Freeze In DM Benchmarks in Direct Detection Experiments

In collaboration with David Cerdeño, Patrick Foldenauer and Óscar Zapata

[2603.16863]

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Light Dark World

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WIMPs parameter space is extensively probed

Sub-GeV DM particles searches through:

ERs

NRs in low energy threshold experiments

These probes of low-mas DM also test alternative production mechanism

Freeze In

Initial abundance of DM is negligible

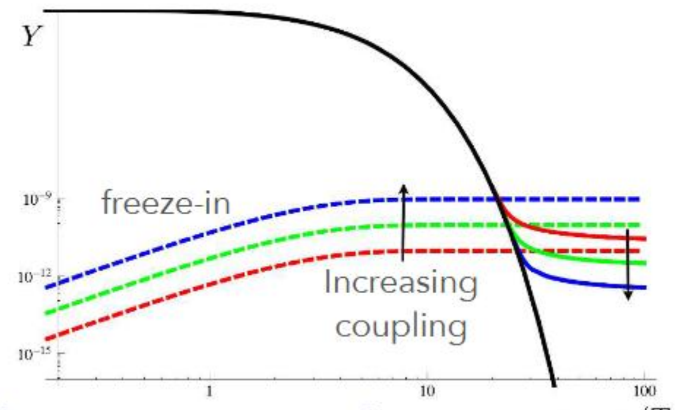
SM annihilation/decays produced DM gradually out of equilibrium

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \left(n_\chi^{\rm eq}\right)^2 \langle\sigma v\rangle$$

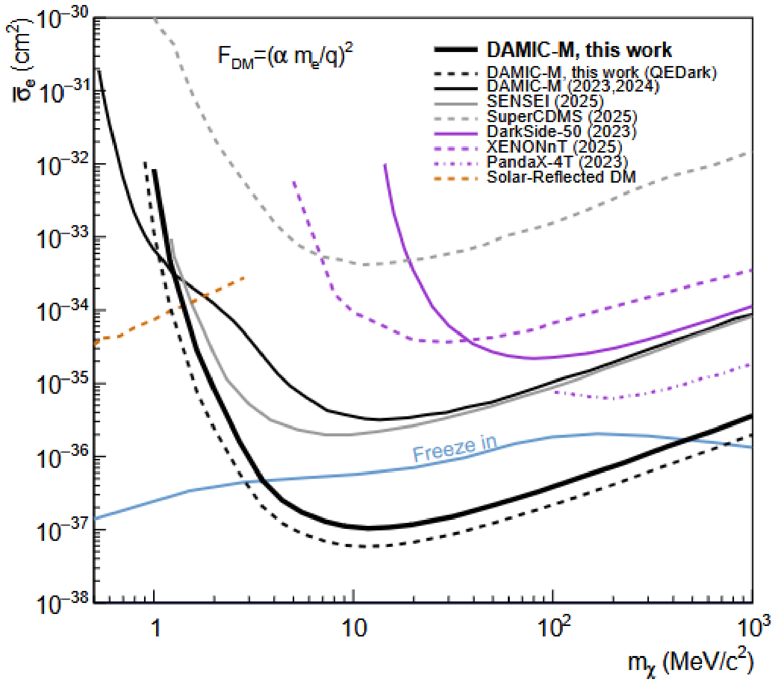
DAMIC-M and PandaX-4T recently published results **excluding** freeze in cross sections

[DAMIC-M; PRL 135 071002]
[PandaX; PRL 135 211011]

What is next for freeze in?



[Hall+; *JHEP 1003:080,2010*]



Our focus is on fermionic dark matter that couples to the SM via:

A' of a secluded $U(1)_D$

$U(1)_{L_i\text{-}L_j}$ gauge bosons

$U(1)_{B\text{-}L}$ gauge boson

Ultralight dark photons could be a subdominant part of DM

Under the new gauge bosons, CEvNS cross section could be enhanced

It opens the possibility of testing BSM physics in both dark and neutrino sector with DD

We further embed each of the U(1) models within a cosmological **scenario featuring low reheating temperatures**

JCAP 12 (2015) 024 [1506.07532]
JHEP 02 (2019) 186 [1811.05478]
JHEP 03 (2025) 079 [2412.12303]

