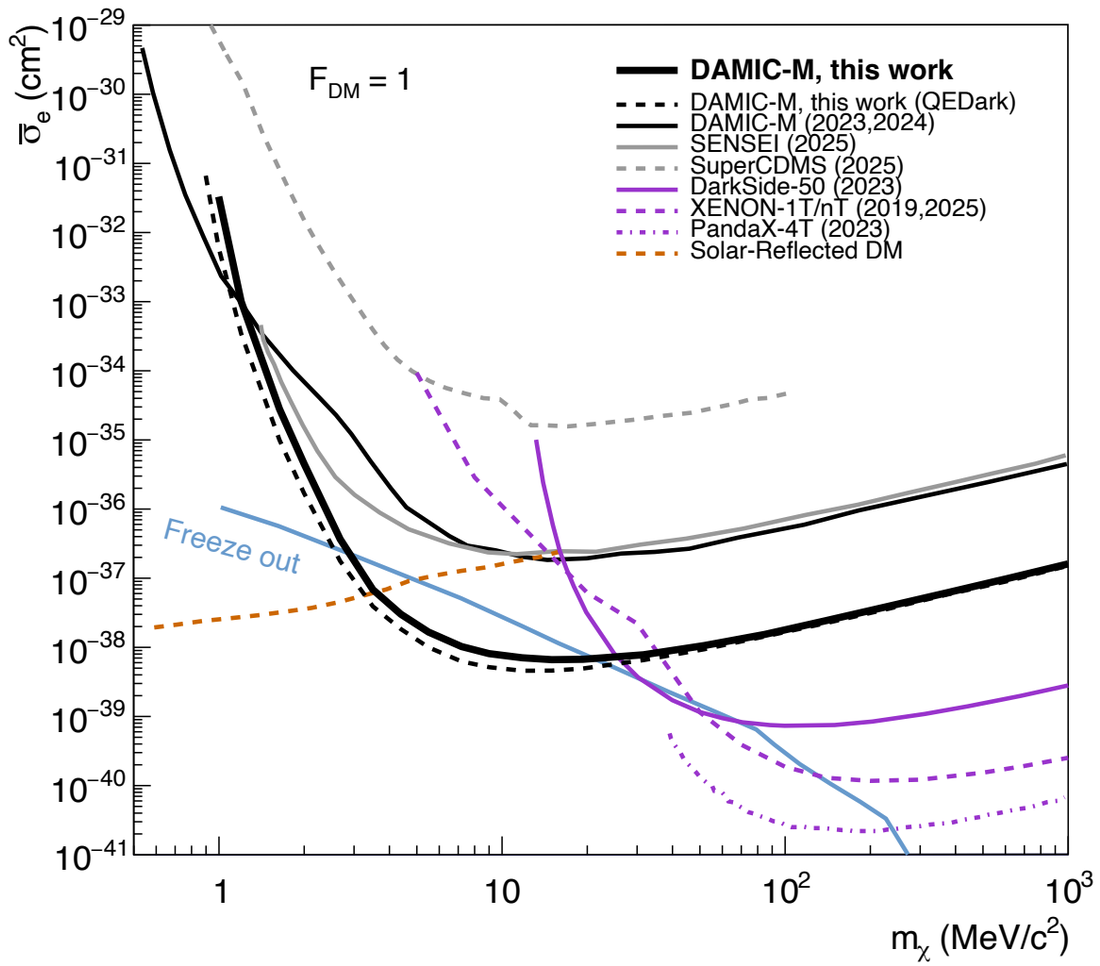
Spin-0, Dirac, Majorana, Pseudo-Dirac

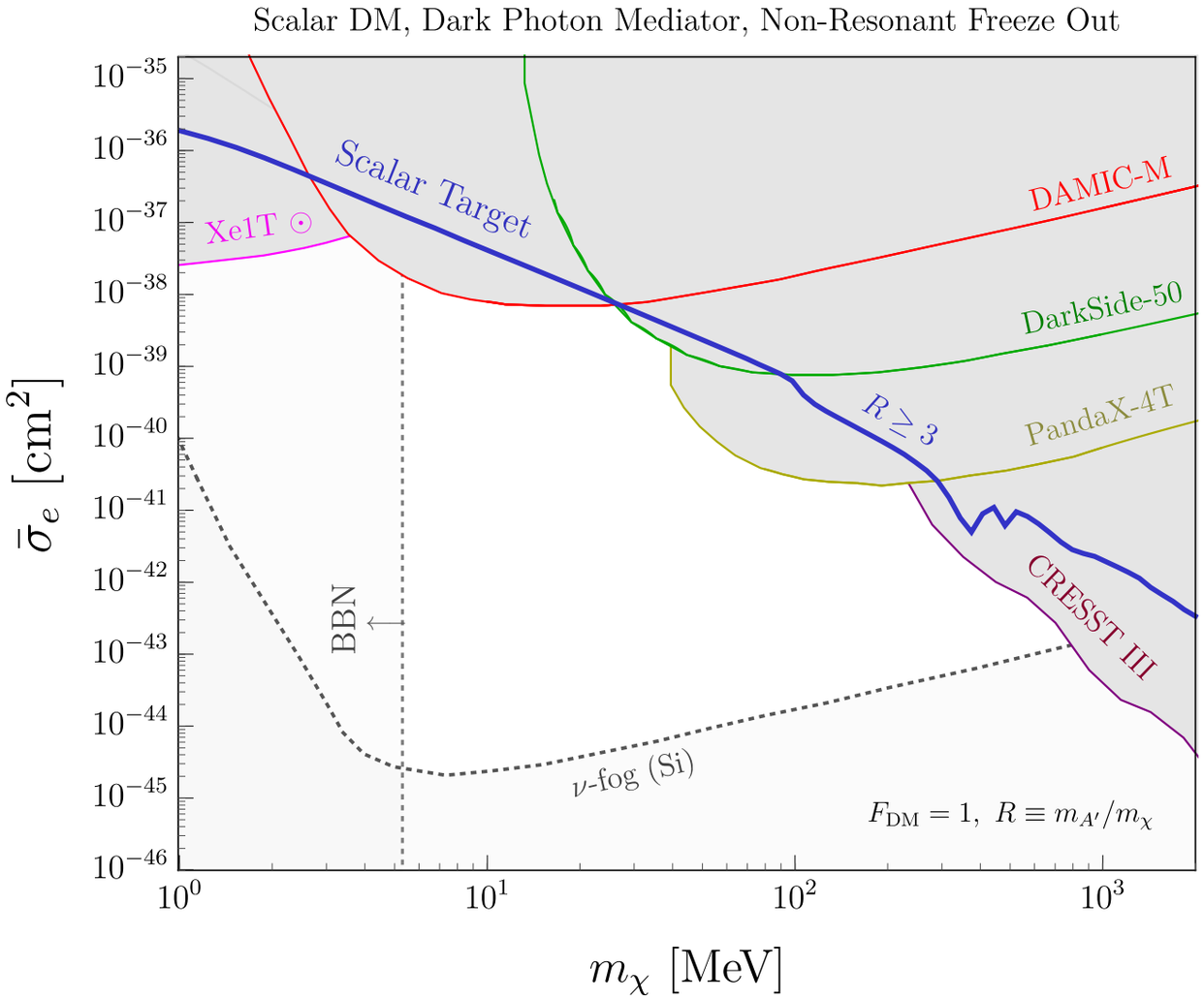
Izaguirre, GK, Schuster, Toro 1505.00011

Excluding Predictive Scalar DM









Scalar DM with A' mediator finally excluded by DAMIC-M in 2025!

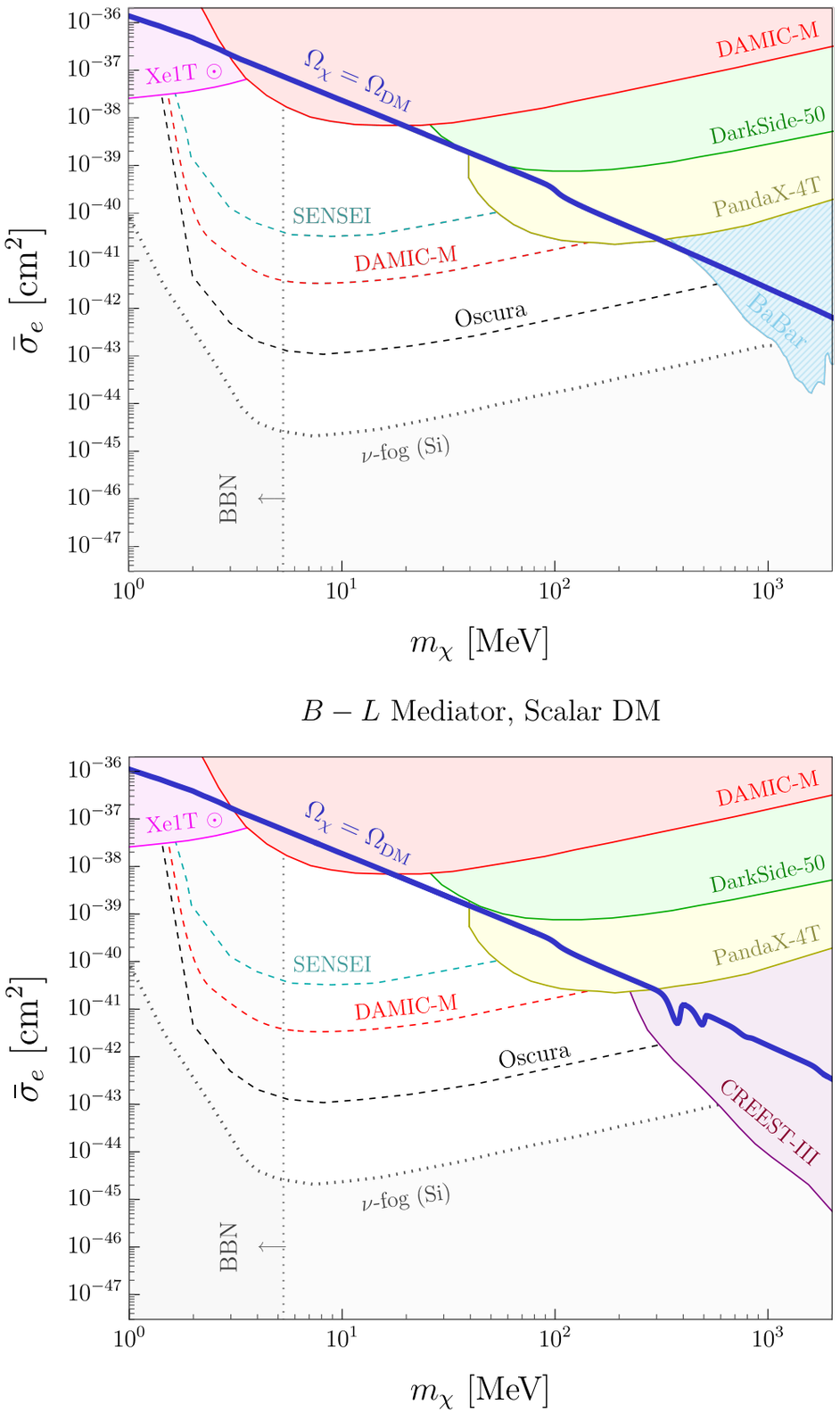
First model in this class to be fully tested and excluded

