Reviving WIMP dark matter with temperature-dependent couplings

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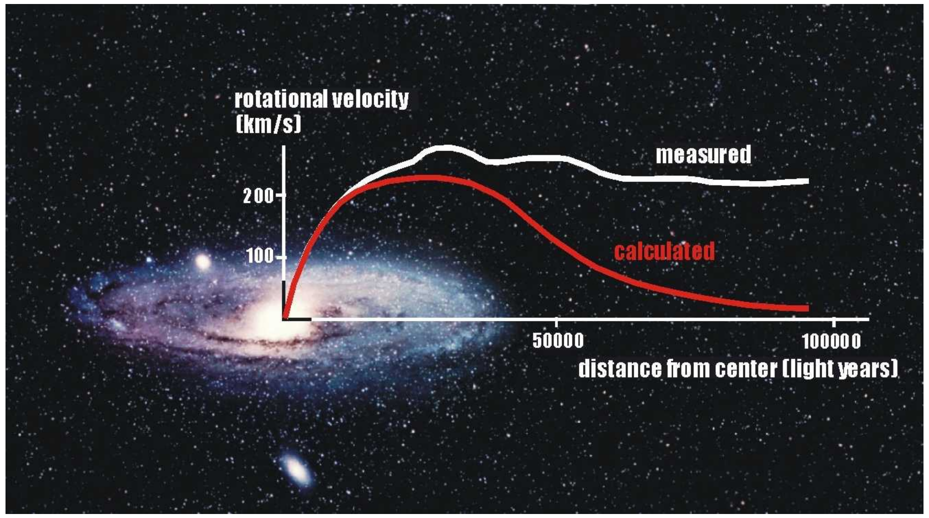
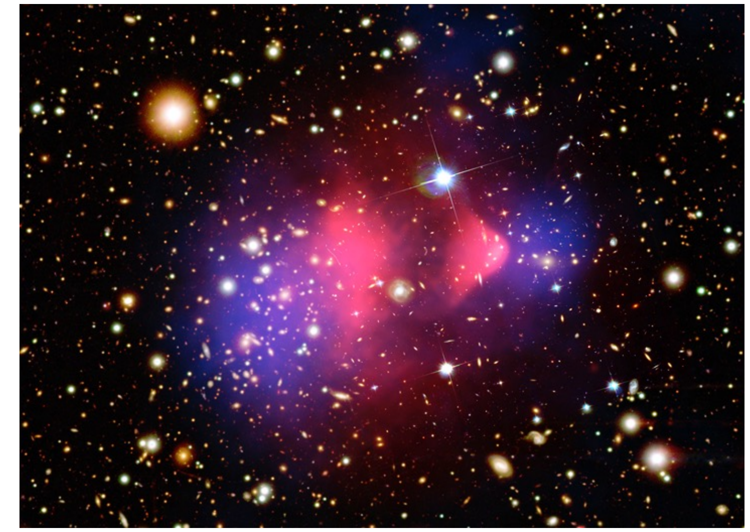
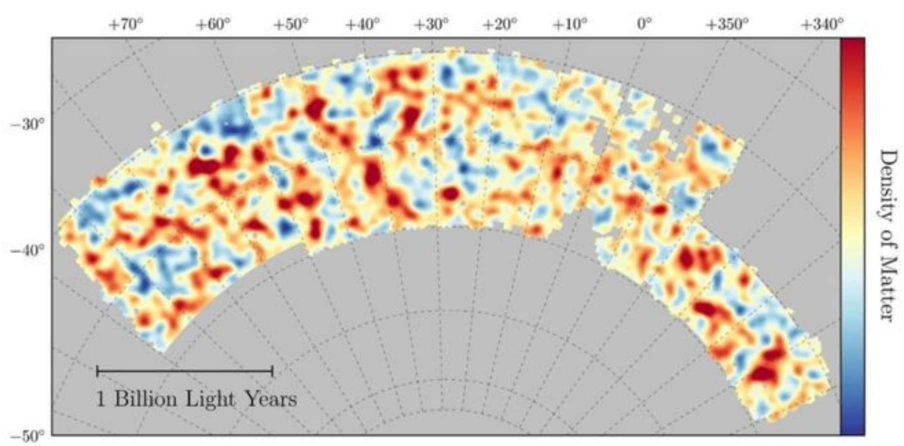
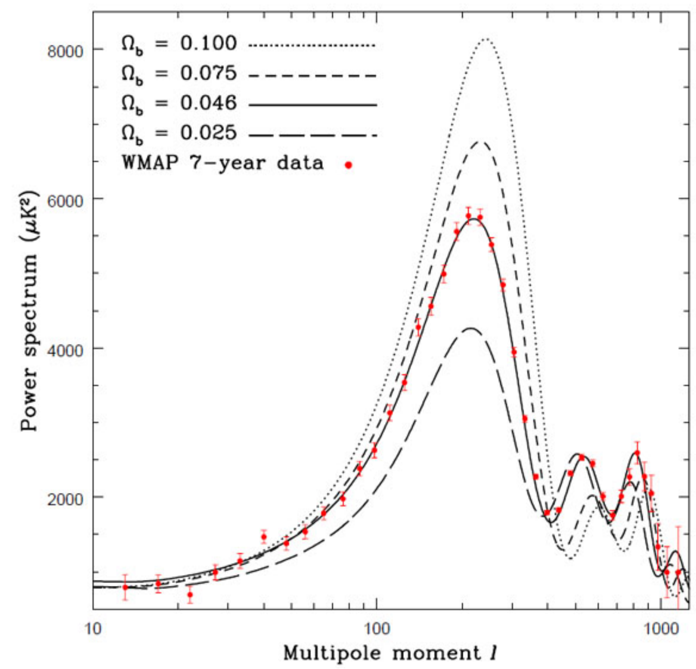
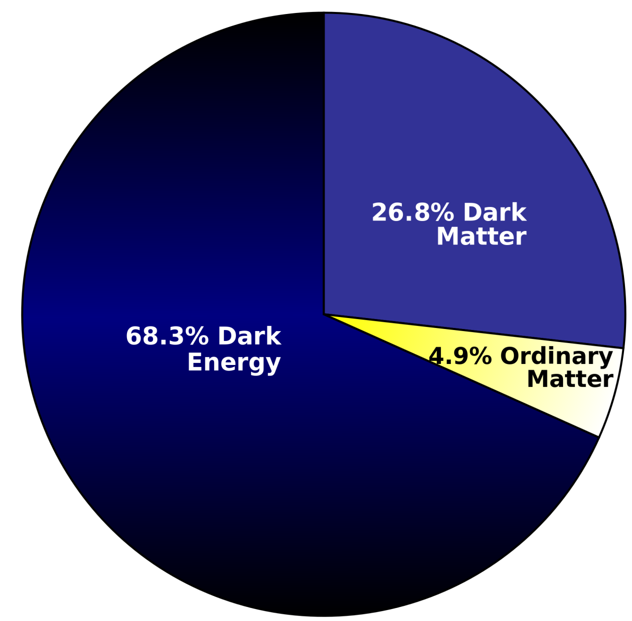
Dark Matter: Evidences