Dark sector-SM interaction arises through kinetic mixing

When the kinetic mixing $\epsilon \ll 1$, and light dark photon mass, $m^2{}_X/v^2 \ll 1$

$$\mathcal{L} \supset - A^\mu(e\, j_\mu^{\mathrm{EM}}) - Z^\mu(g_Z\, j_\mu^Z) + A'^\mu(e\, \epsilon_A\, j_\mu^{\mathrm{EM}})$$

$$\boxed{m_{A'} \ll m_\chi}$$

DAMIC-M and Pandax-4T excluded m_χ **~ [3,400] MeV**

Under-abundant components Phys. Rev. Lett 134, 121002

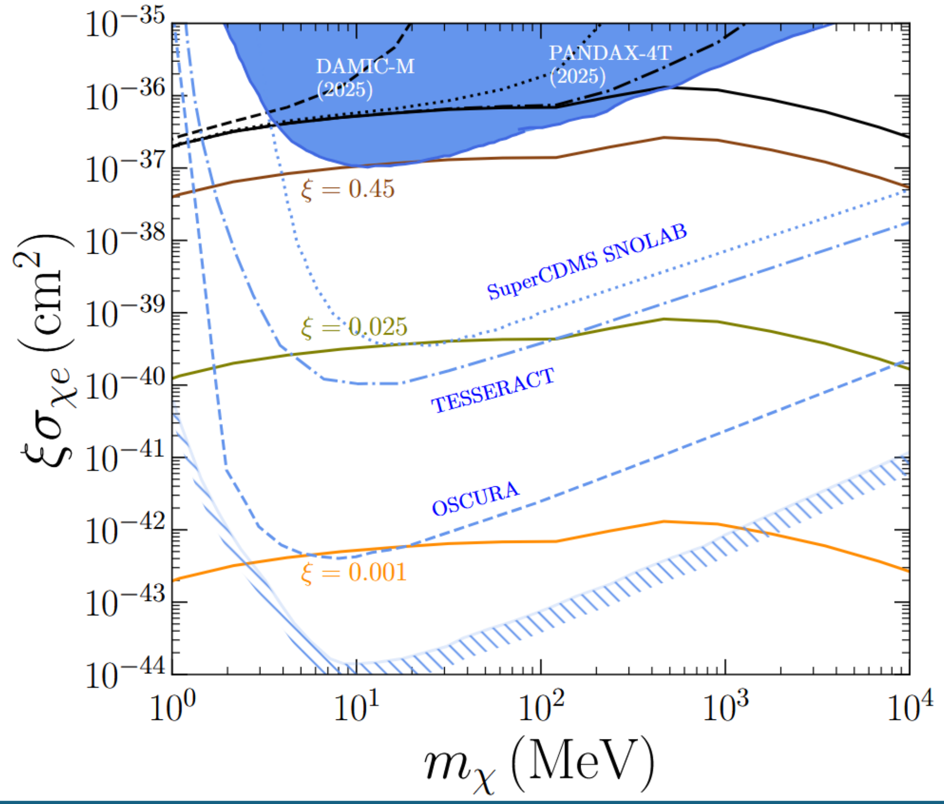
$$\xi = \Omega h_\chi^2/\Omega h_{\mathrm{DM}}^2$$

Freeze In

$$\xi \sim \Omega_\chi h^2 \propto k^2$$

$$\xi\sigma_{\chi e} \propto k^4$$

[Cerdeño, Foldenauer, RLN, Zapata; 2603.16863]



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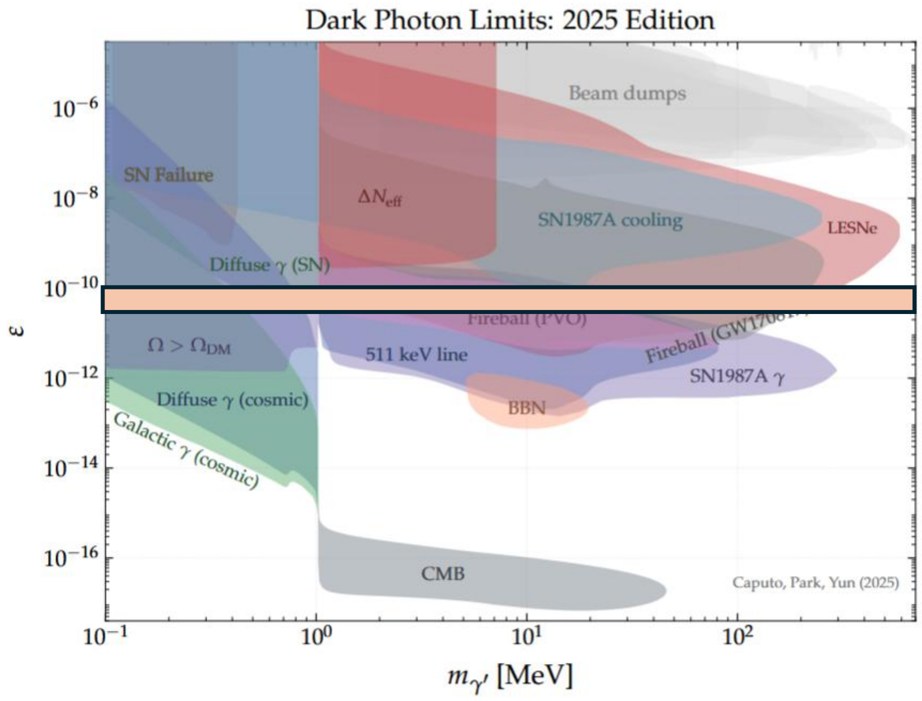
MeV dark photons are severely constrained from beam dump searches, astrophysics and cosmology