DAMIC-M 2503.14617

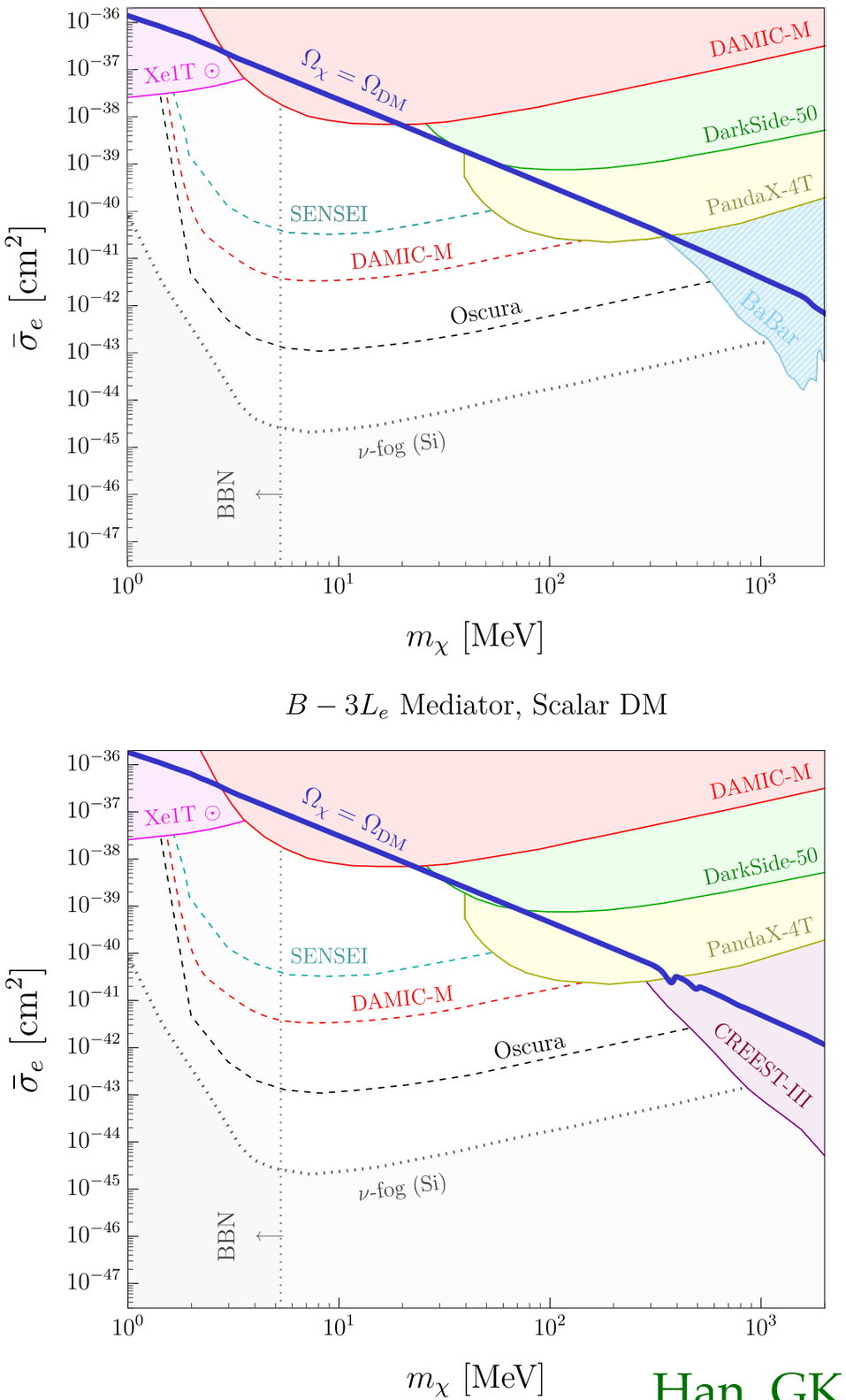
GK 2505.04626

Scalar DM coupled to other forces?

$L_\mu - L_e$ Mediator, Scalar DM



$L_e - L_\tau$ Mediator, Scalar DM

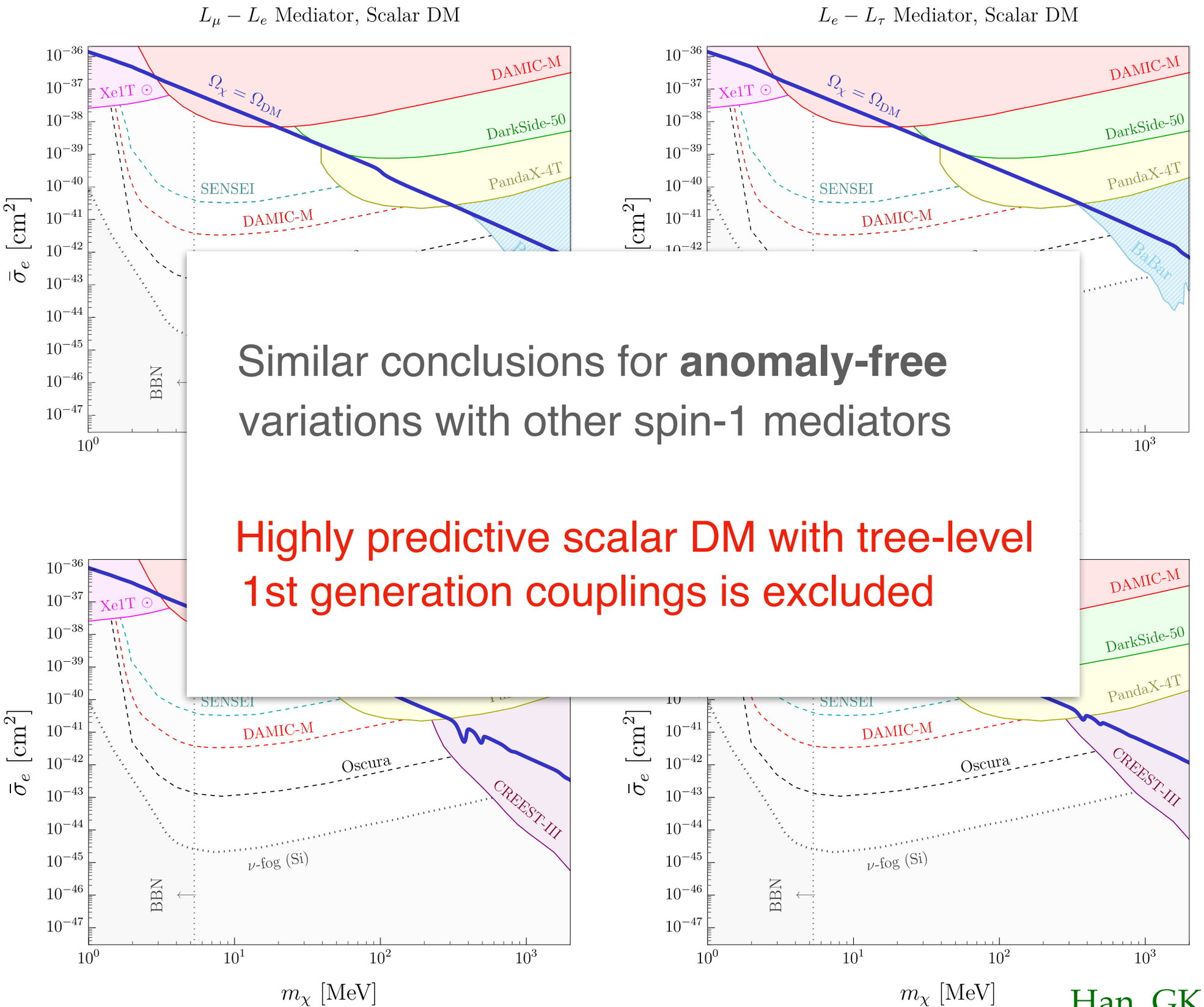


$B - L$ Mediator, Scalar DM

$B - 3L_e$ Mediator, Scalar DM

Han, GK 2603.03444

Scalar DM coupled to other forces?



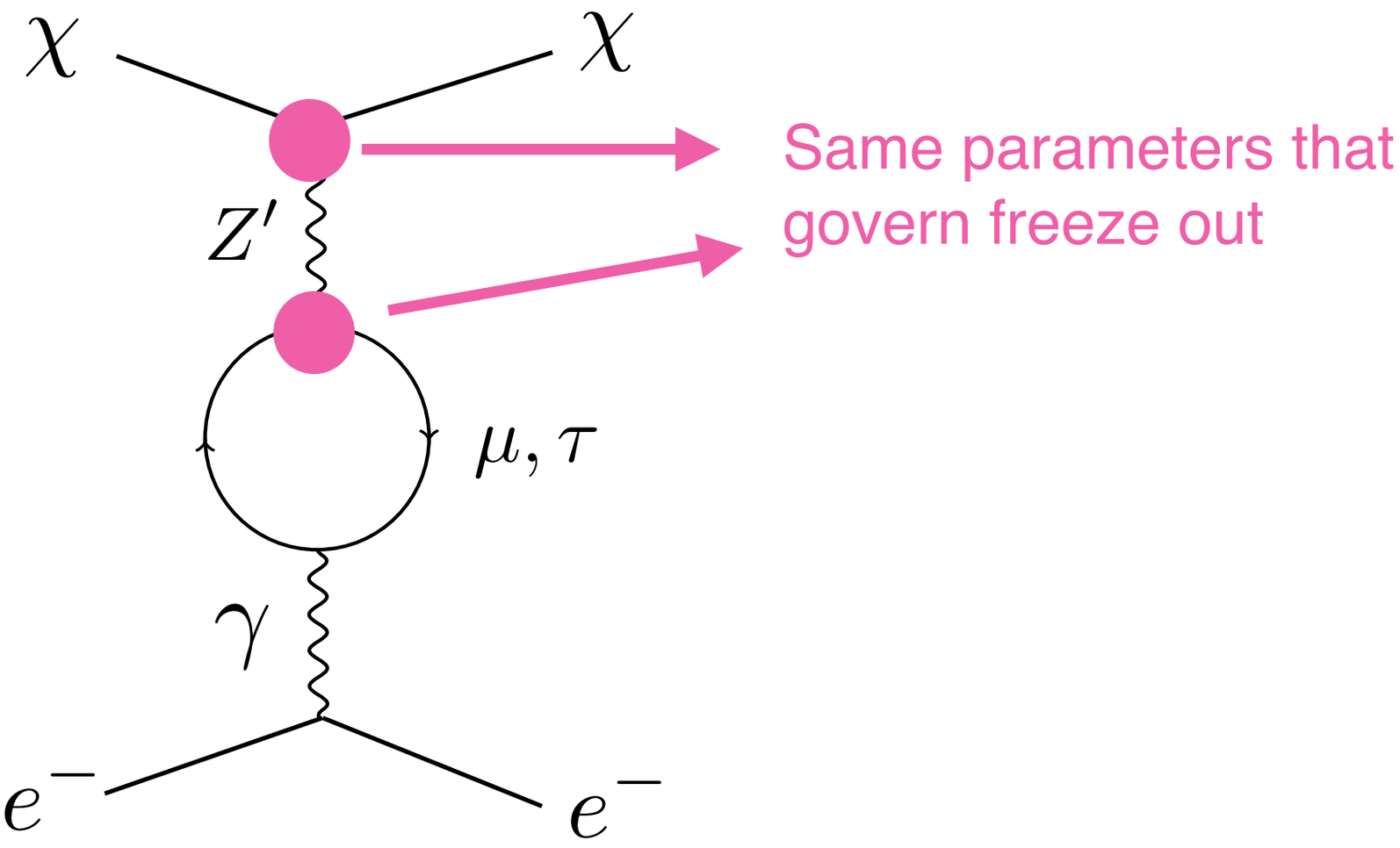
Similar conclusions for **anomaly-free** variations with other spin-1 mediators