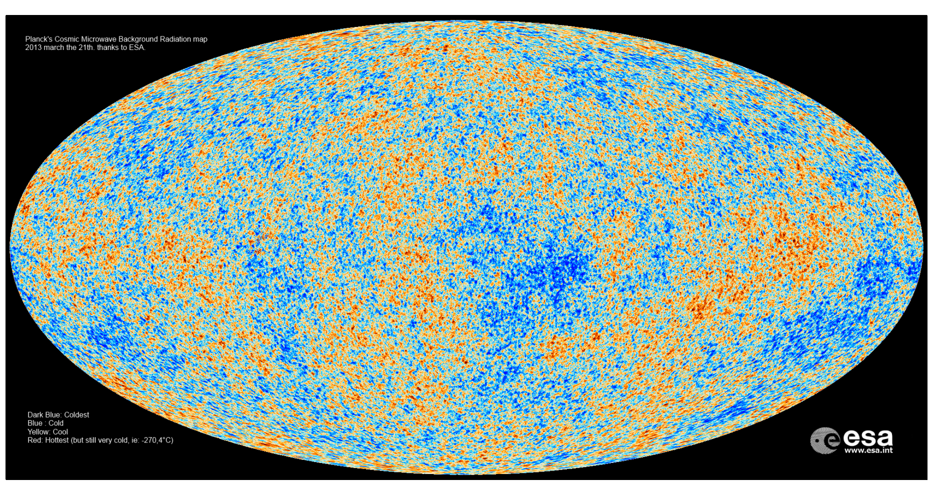








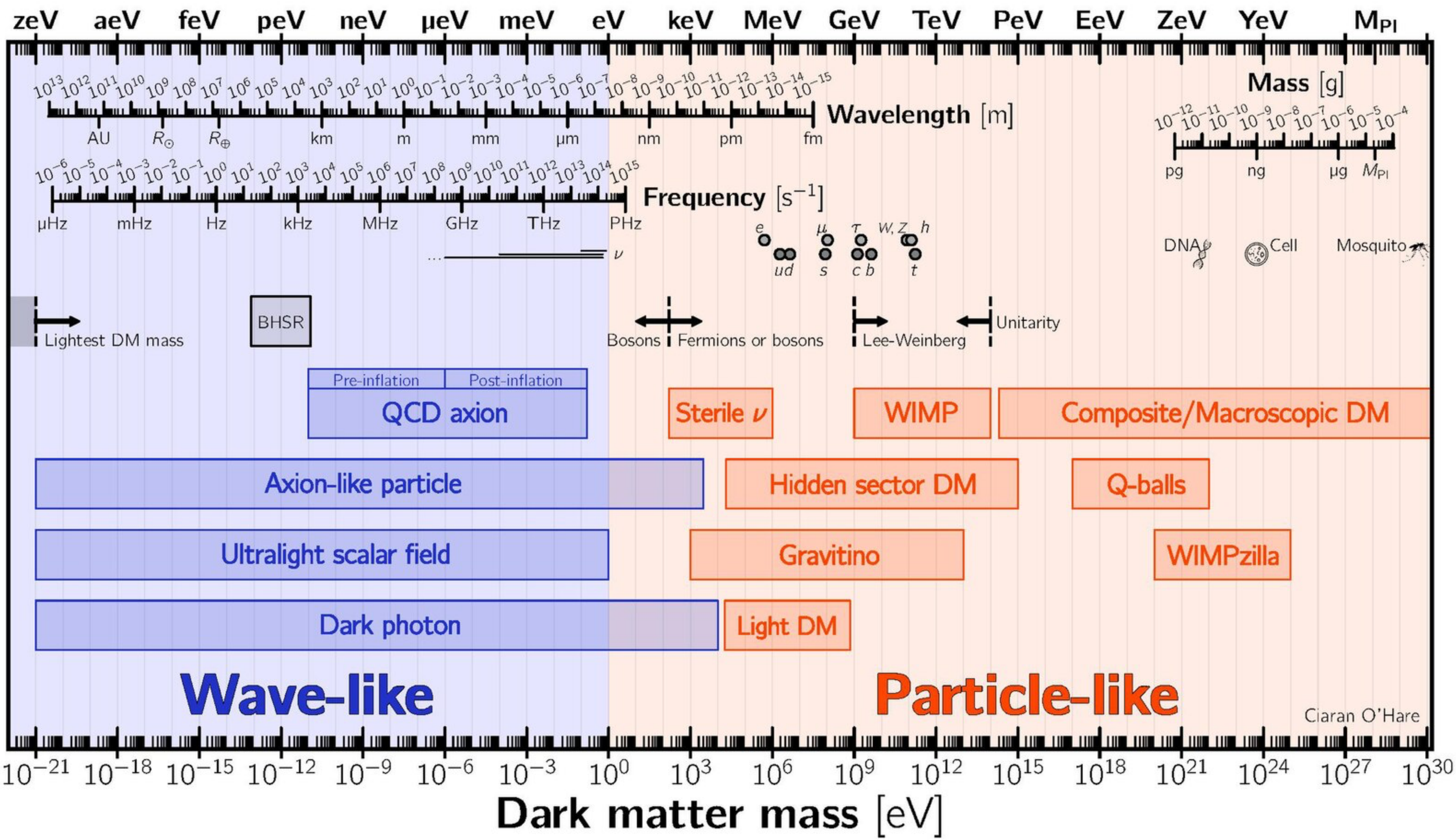




Credits:

HST, Chandra, DE Survey, WMAP, Planck

DM Candidates



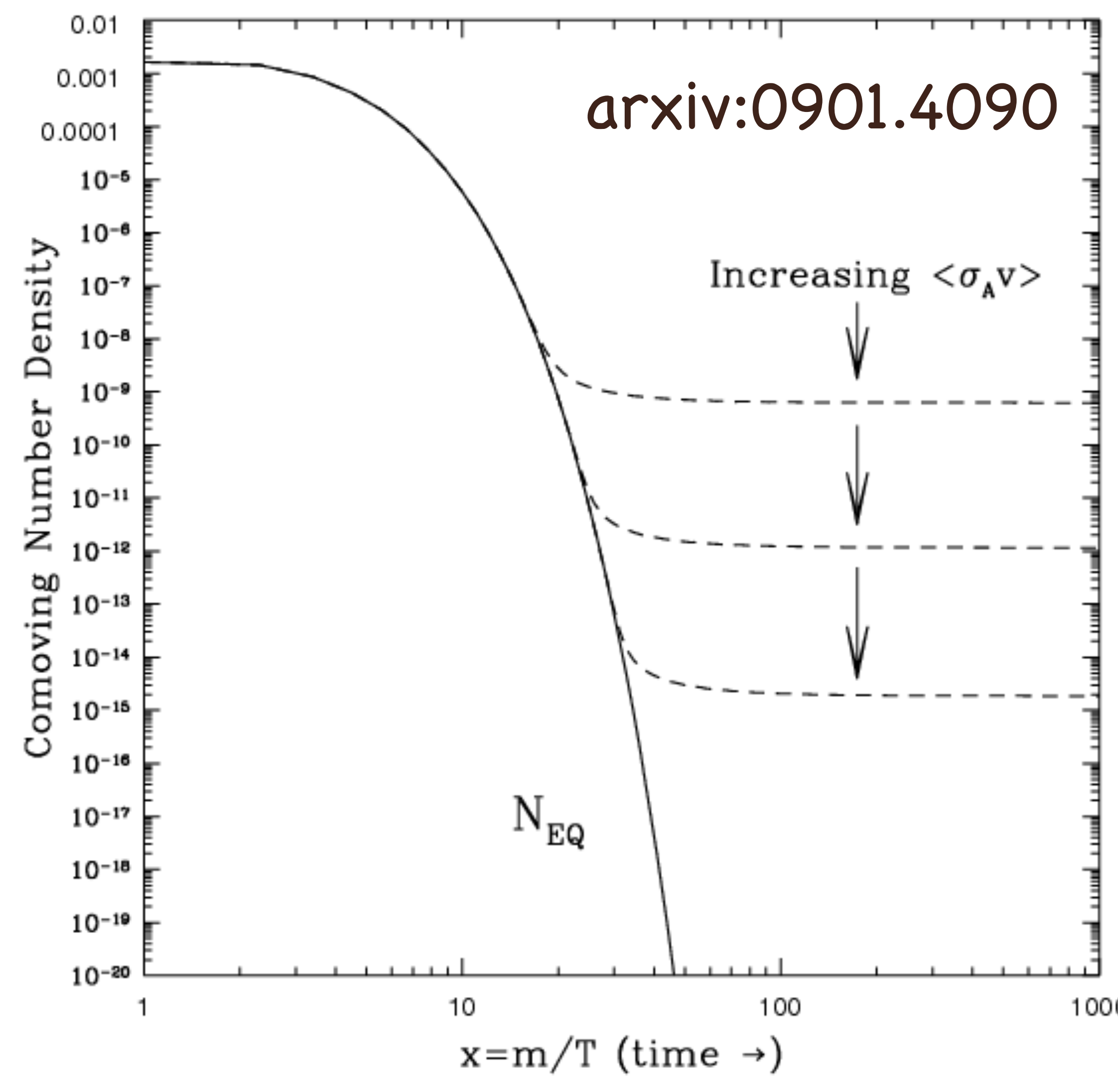
Freeze-out: WIMP Miracle

- The relic abundance of dark matter which was in thermal equilibrium in the early Universe can be calculated by solving the Boltzmann equation:

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

$$\Omega_{\rm DM}h^2 \approx \frac{3\times10^{-27}cm^3s^{-1}}{\langle\sigma v\rangle}$$ Gondolo & Gelmini'91

- A particle having mass and interactions around the electroweak scale, can satisfy the correct relic criteria: WIMP Miracle!



Assumptions:

1. DM follows Maxwell-Boltzmann statistics, decouples at $T \ll m_{\rm DM}$, well before kinetic decoupling of DM. Chemical decoupling precedes kinetic decoupling.

2. Annihilation products are part of the standard model (SM) heat bath.

Deviations from these assumptions can change the parameter space!

$$\Omega_{\rm DM}h^2 = \frac{\rho_{\rm DM}}{\rho_{\rm c}}h^2 = 0.1186 \pm 0.0020$$

Planck 2015, Astron. Astrophys. 2016

WIMP: Summary

- WIMP abundance $\rho_{\rm DM} = m_{\rm DM} n_{\rm DM} \propto m_{\rm DM} \frac{1}{\langle \sigma v \rangle}$
- For $m_{\rm DM} \lesssim \mathcal{O}(1\,{\rm GeV})$, it is difficult to get sufficient annihilation cross-section to get the correct abundance (Lee & Weinberg'77; Kolb & Olive'86).
- For $m_{\rm DM} \gtrsim \mathcal{O}(100\,{\rm TeV})$, the required annihilation cross-section exceeds unitarity limit (Griest & Kamionkowski'90).

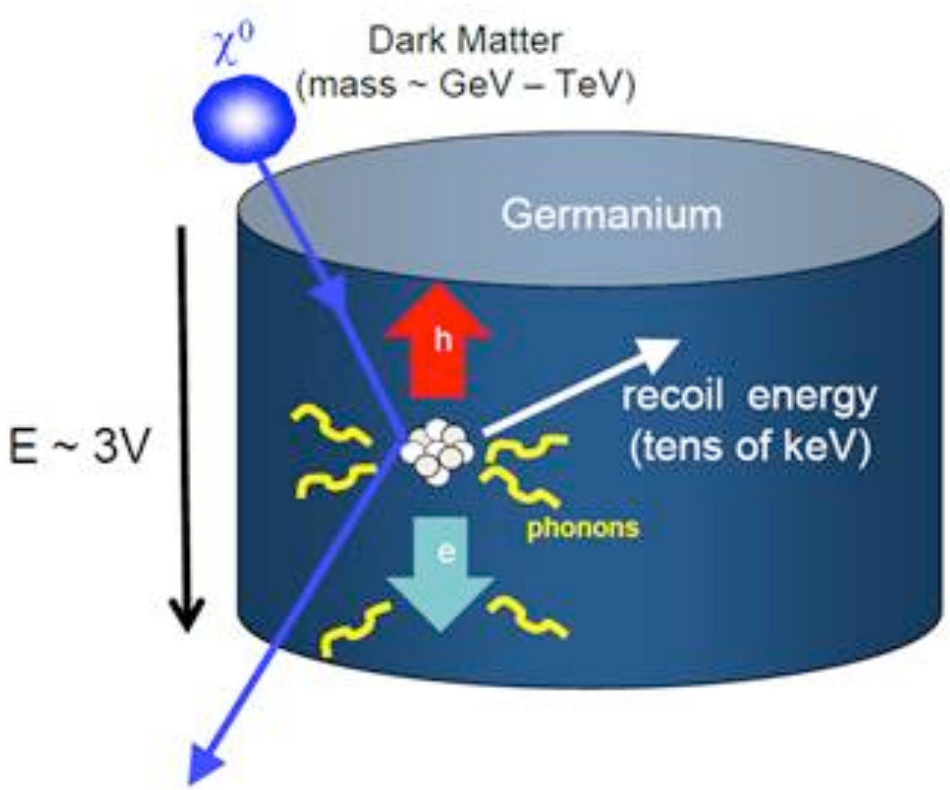
WIMPs can be detected!

