Defect-Mediated Conversion: Dark Matter from Cosmological Domain-Wall Scattering

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Work in collaboration with **Joao Paulo Pinheiro**.

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Motivation and main idea

Typical mechanisms for Dark Matter production

Freeze-out mechanism:

DM was in thermal eq. with the thermal plasma. The density of DM is fixed when the expansion rate of universe is higher than the annihilation rate of DM.

Freeze-in mechanism:

DM is never in thermal eq. With plasma, but is produced via a mediator between the DM and the thermal plasma.
This requires small couplings between SM and DM.

Misalignment mechanism:

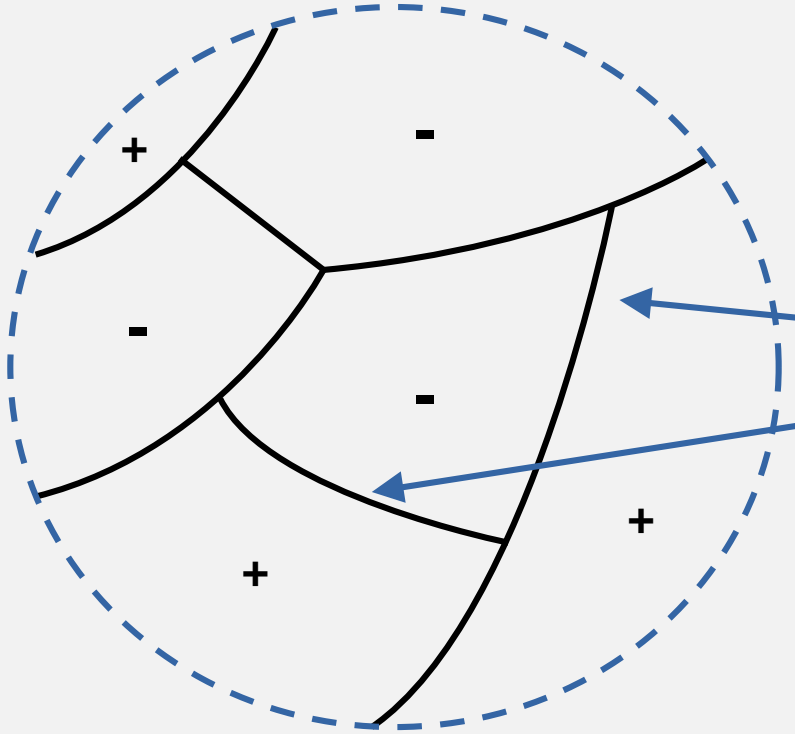
Creates DM via the oscillations of a scalar field (e.g. Axion), which starts at an initial value away from the minimum of the potential

All these mechanisms are caused by particle interactions with the thermal plasma in a homogeneous background.

Motivation and main idea

But, what if the scalar field background is not homogeneous?

In several scalar BSM models, the breaking of a Z_2 symmetry leads to the formation of domain walls.



Domain walls separating two domains with different sign of the VEV.