Highly predictive scalar DM with tree-level 1st generation couplings is excluded

Han, GK 2603.03444

Beyond Leading Order

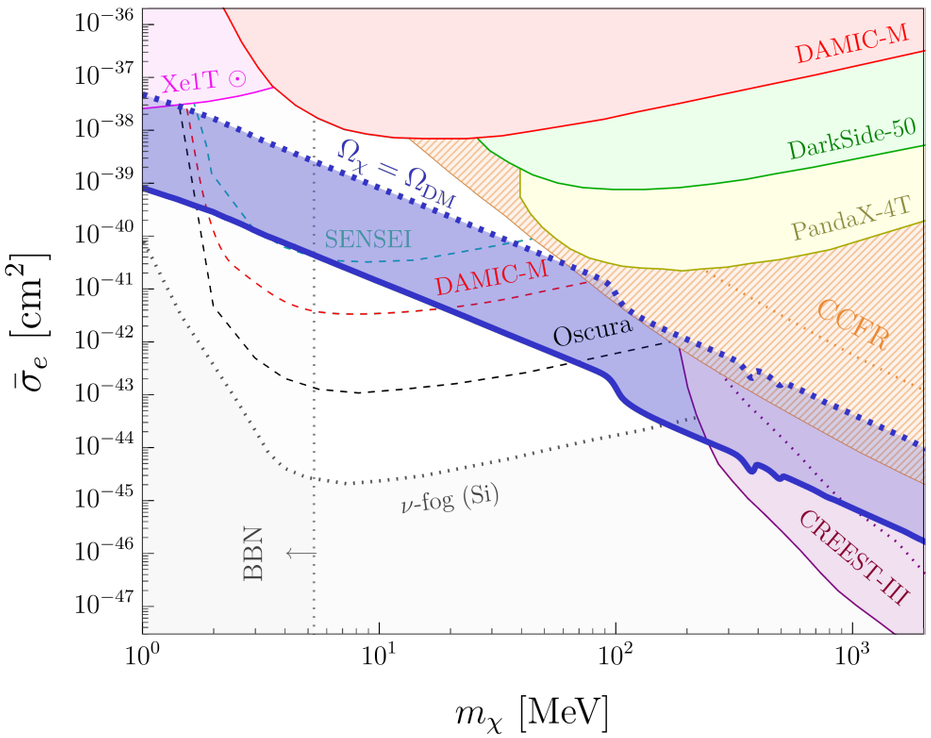
Example: Z' mediator with gauged $L_\mu - L_\tau$



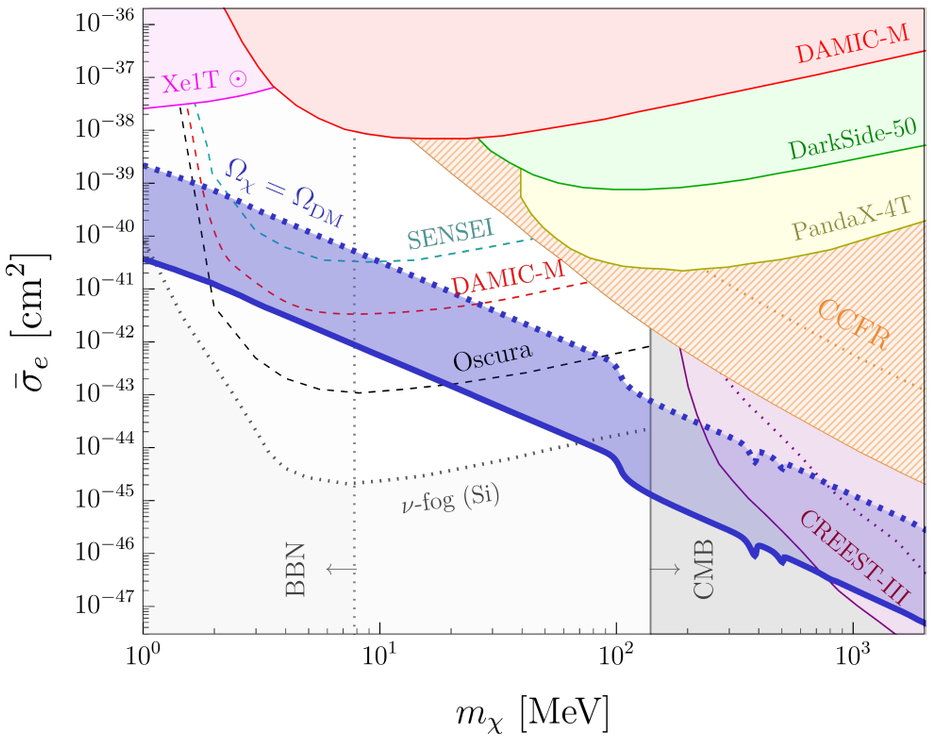
Irreducible electron couplings arise at loop level, with extra suppression relative to freeze-out annihilation diagrams