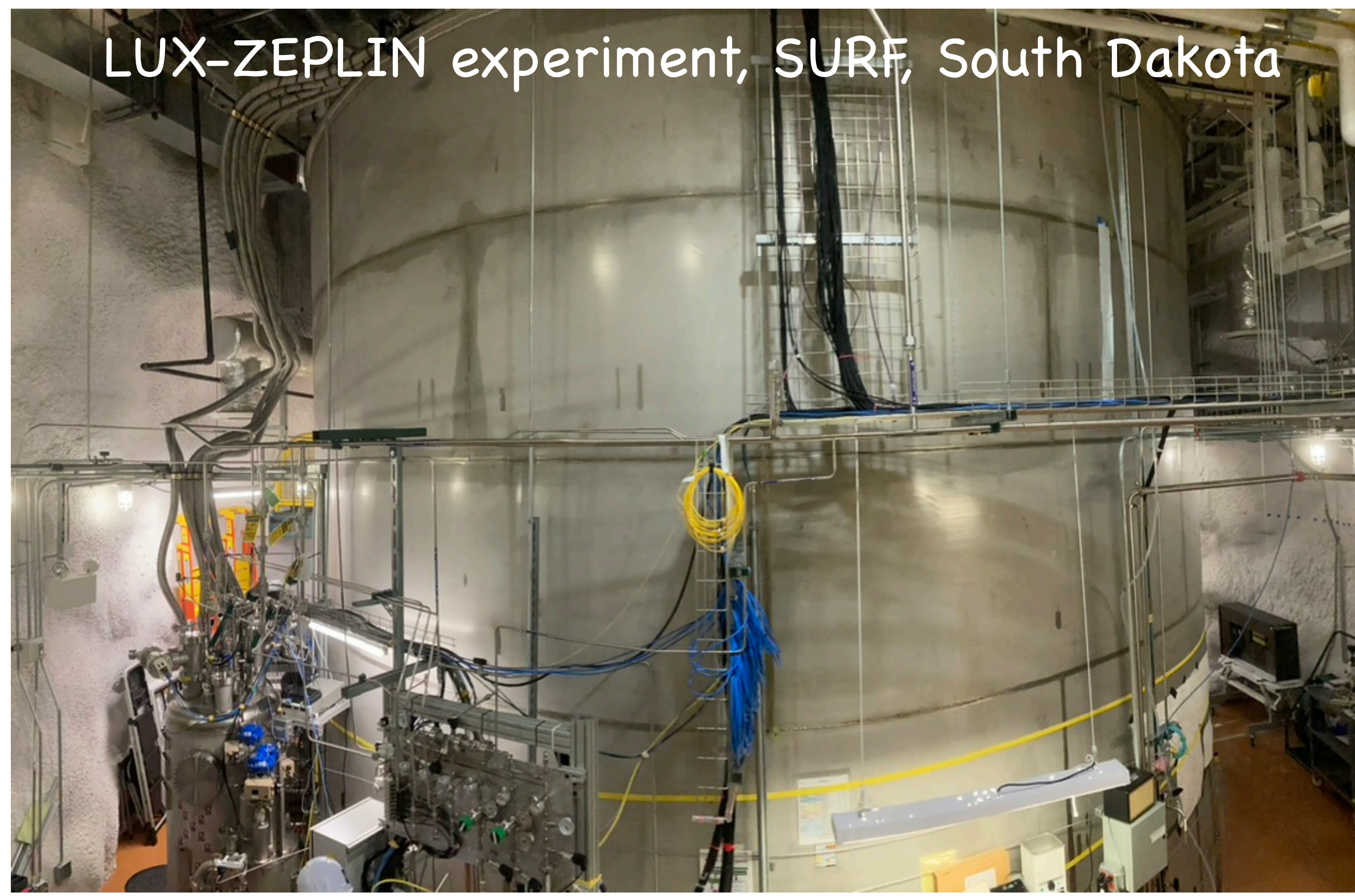
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

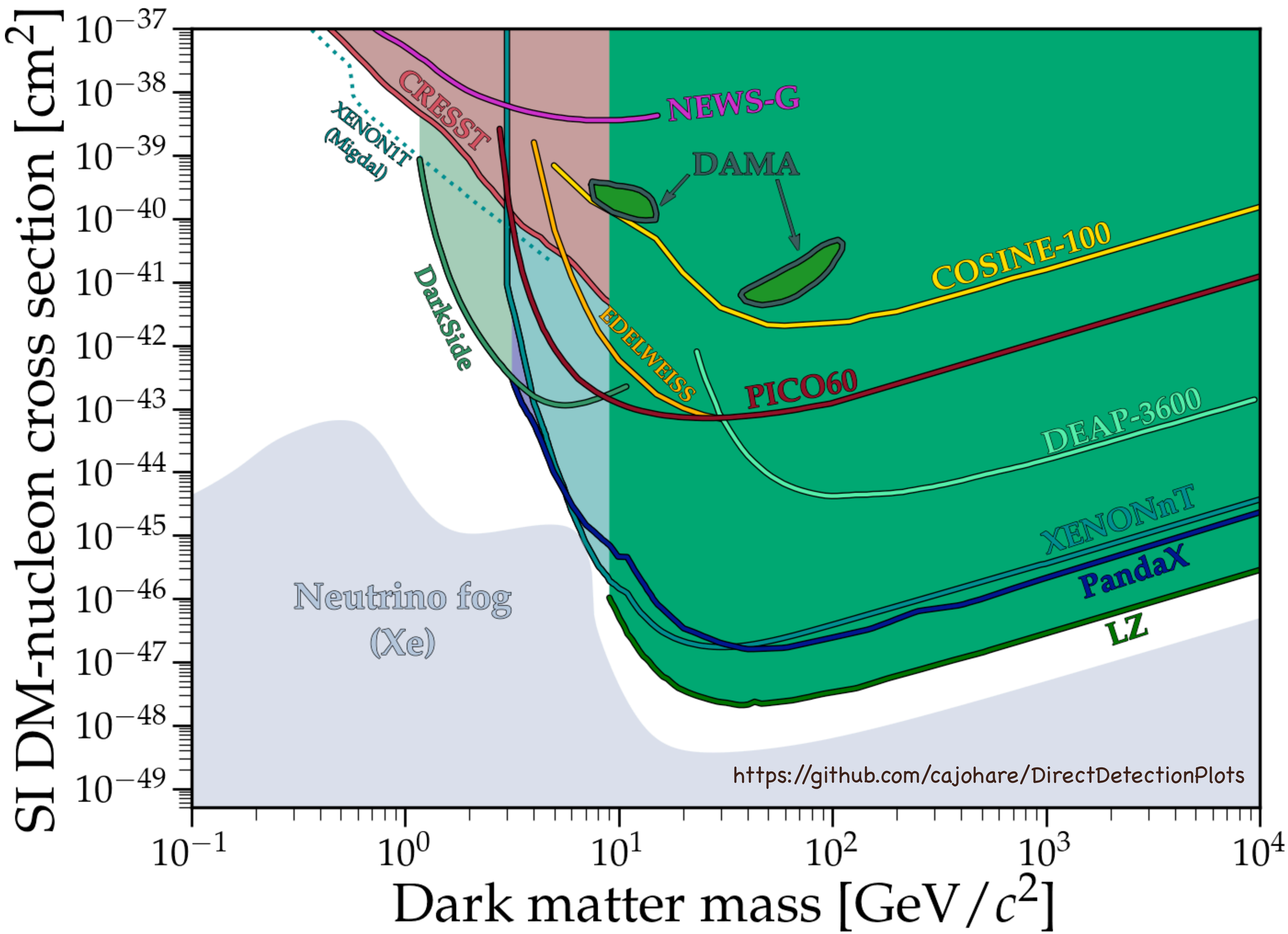
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.