At the end of inflation, inflaton decay injects entropy in SM bath
→ Reheating

$T_{rh} < m_\chi$

Enhancement in the coupling needed to reproduce the correct relic density



[Caputo, Park, Yun; 2511.15785]

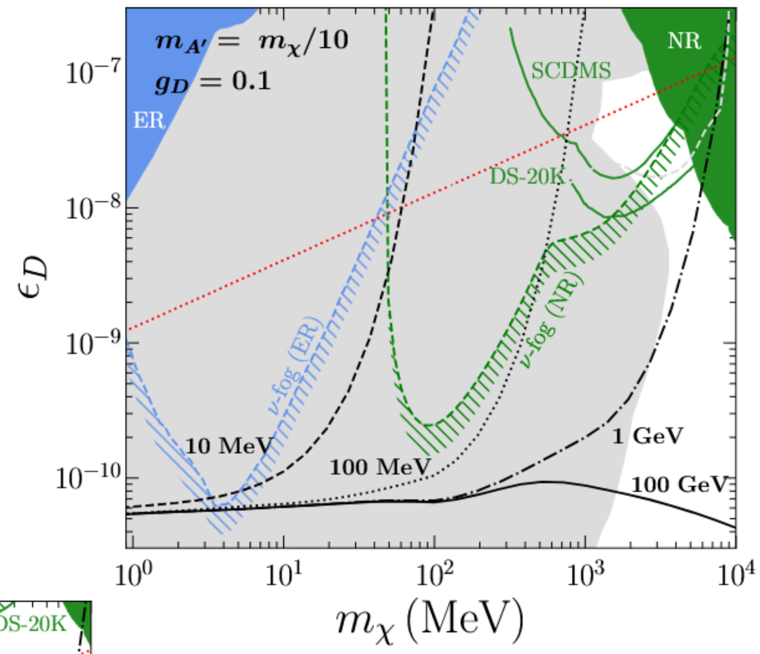
$$\boxed{m_{A'} \lesssim m_\chi}$$

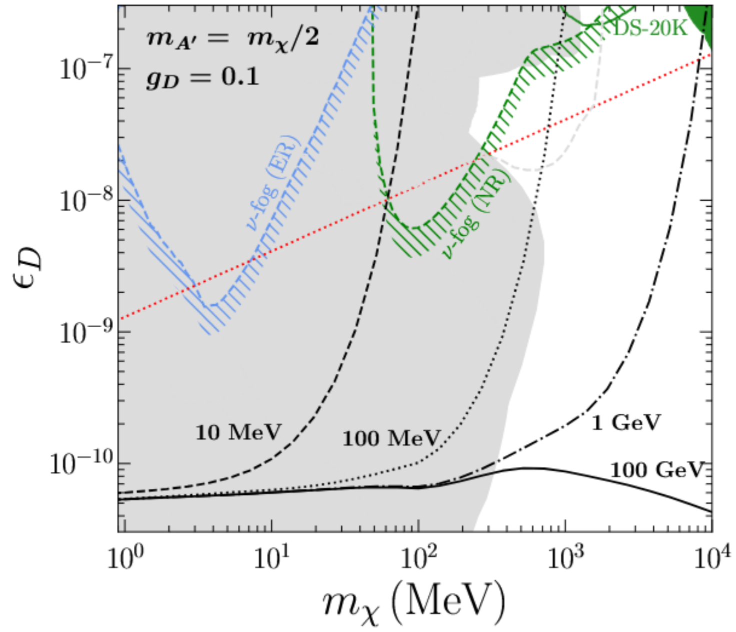
MeV dark photons are severely constrained from beam dump searches, astrophysics and cosmology