Next Generation Targets

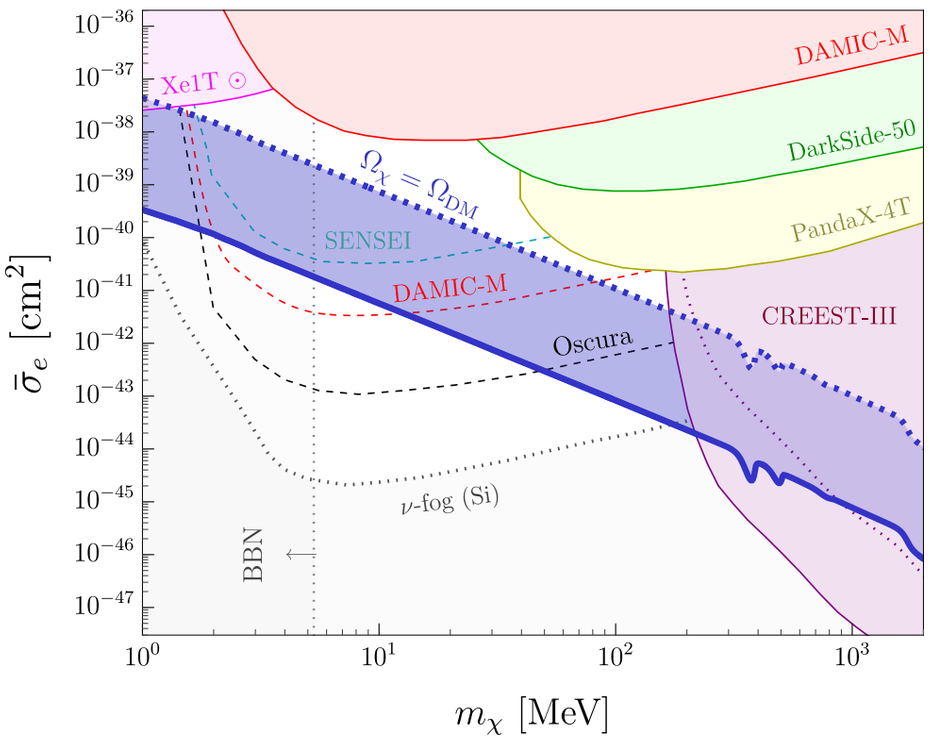
$B - 3L_\mu$ Mediator, Scalar DM



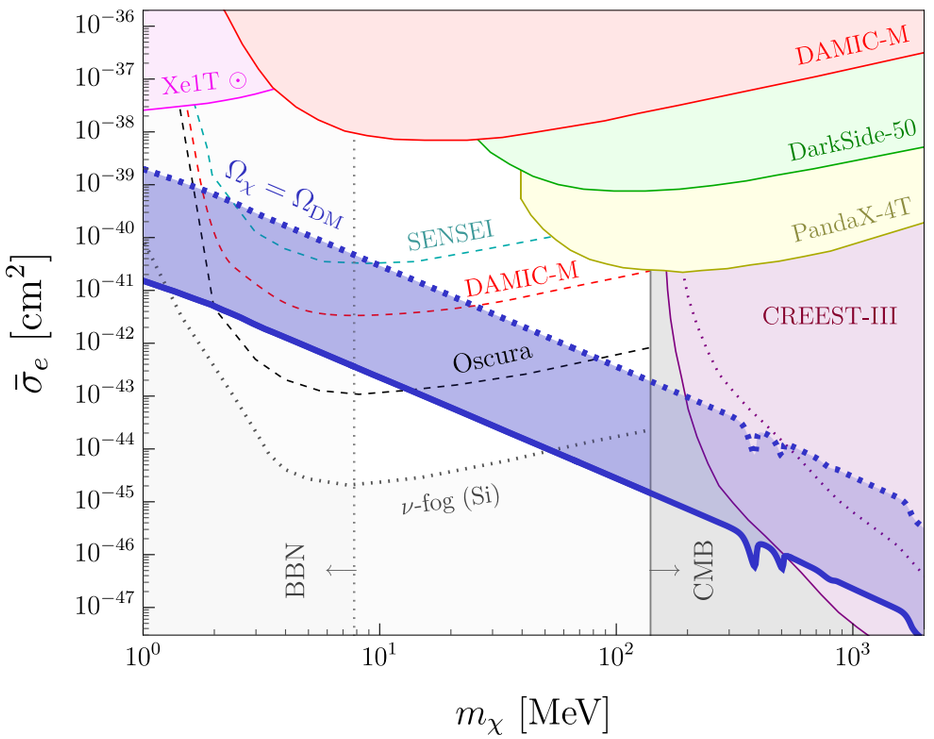
$B - 3L_\mu$ Mediator, Dirac DM



$B - 3L_\tau$ Mediator, Scalar DM



$B - 3L_\tau$ Mediator, Dirac DM

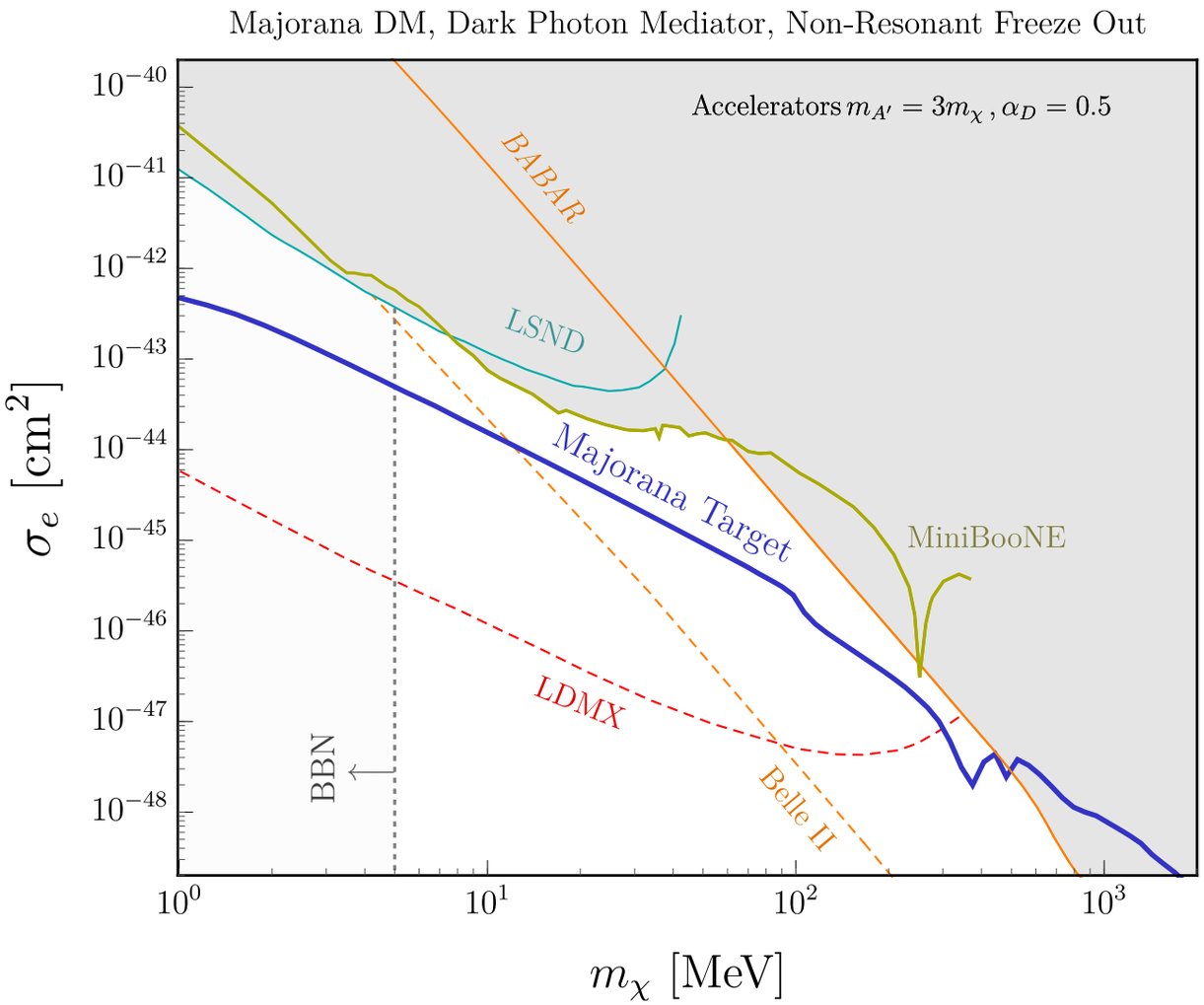


$\Omega_\chi = \Omega_{\rm DM}$

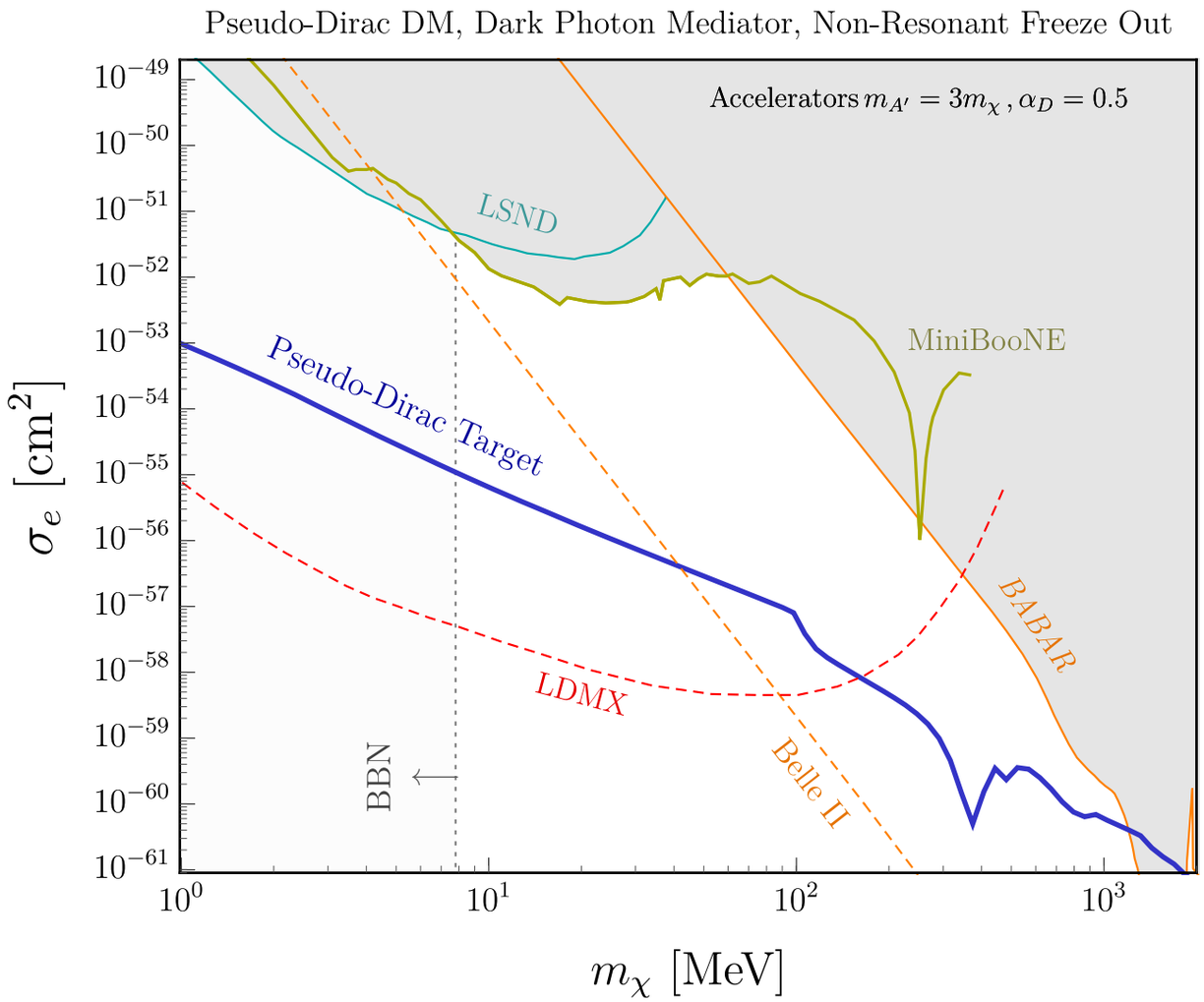
Han, GK 2603.03444

Other DM Spins Require Accelerators

Majorana Fermion



Pseudo-Dirac Fermion



Accelerator + direct-detection searches will test nearly all *predictive* models … including ones with suppressed non-relativistic cross sections

Similar conclusion for other U(1) mediators GK 2505.04626

Overview

1. Classifying “highly predictive” models

2. Freeze-Out Production

3. Freeze-In Production

What is “highly predictive” freeze in?

Production governed only by IR parameters (not reheat temp…)

1. If DM is **stable**, couplings govern **scattering** rate
   also need mediator for both production/detection

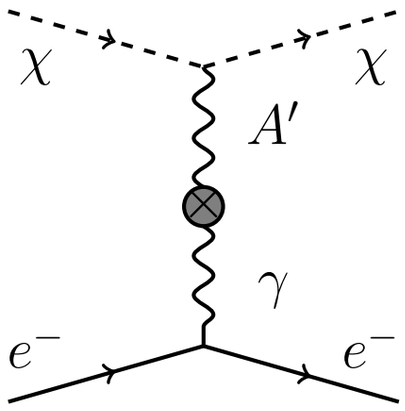
2. If DM is **unstable**, couplings govern **decay** rate
   No additional particles needed, highly minimal

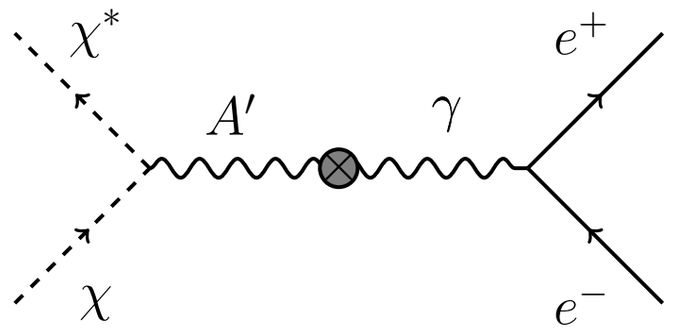
Need renormalizable couplings to SM for IR dominance

Need m > keV to avoid warm dark matter limits

Can we test stable freeze-in DM?