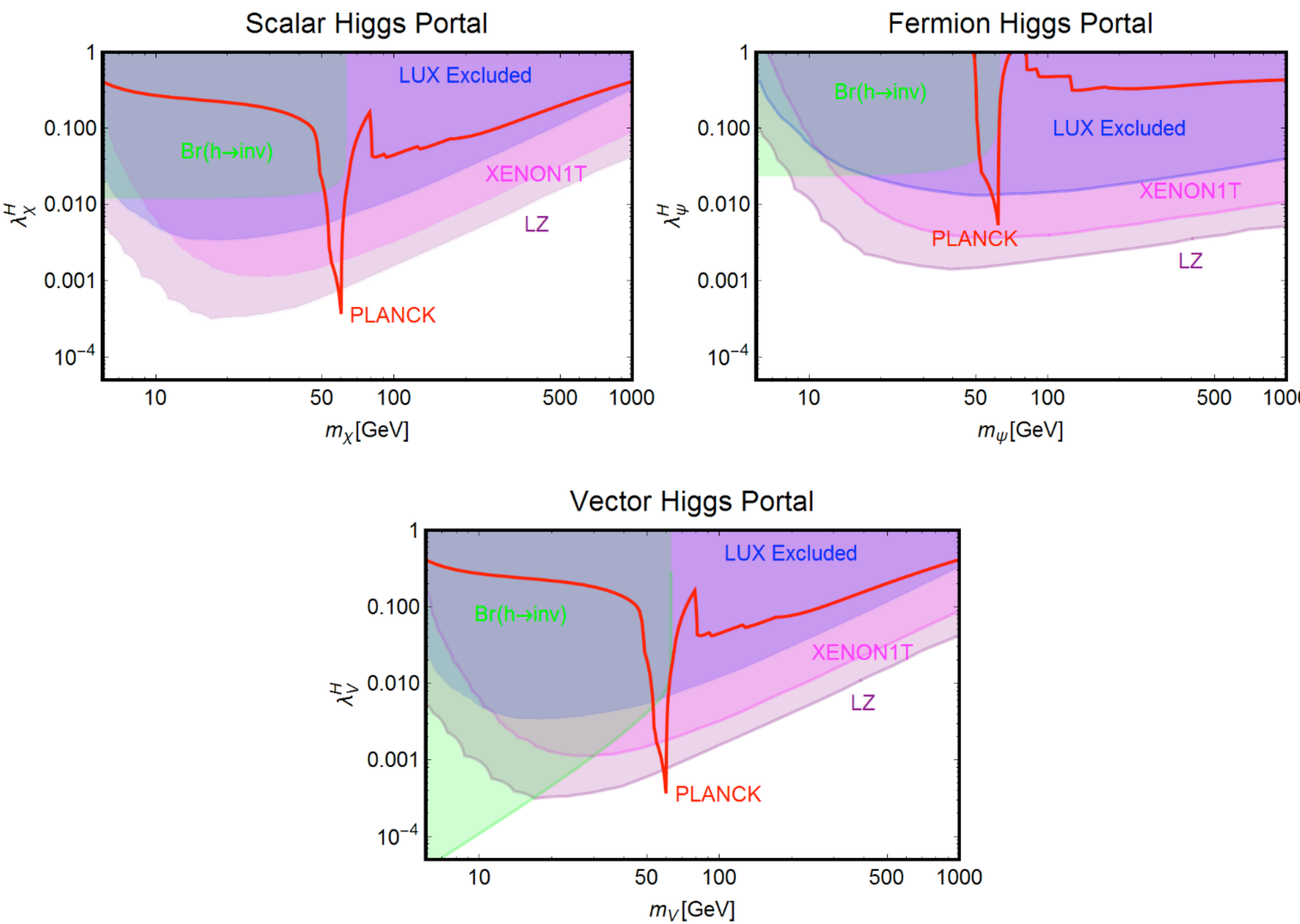


Credit: SLAC

But WIMPs are being pushed to the edge!



Implications for the simplest WIMPs



arxiv:1703.07364

The way forward

- Study the low mass window carefully where current bounds are weaker. Several new detection avenues are in the proposal for such DM below GeV scale.
- Go beyond the minimal WIMP scenario: a richer dark sector.
- Abandon the WIMP paradigm altogether and pursue other alternatives like Freeze-in DM, axions, Primordial black holes etc.

Non-minimal WIMPs

- New mediators of DM-SM interactions or DM annihilation into dark/secluded sectors (see arxiv:1703.07364, 2403.15860 for reviews).
- DM freeze-out is assisted by another particle with which DM coannihilates (Griest & Seckel'91).
- Multi-component DM (Zurek'08+).
- And so on..