High reheating temperatures buried in the neutrino fog

Low reheating scenarios for T_{rh} ~100 MeV – 1 GeV within reach of future direct detection experiments

Simultaneous dark photon signal in fixed target experiments like SHiP





[Cerdeño, Foldenauer, RLN, Zapata; 2603.16863]

U(1)$_X$ can also be coupled to SM by gauge interactions

$$\mathcal{L} \supset -A^\mu (e\, j_\mu^{\mathrm{EM}}) - Z^\mu \left[g_Z\, j_\mu^Z - g_X\, \epsilon_Z\, j_\mu^X \right] - A'^\mu \left[g_X\, j_\mu^X - e\, \epsilon_A\, j_\mu^{\mathrm{EM}} \right]$$

SM fields

$$j_X^\mu = \sum_\psi \bar{\psi}\, Q_\psi\, \gamma^\mu \psi \qquad \text{with} \quad \psi = Q, L, u, d, \ell, \nu$$

Anomaly-free *U(1)* models

$L_\mu - L_\tau$ | $L_e - L_\tau$ | $L_\mu - L_e$ | $B - L$

Each charges different lepton generations/quarks, but all have interactions with neutrinos

Solar neutrino scattering enhance in direct detection!

BSM observables in both DM and neutrino signals

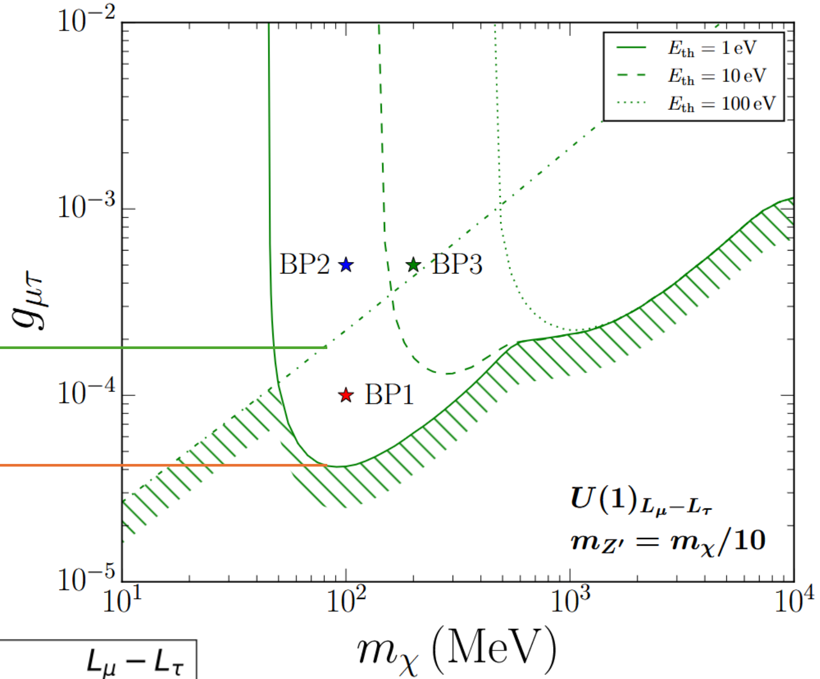
[Cerdeño, Foldenauer, RLN, Zapata; 2603.16863]