Yes, but there is **exactly one** testable model via scattering





Freeze-in couplings are **extremely tiny!**

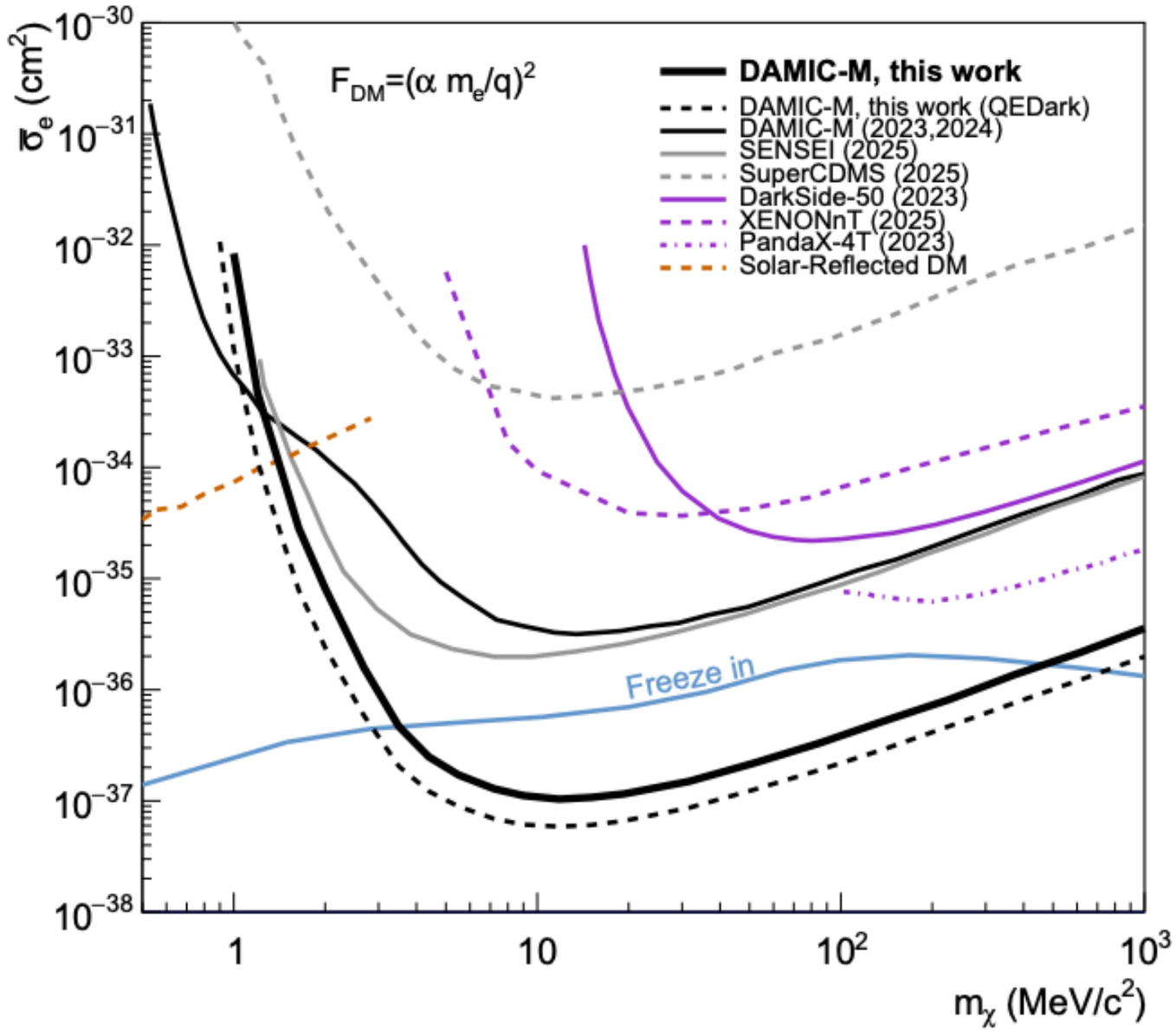
$$\bar{\sigma}_e \propto \frac{\varepsilon^2 \alpha_\chi \mu_{e\chi}^2}{v^4} \quad , \quad \varepsilon^2 \alpha_\chi \sim 10^{-20} \qquad v \sim 10^{-3}$$

Need tiny denominator to compensate $\Longrightarrow$ $m_{A'} \ll \mathrm{keV}$

Only one model allows this limit: millicharged DM (ultralight A' mediator)

Can we test stable freeze-in DM?

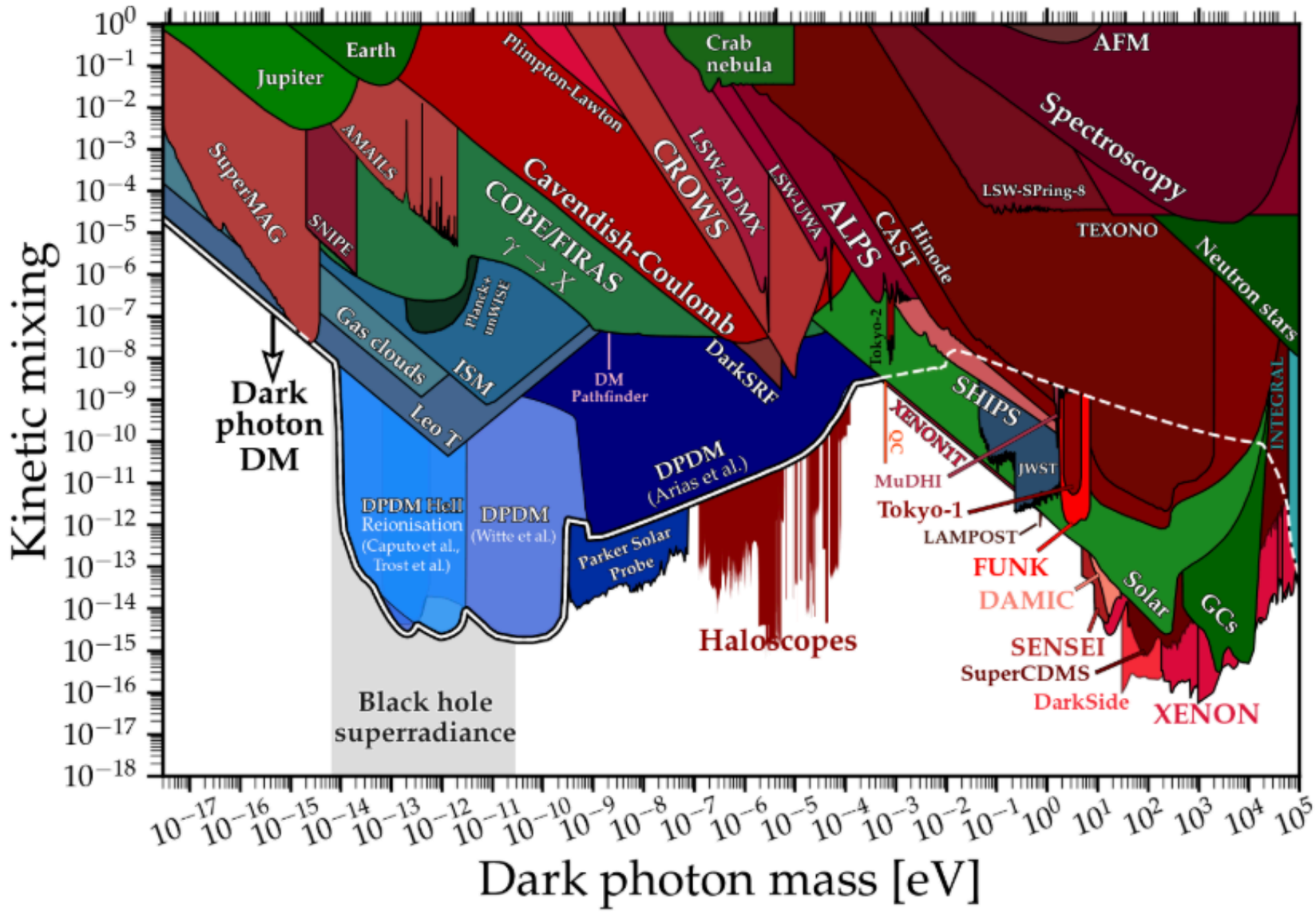
Yes, but there is **exactly one** testable model via scattering



And we are finally testing it!

DAMIC-M 2503.14617

Can we test stable freeze-in DM?

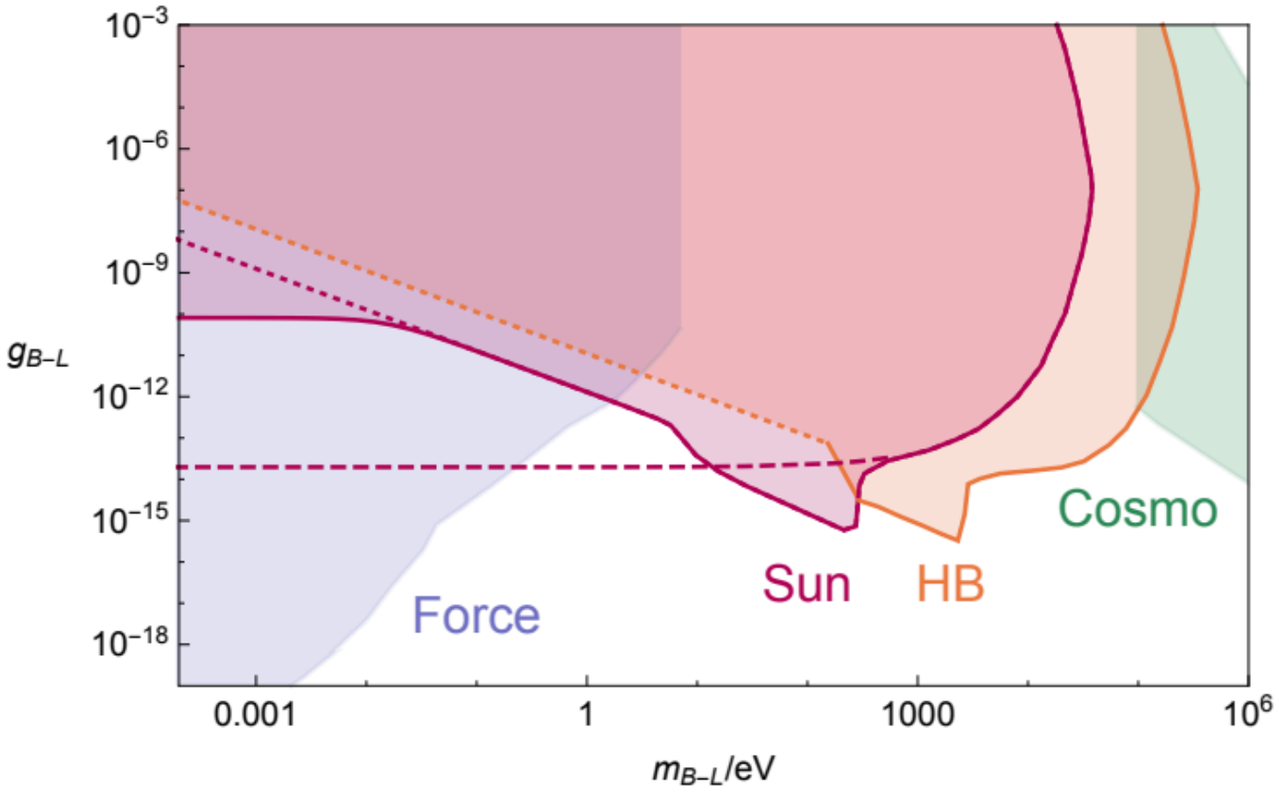


Dark photons are special and decouple at low mass = weak bounds!