WIMPs with temperature-dependent couplings

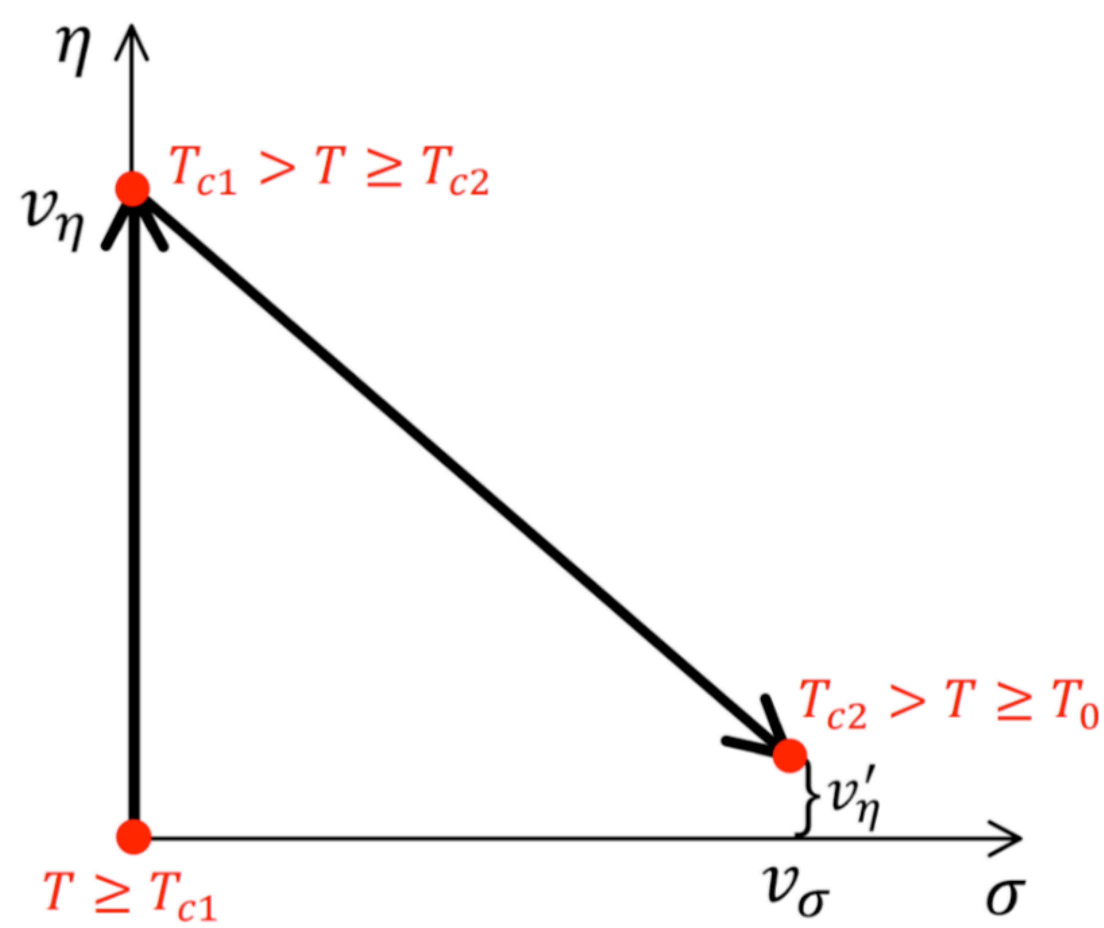
- WIMPs have strong interaction rate with the SM particles in the early Universe when their annihilations were dominant.
- WIMPs have weak interaction rate with the SM particles in the present Universe such that their scattering off nucleons have not been observed yet.
- Possible to have other observable signatures while implementing this in a realistic model.

arxiv:2509.07070 DB, Dasgupta, Wu

WIMP with T-dependent couplings

$$-\mathcal{L}_{\rm DM-SM} = \begin{cases} \frac{1}{\Lambda^2}\eta\bar{\chi}\chi H^\dagger H, & \text{fermion DM} \\ \frac{1}{\Lambda^3}\eta\phi\phi H\bar{f}f, & \text{scalar DM} \end{cases}$$

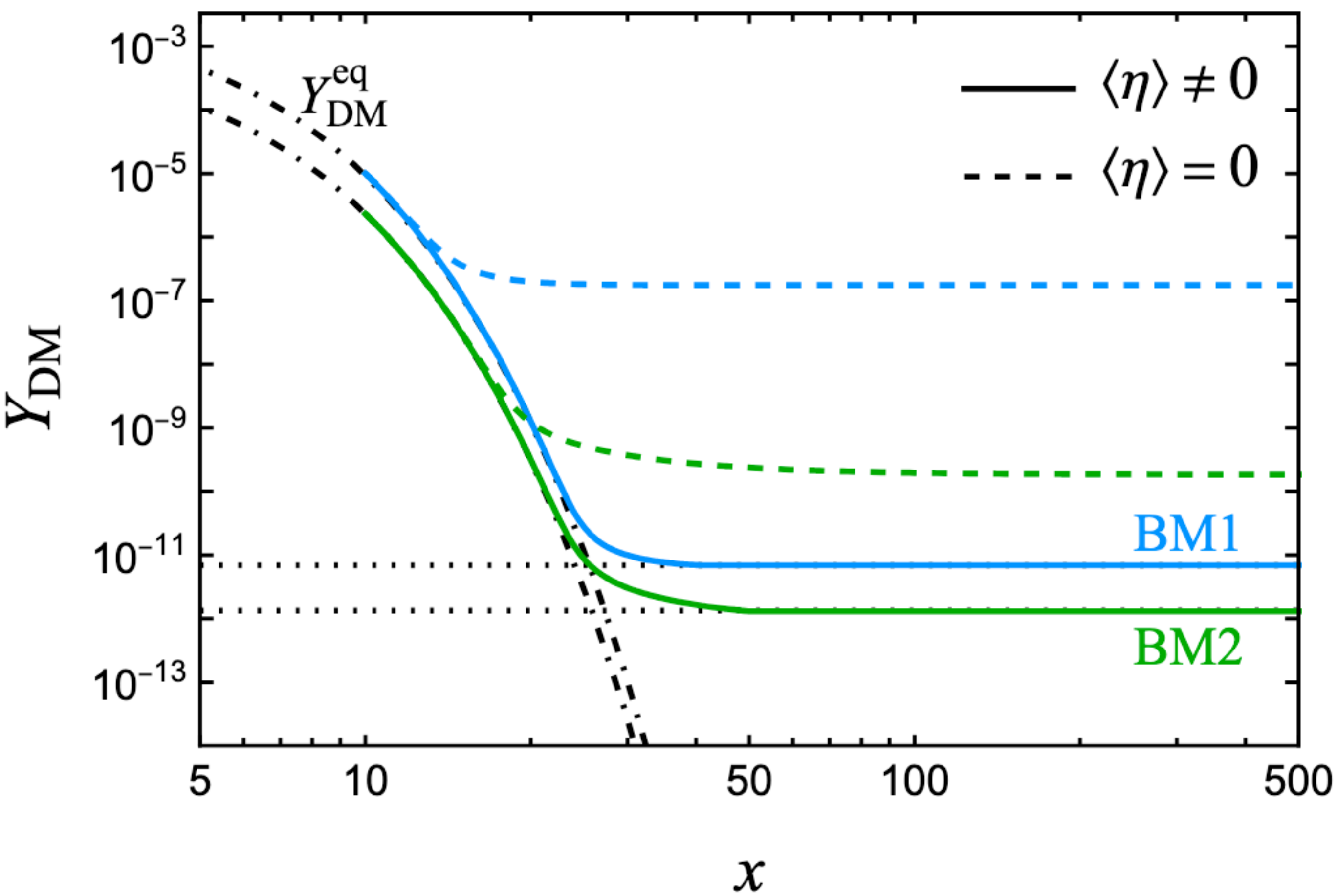
- The auxiliary field η sits at non-zero minima $\langle\eta\rangle = v_\eta$ at high temperatures $T_f \sim m_{\rm DM}/30$ when DM χ/ϕ freezes-out with sizeable effective coupling v_η/Λ^2.
- At lower temperatures $T < T_f$, a new minima appears to which η makes a transition resulting in suppressed effective coupling v'_η/Λ^2 with the SM.
- This late transition can naturally be of first-order, resulting in stochastic gravitational waves (GW).