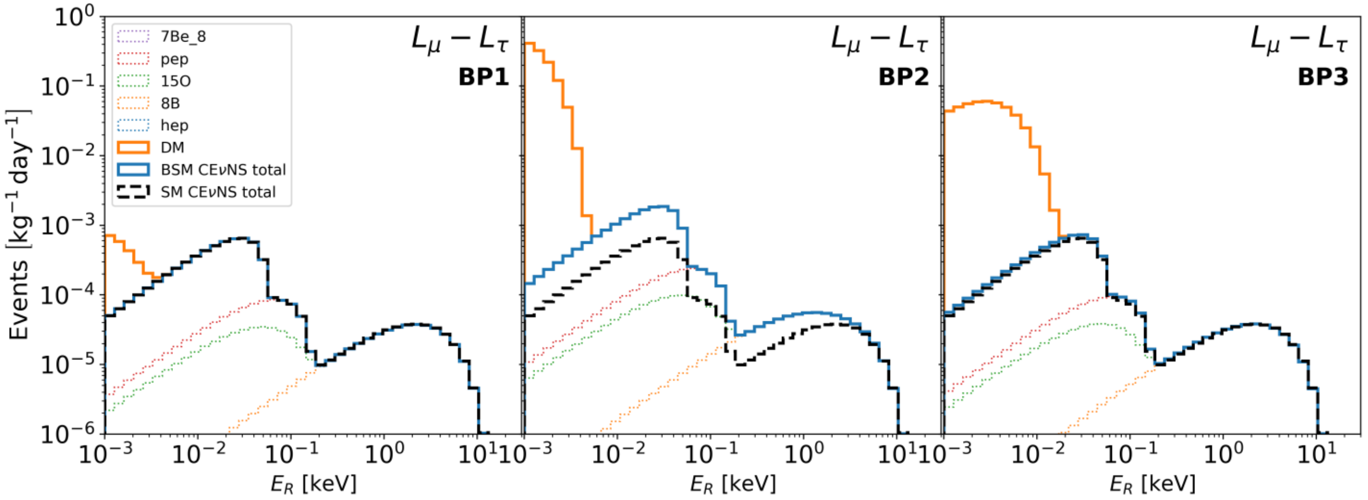
The potential observation depends on the experimental E_{th}