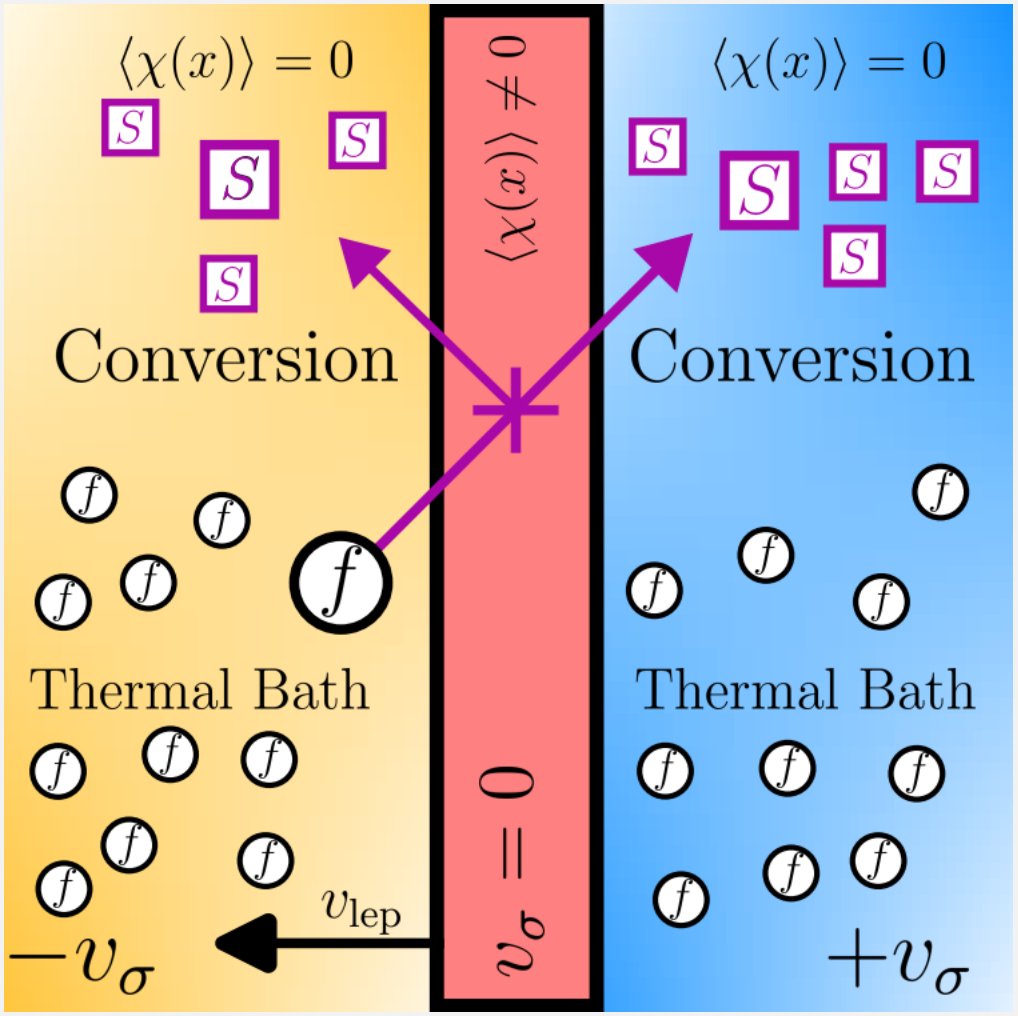
I will show in this talk that domain walls can open a portal (localized only inside the wall) that converts SM particles into dark sector particles! Such conversion is forbidden outside the wall.

Key idea of this talk

- In the early universe a **scalar field σ** is spontaneously broken and a **domain wall network is produced**.
- **The scalar field mediator χ** between the SM and the dark sector obtains a localized non-zero condensate inside the domain wall.
- This condensate induces a **mass mixing** between the SM and the dark sector.

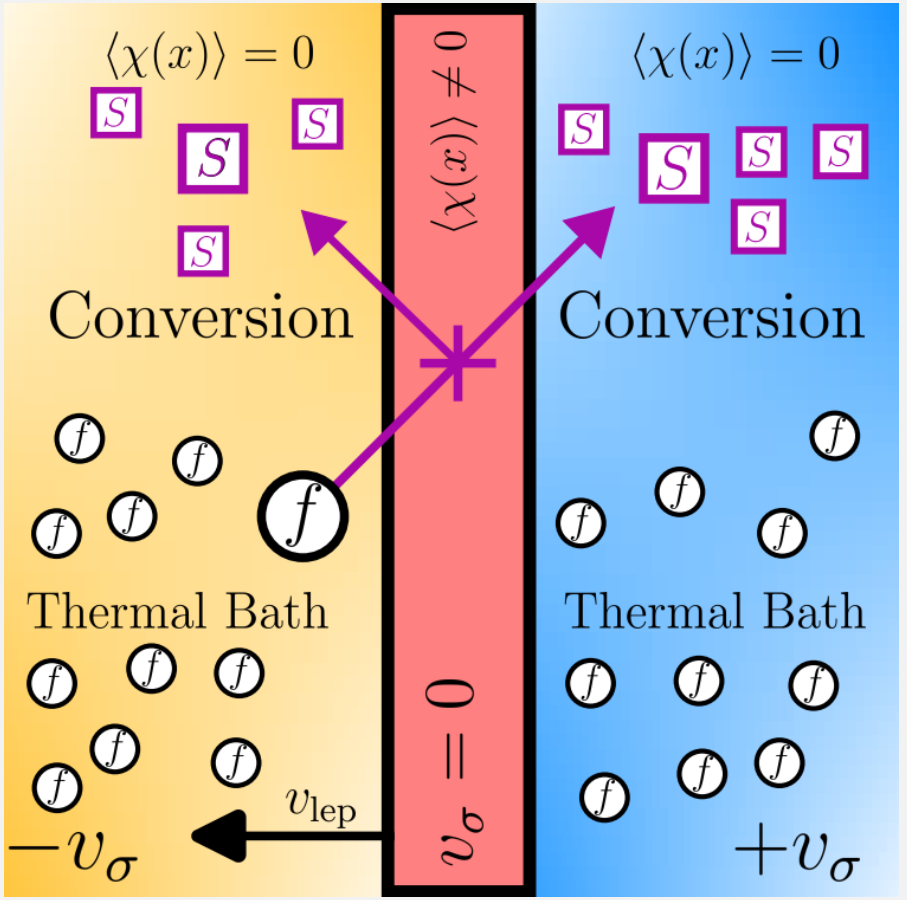
$$y\chi(x)\bar{f}S$$

- **SM particles scattering off this condensate on the wall have a non-zero probability of being converted into a dark sector particle. This conversion is prohibited outside the wall!**