arxiv:2509.07070 DB, Dasgupta, Wu

DM relic with T-dependent couplings

	$m_{\rm DM}/\text{GeV}$	Λ/GeV	$\frac{\langle\eta\rangle}{\Lambda}(T_f)$	$\frac{\langle\eta\rangle}{\Lambda}(T_0)$
BM1	58	2045	0.063	1.1×10^{-4}
BM2	300	1620	0.41	1.4×10^{-4}



- For fermion DM (BM1), the relevant v_η-independent channels for DM annihilation are $\chi\bar{\chi}\to f\bar{f}, VV, hh$. The v_η-independent channels like $\chi\bar{\chi}\to\eta h$ remains sub-leading.
- For scalar DM (BM2), the leading channel remains $\phi\phi\to f\bar{f}$ while $\phi\phi\to f\bar{f}\eta$ remains suppressed.

arxiv:2509.07070 DB, Dasgupta, Wu

Direct and Indirect DM Detection with T-dependent couplings

	$m_{\rm DM}/{\rm GeV}$	$\Lambda/{\rm GeV}$	$\frac{\langle\eta\rangle}{\Lambda}(T_f)$	$\frac{\langle\eta\rangle}{\Lambda}(T_0)$
BM1	58	2045	0.063	1.1×10^{-4}
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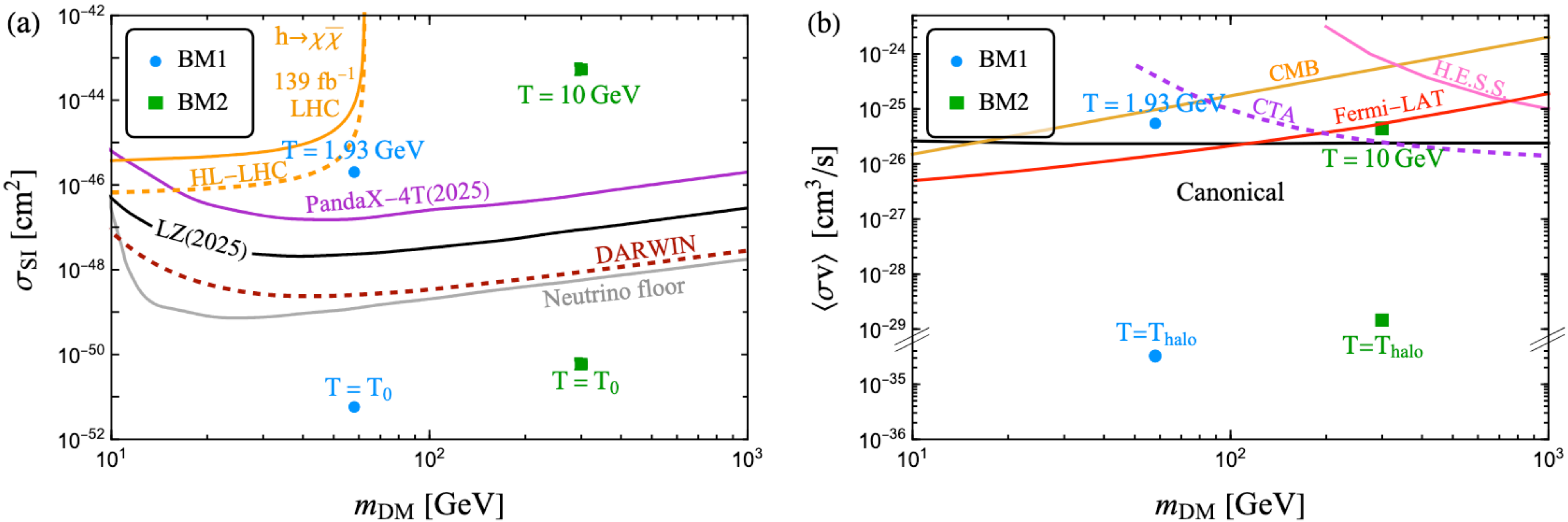
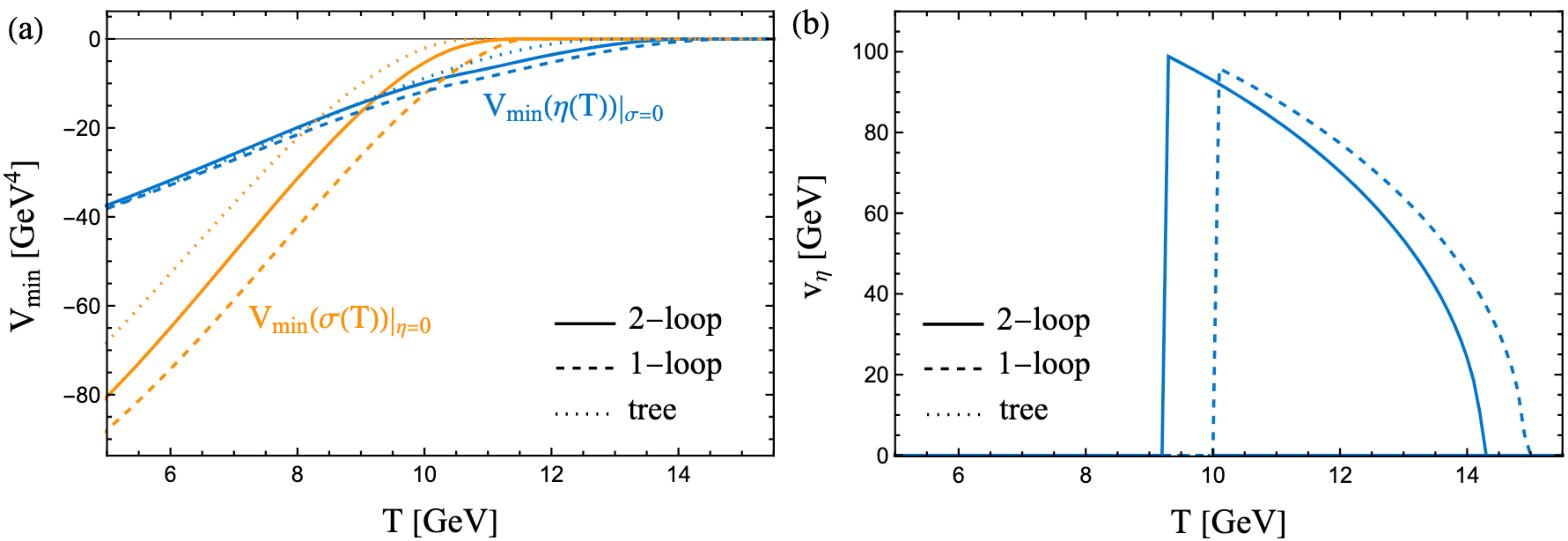