Potential signal discrimination via spectral info

BSM neutrino discovery limit

DM discovery limit



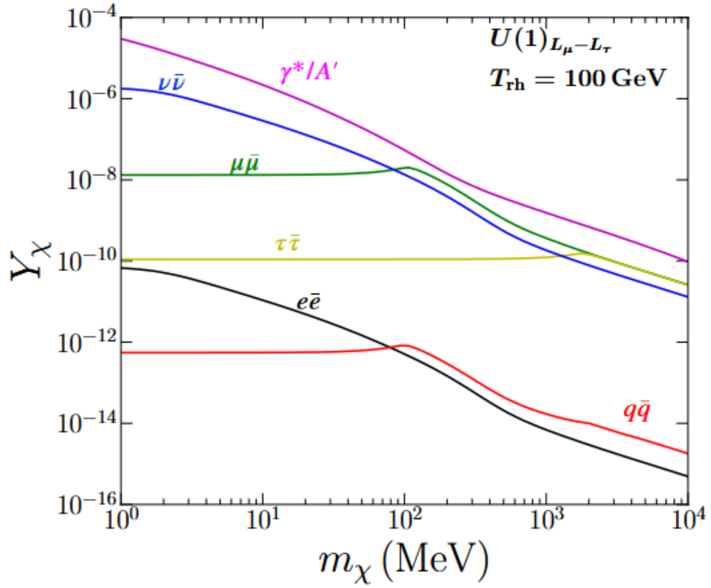


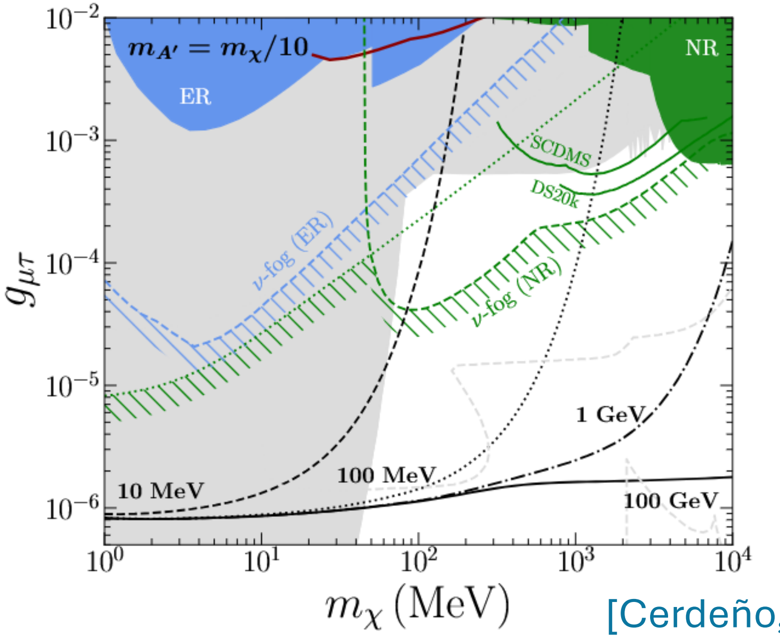
L_μ - L_τ

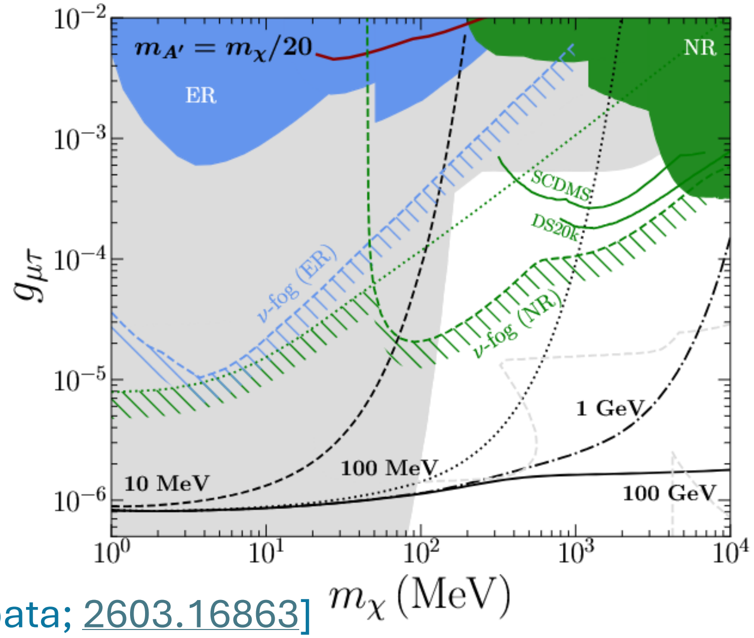
Production is dominated by (thermalized) A' and $\nu_{\mu,\tau}$ annihilation

Low reheating freeze-in within reach of next gen experiments for T_{rh} ~10 – 100 MeV

Predicts consistent signatures in NR and fixed target experiments







[Cerdeño, Foldenauer, RLN, Zapata; 2603.16863]

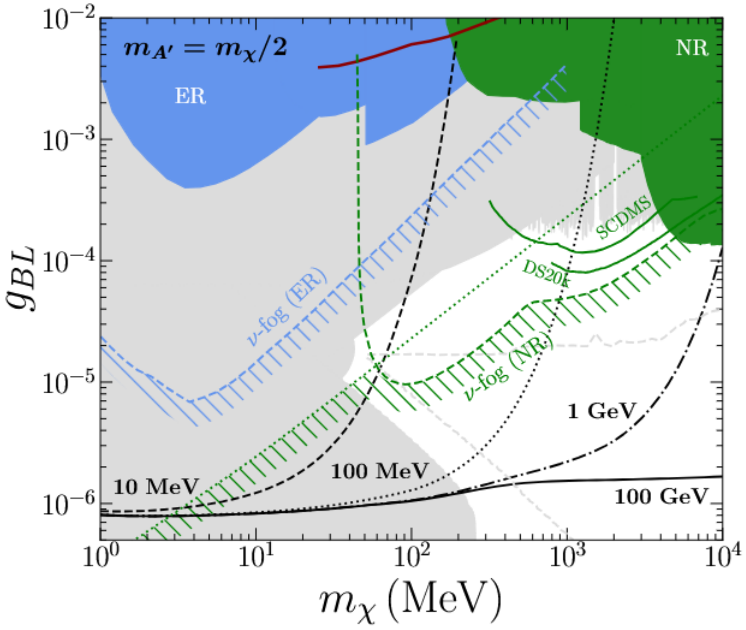
B - L

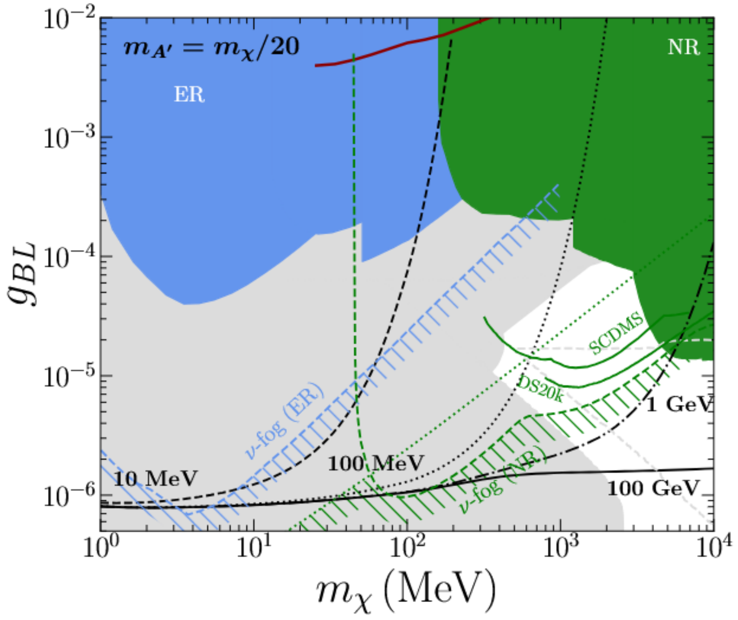
Direct gauge coupling with nucleons→ NRs more sensitive, sensitive to a larger region of parameter space