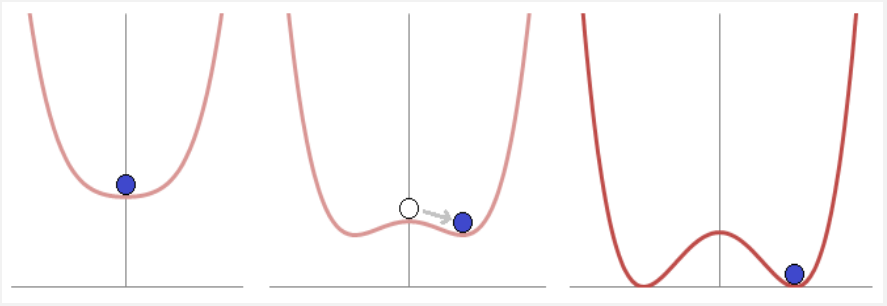
Outline of the talk

- What are domain walls and how do they form?
- How does the condensate form inside the wall?
- How does this condensate mix the SM and dark sector particles, leading to the conversion of SM fermions into dark sector fermions?
- How large is the dark matter abundance induced by this mechanism and how does it compare to standard Freeze-in mechanism?



Introduction to domain walls

Domain walls are a type of **topological defects** that arise after **spontaneous symmetry breaking** (SSB) of a **discrete symmetry** in the early universe.



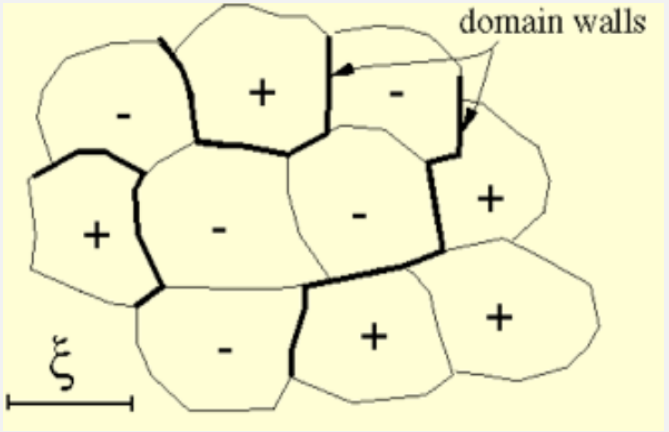
[Credit:Wikipedia]

Simplest example (real singlet scalar)

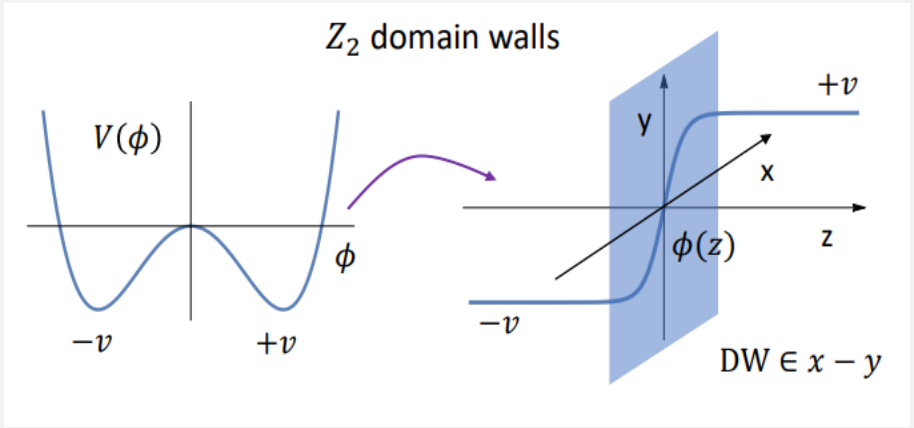
$V(\phi) = \mu\phi^2 + \lambda\phi^4$ is **invariant** under **Z_2 :** $\phi \to -\phi$

Vacuum manifold: two points v and -v.

Universe is divided into different cells with different signs for v.