arxiv:2509.07070 DB, Dasgupta, Wu

The phase transition

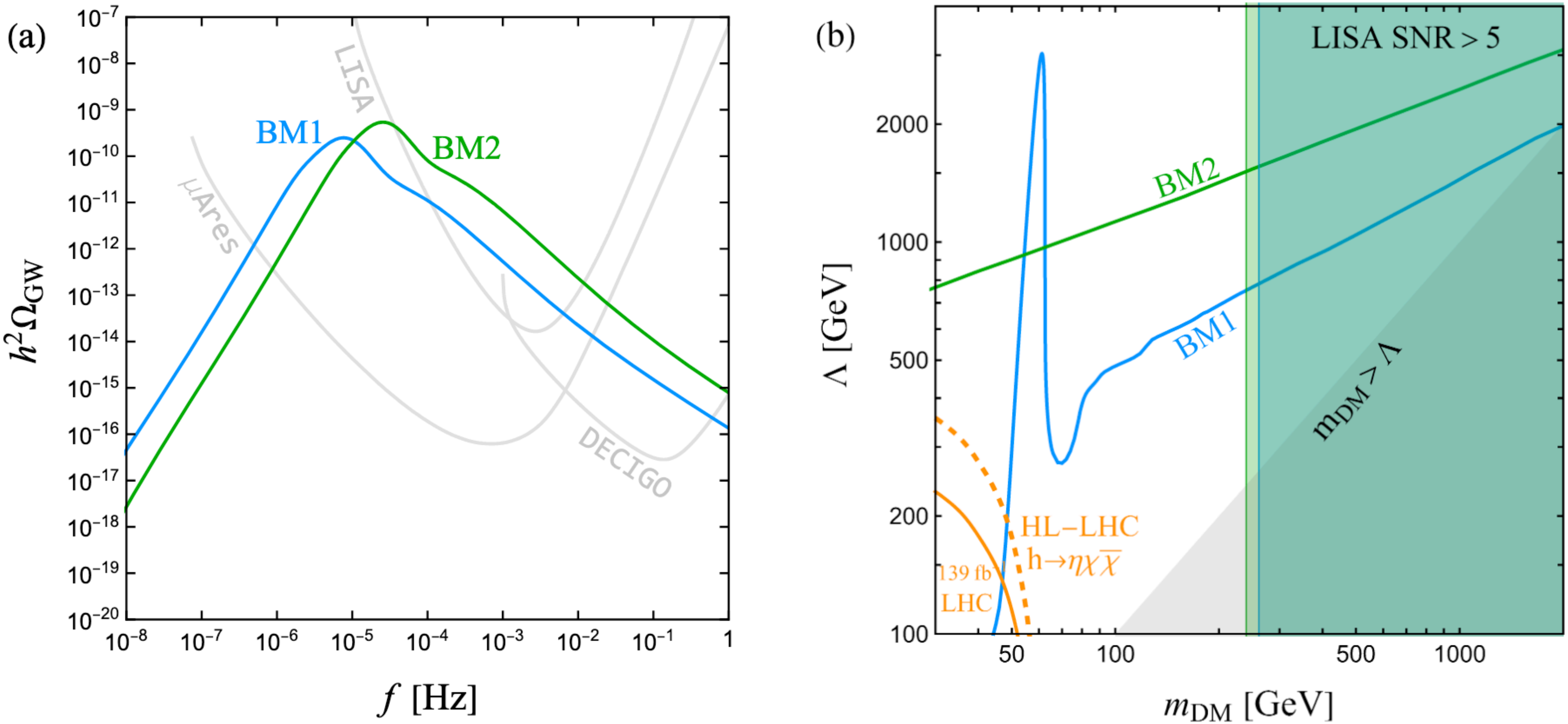
$$V(\sigma,\eta) = \frac{\mu_\sigma^2}{2}\sigma^2 + \frac{\lambda_\sigma}{4}\sigma^4 - \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_\eta}{4}\eta^4 + \frac{\lambda_{\sigma\eta}}{4}\sigma^2\eta^2 - \tilde{\mu}\sigma^2\eta$$

	μ_σ/GeV	μ_η/GeV	λ_σ	λ_η	$\lambda_{\sigma\eta}$	$\tilde{\mu}$/GeV
BM1	3.8	0.11	0.47	7.1×10^{-7}	0.001697	1×10^{-4}
BM2	18	0.6	0.27	8.1×10^{-7}	0.001461	1×10^{-4}



arxiv:2509.07070 DB, Dasgupta, Wu

	α_*	$\beta/\mathcal{H}$	T_n/GeV	v_w
BM1	3.8	97	0.9	1
BM2	1.8	50	6	1



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Conclusion

- Minimal WIMP scenarios are tightly constrained by direct-detection data with some Higgs/Z portal models being already ruled out.
- Light WIMP has become a popular arena for both theoretical (to get correct thermal relic below GeV scale) and experimental (DM-electron recoil, new detection techniques e.g., arxiv:2203.08084) studies.
- Richer WIMP models help in reconciling relic with direct-detection constraints.
- Temperature dependent WIMP coupling is one such scenario with a rich dark sector which relies on a generic a first-order VEV restoring phase transition with observable consequences like gravitational waves with peak frequencies in $\lesssim 0.1$ Hz ballpark.
- Such models also come with additional light degrees of freedom which can be have complementary detection prospects at terrestrial experiments.

Thank You