Significant sensitivity to **BSM neutrino signal**

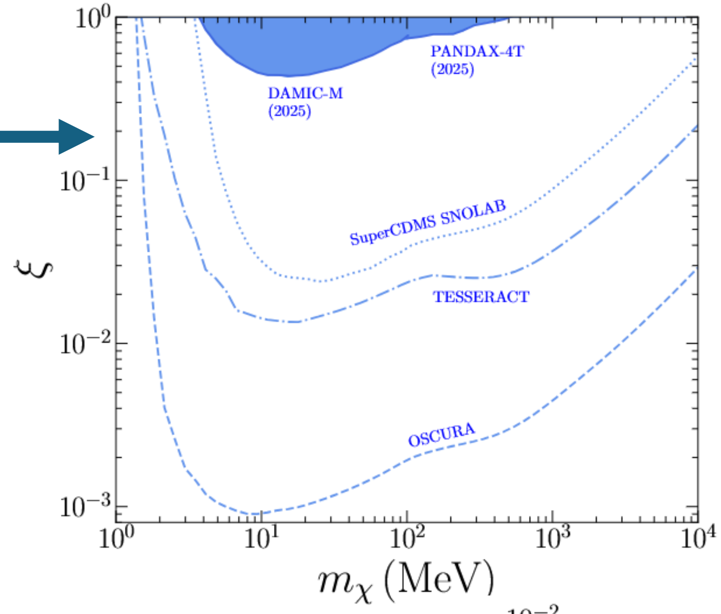
Simultaneous signals at **LHCb and Belle-II**

[Cerdeño, Foldenauer, RLN, Zapata; 2603.16863]





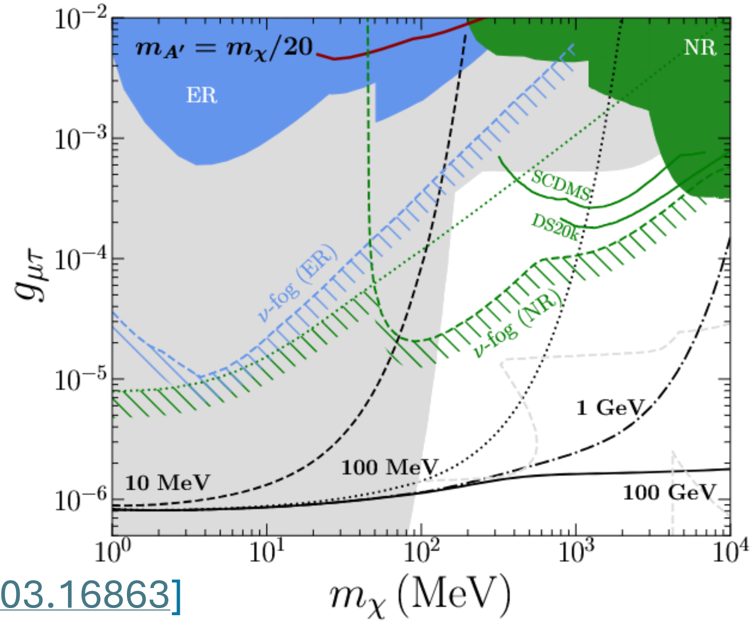
- Freeze-in with ultralight dark photons excluded by direct detection. Under-abundance still available



- Next generation of direct detection experiments **can probe low reheating scenarios with massive mediators**

- Leptophilic mediators provide new freeze-in benchmarks. **Simultaneous DM and neutrino signal**

- Prime opportunities to test BSM physics!