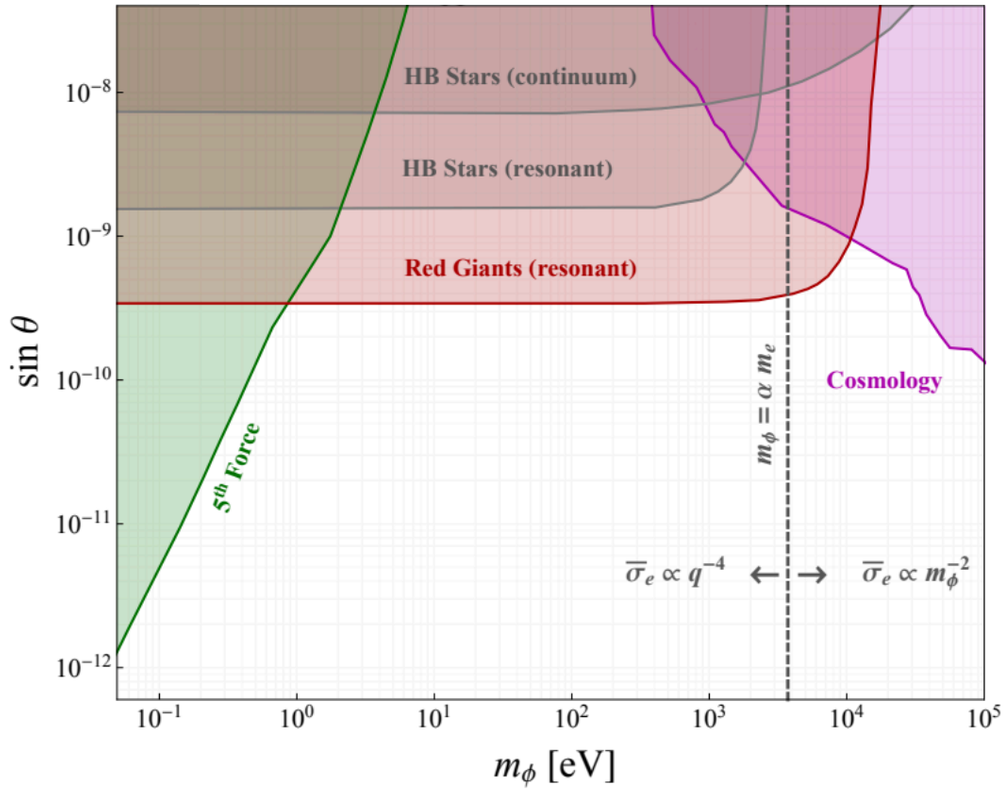
Allows couplings that mediate freeze-in production

Ciaran O'Hare

Can we test stable freeze-in DM?



B-L vector



Higgs-mixed scalar

Other mediators are excluded for m < keV for freeze-in couplings

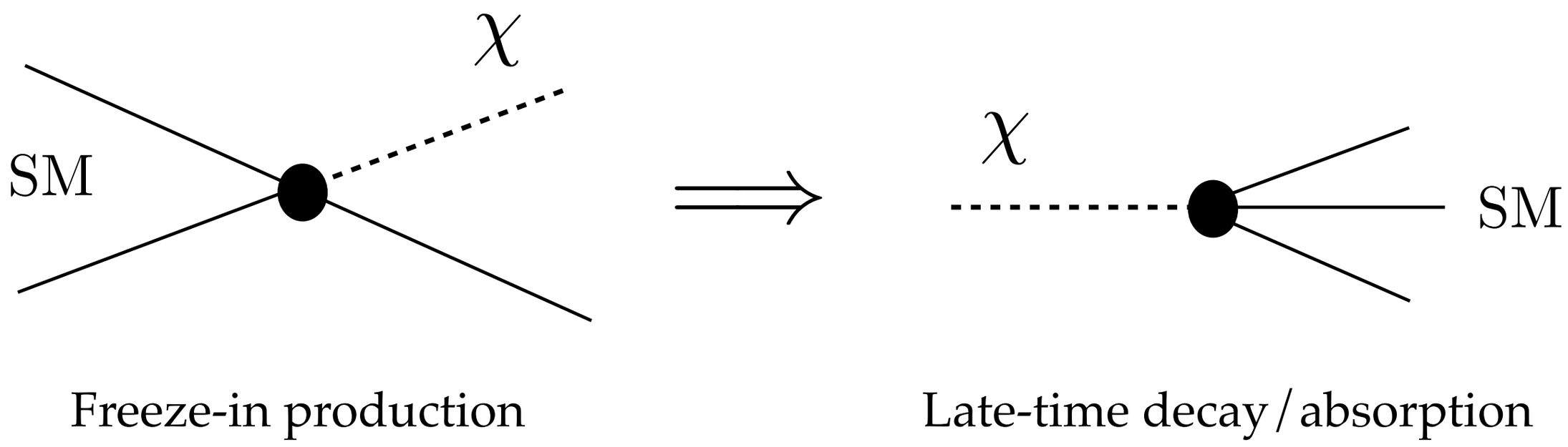
Freeze-in mechanism still allows m > keV, but cross sections untestable

Hardy Lasenby 1611.05852

GK 1711.11038

Can we test **unstable** freeze-in DM?

Here we don't need mediator — just produce one unstable particle!



Freeze-in production Late-time decay / absorption

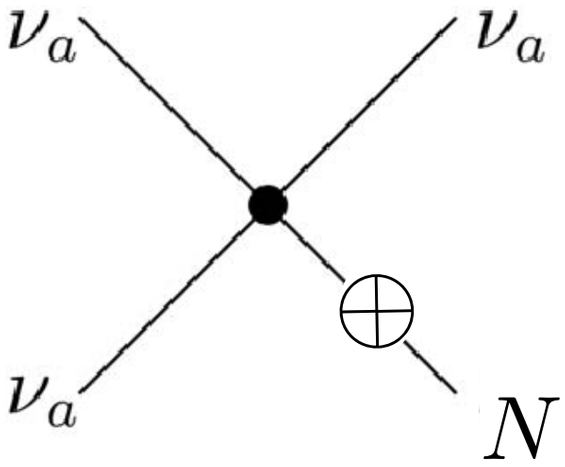
Same coupling governs production and decay/absorption