[Cerdeño, Foldenauer, RLN, Zapata; 2603.16863]

Assumption

DM particles never attain thermal equilibrium with the plasma

SM thermal bath is populated at T_{rh} , which is ~ maximum temperature of the plasma

No DM at T_{rh}

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \left(n_\chi^{\rm eq}\right)^2 \langle\sigma v\rangle \longrightarrow Y_\chi(T_0) = \int_{T_0}^{T_{\rm rh}} dT\, \frac{s}{HT}\left(1 + \frac{1}{3}\frac{d\ln g_{*s}}{d\ln T}\right)^{-1} \left(Y_\chi^{\rm eq}\right)^2 \langle\sigma v\rangle$$

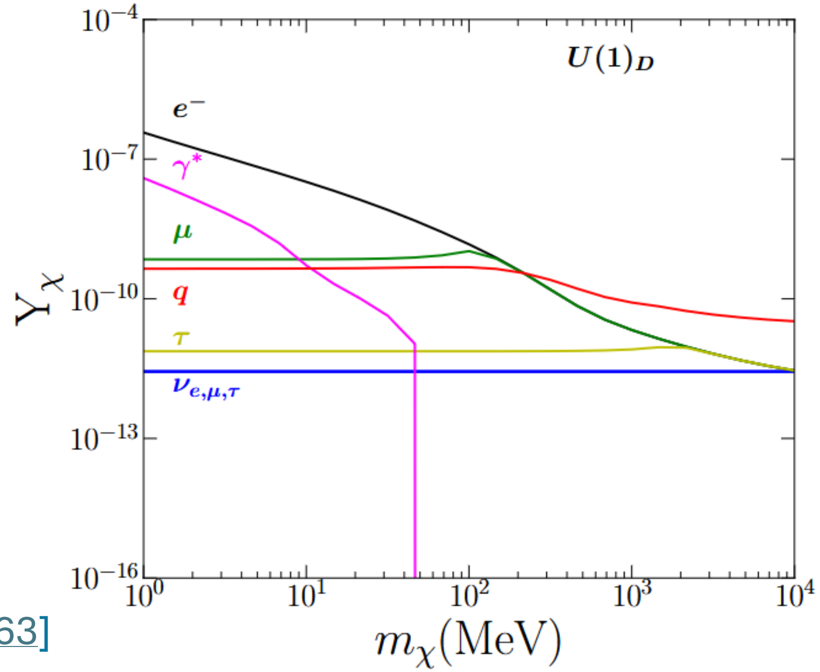
Freeze in production ceases at $T \sim max(m_{A'}, m_\chi)$

$T_{rh} >> m_\chi$

Standard cosmology scenario

Upper limit of the integral becomes irrelevant

DM abundance insensitive of the initial conditions



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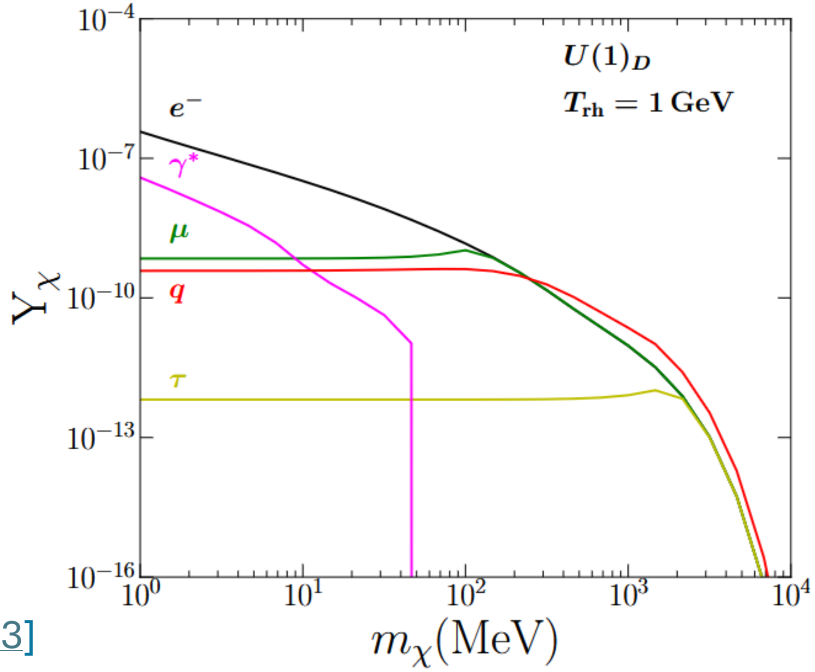
Freeze in production ceases at $T \sim max(m_{A'}, m_\chi)$

$T_{rh} < m_\chi$

DM production becomes kinematically suppressed
Only SM particles in the exponentially suppressed tail produce DM
Consequently, significantly reduced in DM yield
Larger couplings needed compared to high-T_{rh}



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