Small coupling is a feature, not a bug since we need long lifetimes

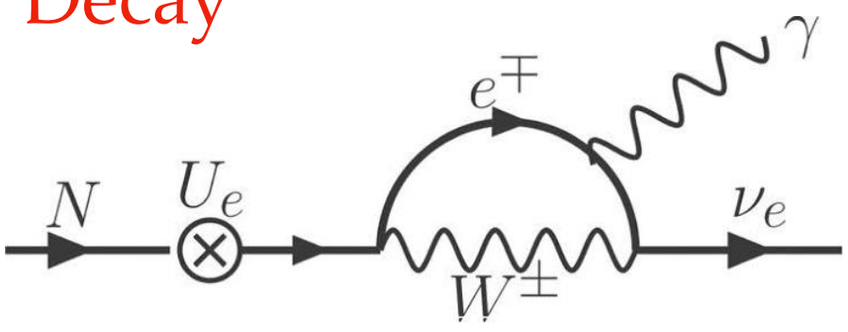
Berlin, Fieg, GK, Trickle 2068.xxxxx

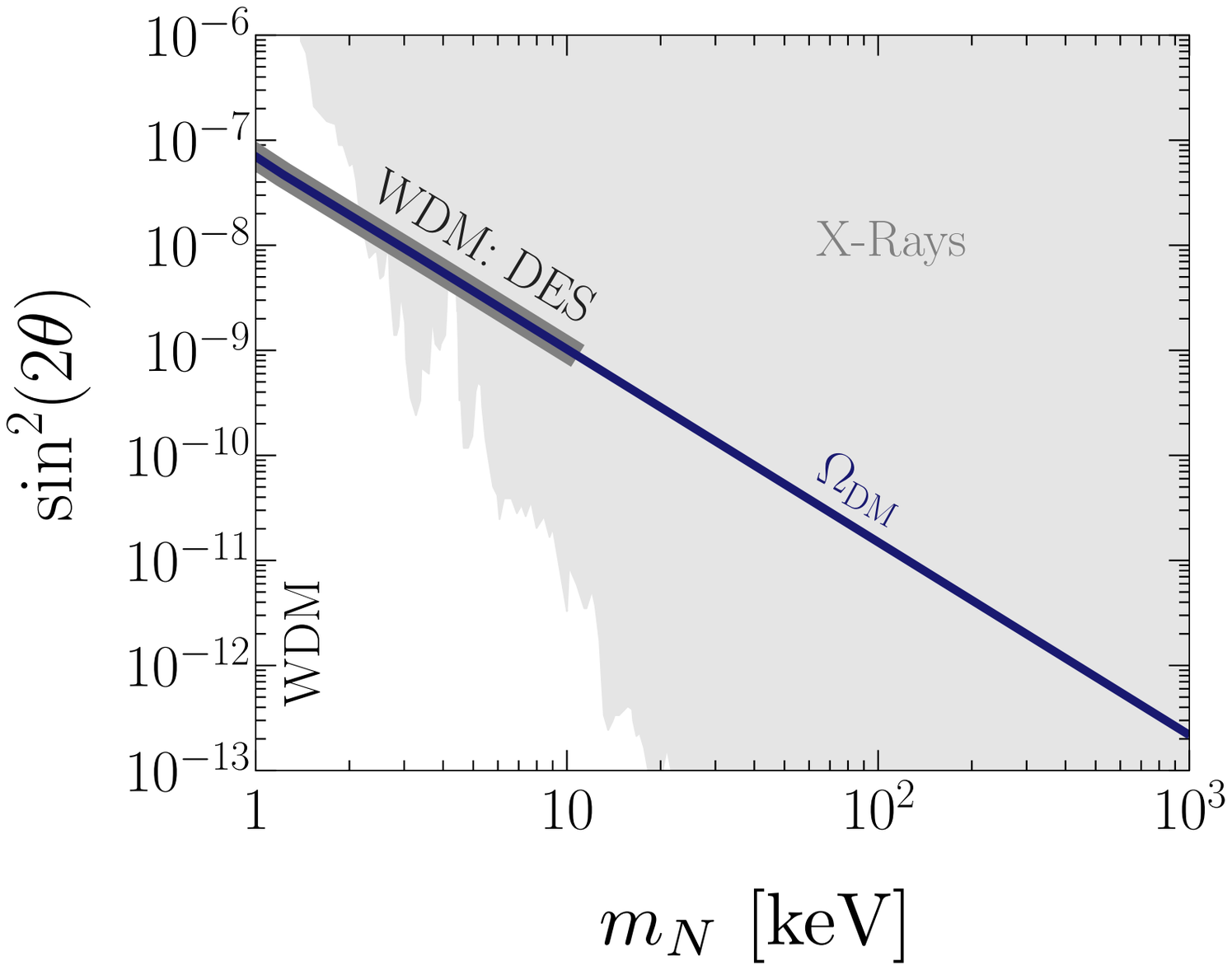
Sterile Neutrino

Production



Decay





Original “freeze in” model: active-sterile neutrino mixing excluded

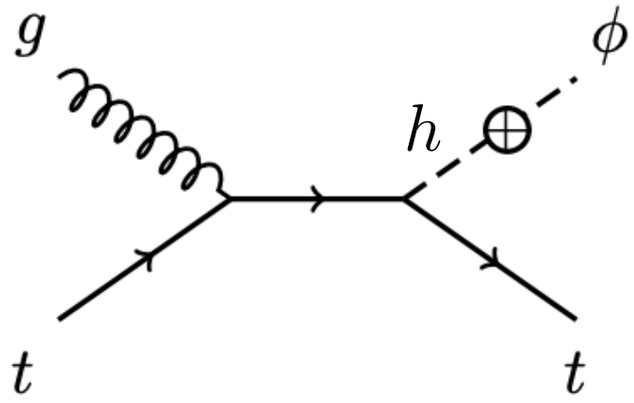
Can evade bound with additional parameters, but not as predictive

Dodelson, Widrow 9303287

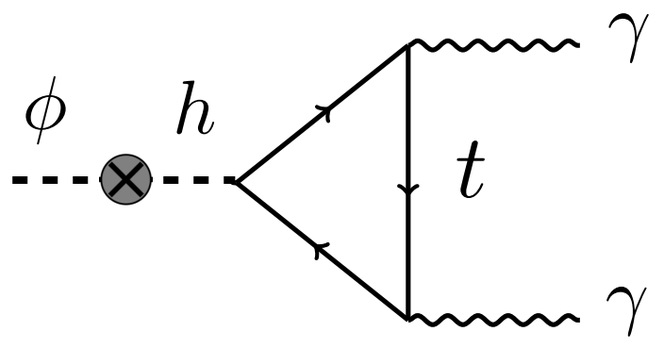
Berlin, Fieg, GK, Trickle 2068.xxxxx

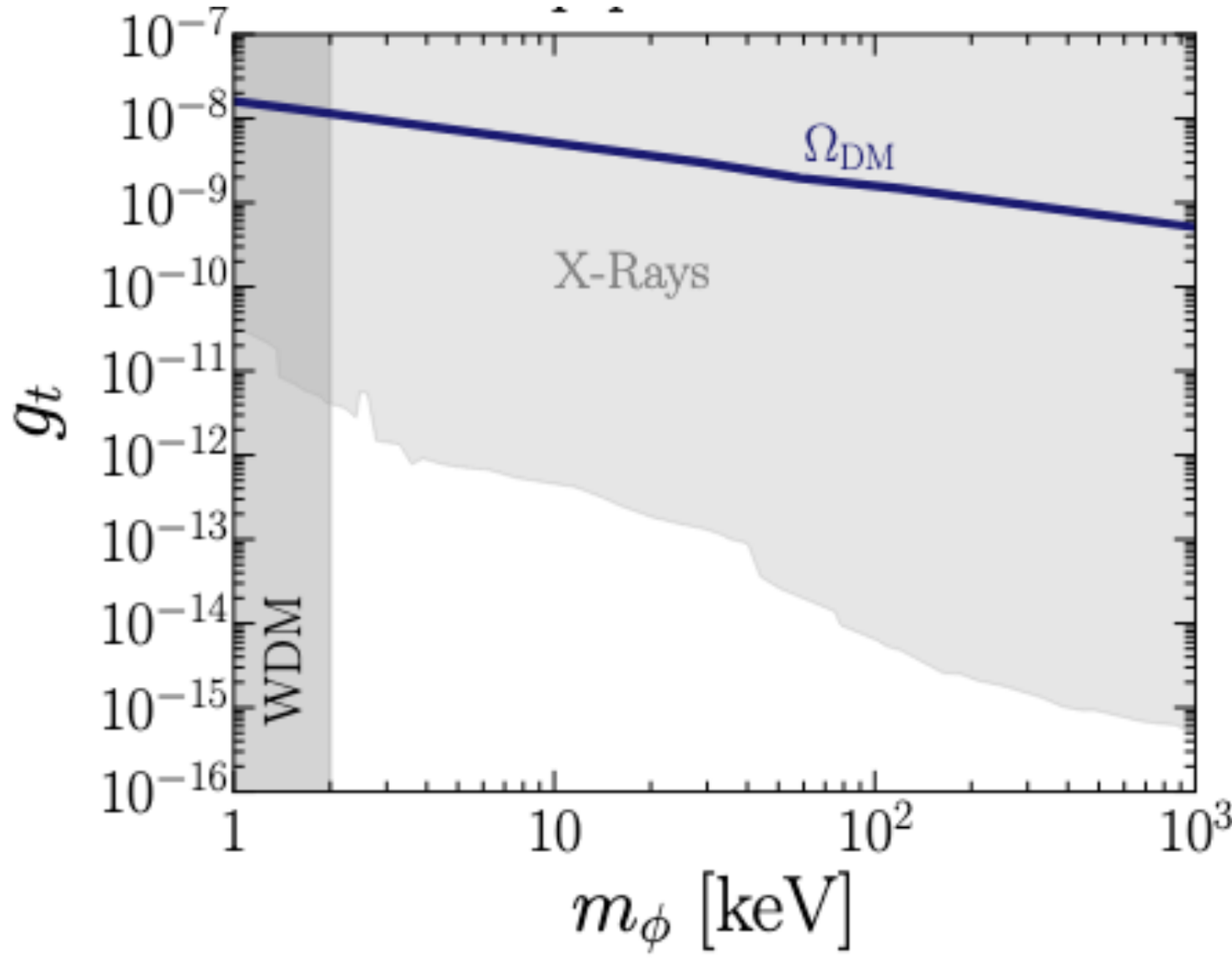
Higgs-Mixed Scalar

Production



Decay





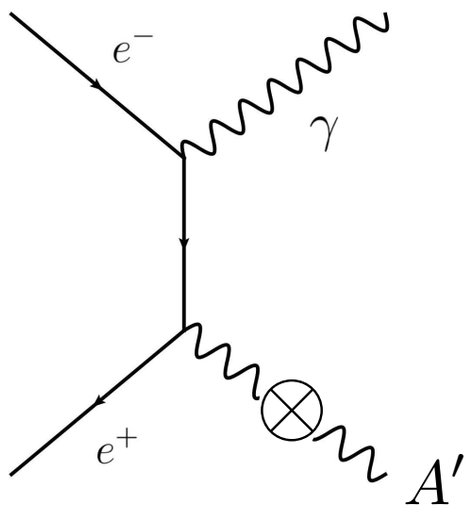
For any 2-body decay: freeze-in couplings = too-short lifetime

Generic problem for any spin-0 mediator

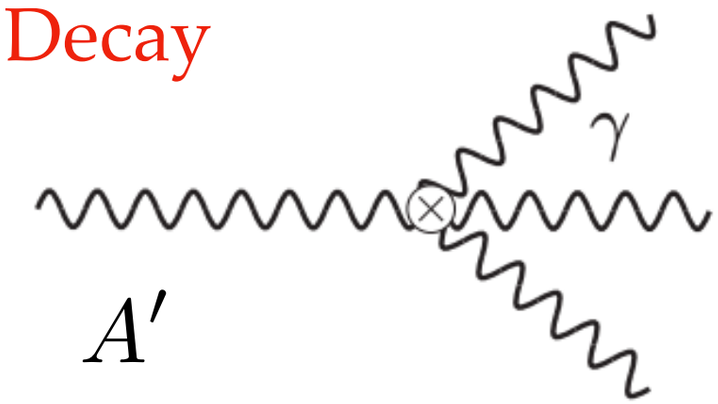
Berlin, Fieg, GK, Trickle 2068.xxxxx

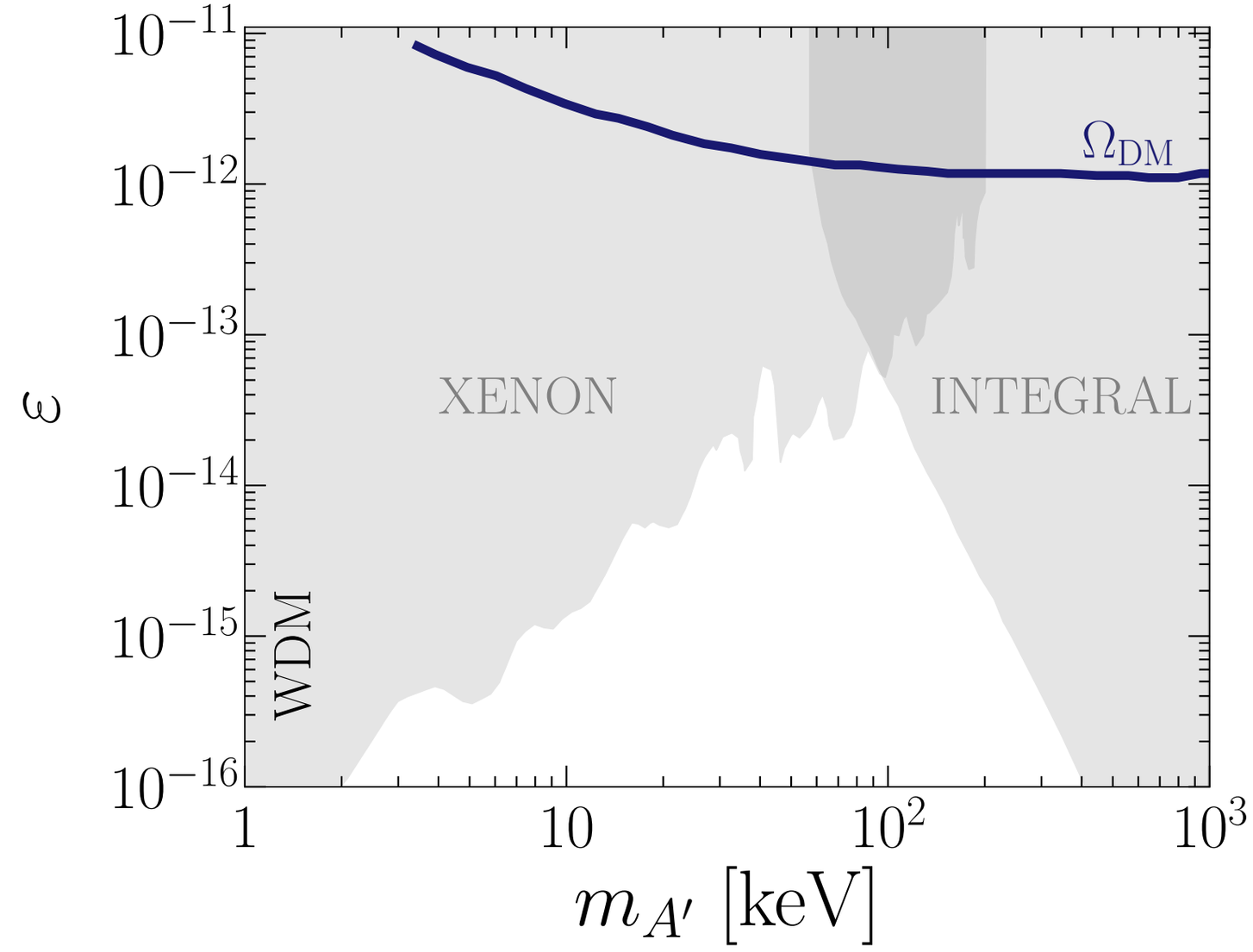
Kinetically-Mixed Dark Photon A'

Production



Decay





Vector can be much longer lived, decay to 3 photons

$$\mathrm{keV} < m_{A'} < 2m_e$$

Pospelov, Ritz, Voloshin 0807.3279

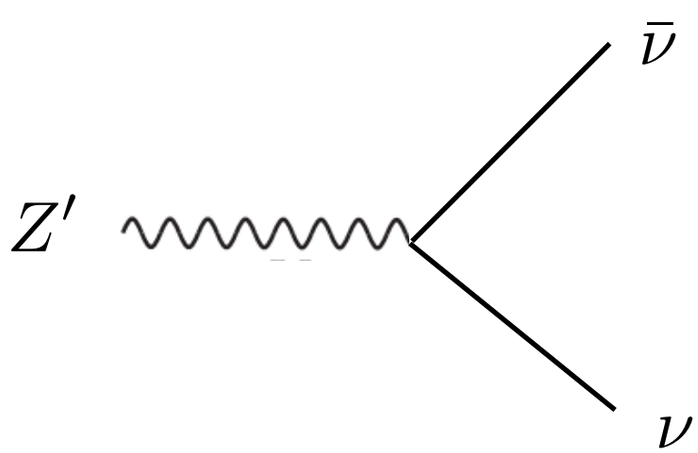
Berlin, Fieg, GK, Trickle 2068.xxxxx

Other Anomaly-Free U(1) Vectors?

Other anomaly-free option gauge at least one lepton family

$$L_i - L_j \quad , \quad B - L \; , \; B - 3L_i \ldots$$

Require at least one kinematically-open neutrino decay channel



$$\tau_{Z'} < 14\,\mathrm{Gyr}$$

For freeze-in couplings, Z' decays too fast to be dark matter

Moral: need anomaly-free leptophobic vector interaction

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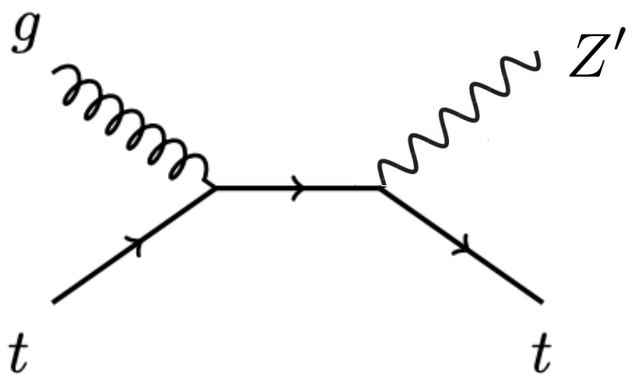
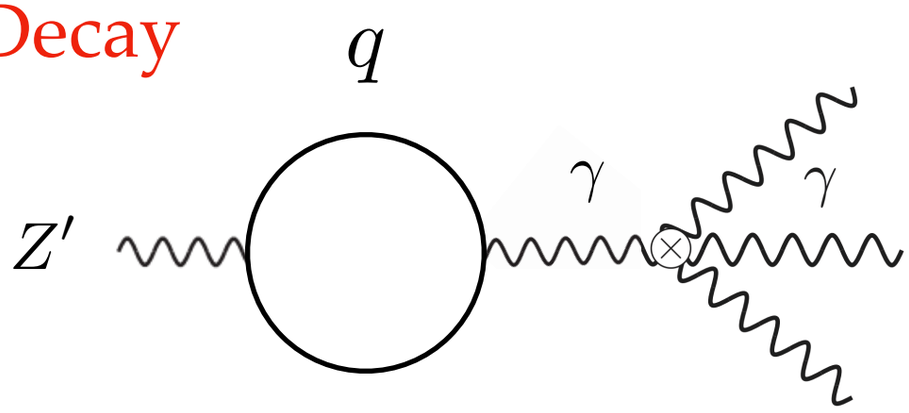
Leptophobic Vector

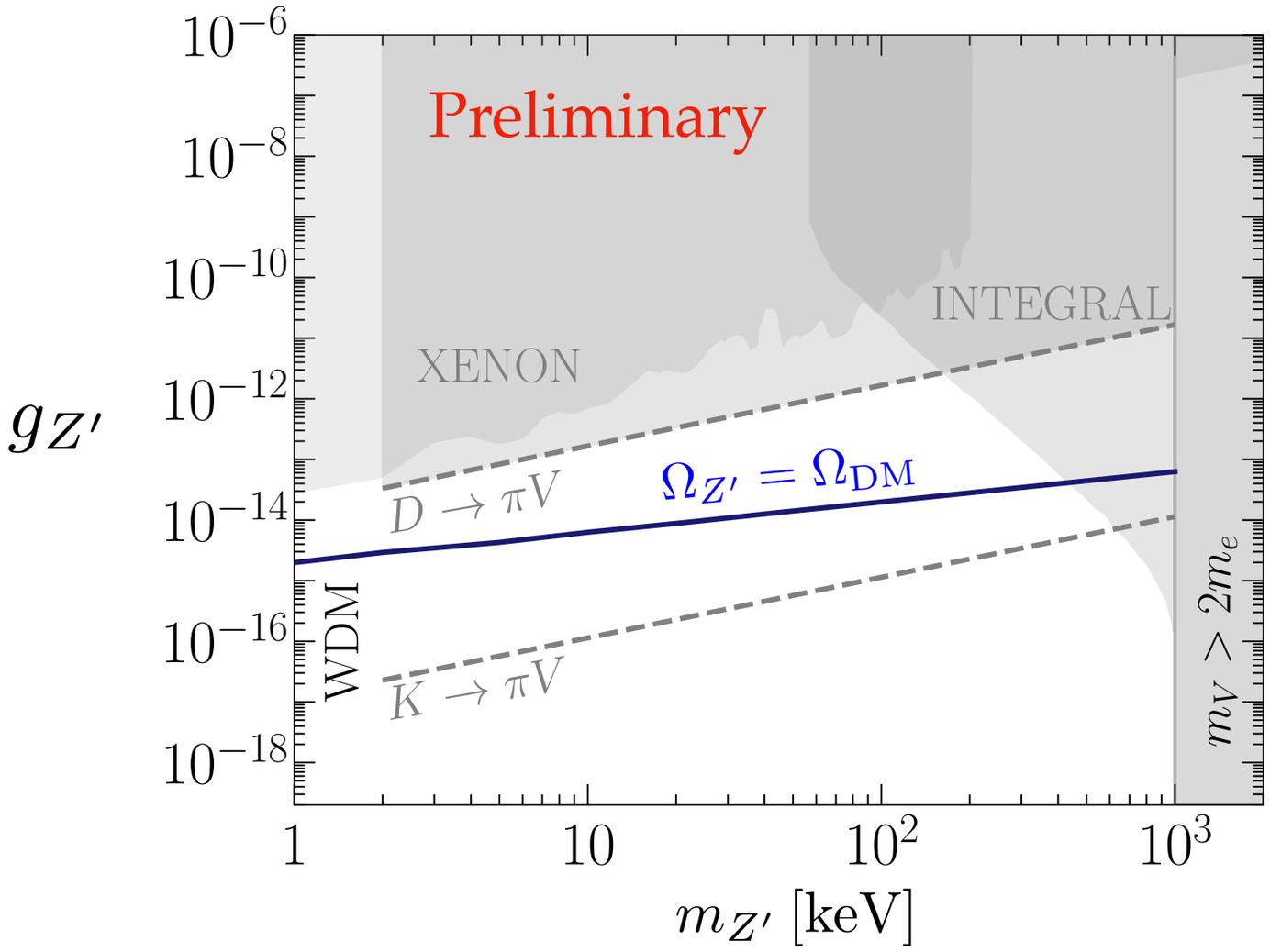
DM is massive gauve boson of anomaly-free $U(1)_{2B_3-B_2-B_1}$

Production



Decay





Viably decays to 3 photons through induced kinetic mixing

Berlin, Fieg, GK, Trickle 2068.xxxxx

Conclusion

Predictive models:

Same couplings govern production & detection

Predictive freeze-out

Scalar DM with 1st gen couplings ruled out for all mediators

Scalar DM with loop-induced 1st gen coupling will be tested

Fermion DM models require accelerator searches

Predictive freeze-in

Stable DM: only testable for millicharge freeze in (or equivalent)

Unstable DM: models ruled out: Higgs-mixing, sterile neutrino, A’

Unstable leptophobic DM: can be viable, within reach of future probes

Thanks!