[Credit: CTC Outreach]



[Credit: Simone Blasi]

How does the condensate form?

Take the example of the toy model:

Real scalar singlet σ charged under a Z_2 symmetry + Complex scalar h^+ with hypercharge 1 + Dark sector particle S.

$$V(\Phi,\sigma,h^+) = V_{\rm SM}(\Phi) + \tfrac{1}{2}\mu_+^2|h^+|^2 + \tfrac{1}{2}\mu_\sigma^2\sigma^2 + \tfrac{1}{4}\lambda_\sigma\sigma^4 + \tfrac{1}{4}\lambda_+|h^+|^4 + \lambda_{\Phi+}|h^+|^2|\Phi|^2$$
$$+ \lambda_{\sigma+}\sigma^2|h^+|^2 + \lambda_{\Phi\sigma}\sigma^2|\Phi|^2 + \boxed{\epsilon\,\sigma^3}.$$

Breaks Z_2 in order to avoid the domain wall domination problem

After σ is spontaneously broken, a domain wall network forms. **This has consequences on the effective mass term of h^+:**

$$M_+(x) = \mu_+^2 + \lambda_{\sigma+}\sigma^2(x)$$

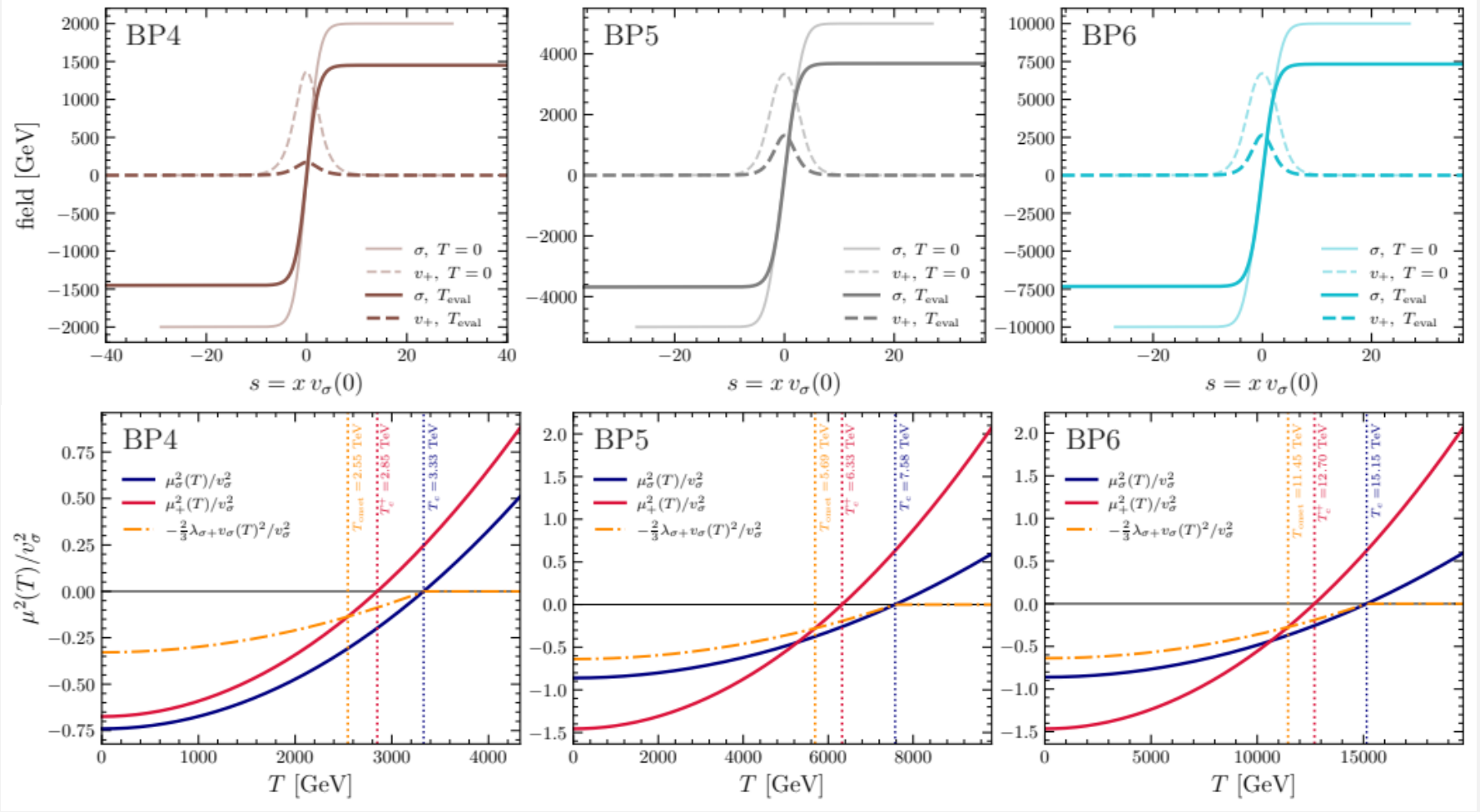
Outside the wall:

$$M_+(\pm\infty) = \mu_+^2 + \lambda_{\sigma+}v_\sigma^2 > 0$$

Inside the wall, x=0 :

$$M_+(0) = \mu_+^2 < 0$$

→ **Possible that h^+ acquires a non-zero condensate inside the core of the wall**



$$\mathcal{E} = \int_{-\infty}^{+\infty} dx \left[\left(\frac{d\sigma}{dx}\right)^2 + \left(\frac{dh^+}{dx}\right)^\dagger \left(\frac{dh^+}{dx}\right) \right] + V_{pot}(\sigma, h^+)$$

Kinetic energy of the scalar field configuration

Domain Wall formation at T_f

↓

$\mu_+(T)$ turns negative at T^+_c

↓

H^+ aqcuires a non-zero condensate inside the wall at T_{onset}

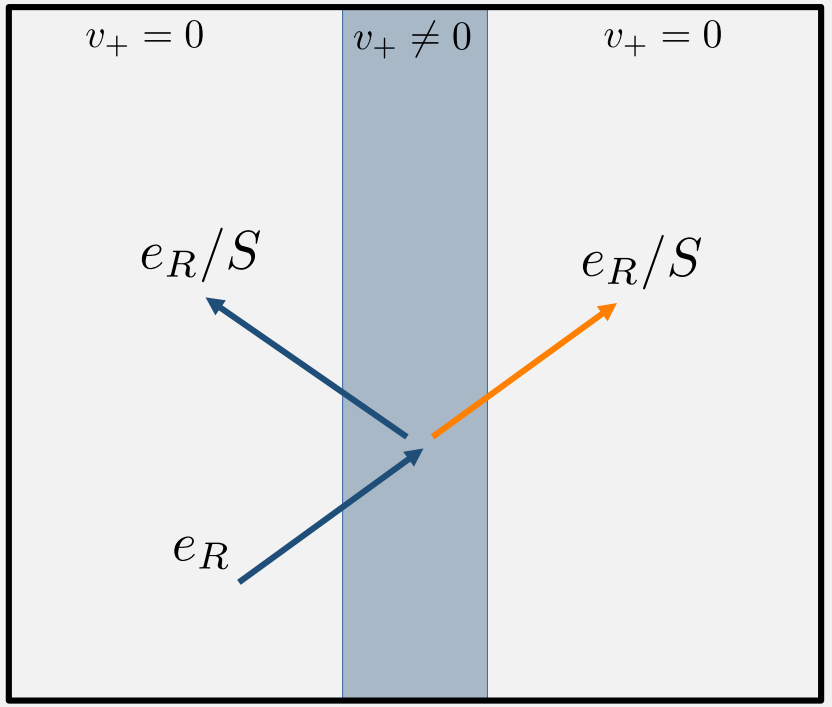
Values for the benchmark points in backup slides

How are SM particles converted into dark particles

Yukawa sector: $y\langle h^+(x)\rangle \bar{e}_R S$

→ **The thin condensate on the wall leads to a localized mixing between the SM leptons and the dark sector.**

We calculate the conversion rate of SM leptons into dark particles by solving the Dirac equation of incoming SM-leptons in the background of the condensate, taking a thin wall limit.



$$P_{l_\alpha \to S} = R_{l_\alpha \to S} + T_{l_\alpha \to S}$$

$$P_{\ell_\alpha \to S}(E_\ell, k_\alpha, M_S) = \frac{8\, g_d\, (g_d^2+1) \sinh^2 k_\alpha}{\left[(g_d-1)^2 - (g_d+1)^2 \cosh k_\alpha\right]^2}$$

$$k_\alpha = y_\alpha v_+(0)\delta_{dw}$$

$$g_d = \sqrt{E_\ell^2 - M_S^2}/(E_\ell + M_S)$$

Boltzmann equation and relic abundance

$$\dot{n}_S + 3Hn_S = \mathcal{A}(T)\, v_{\rm lep} \sum_\alpha \frac{g_{\rm dof}}{2\pi^2} \int_{M_S}^{\infty} dp\, \frac{p^2}{e^{p/T}+1}\, P_{\ell_\alpha \to S}(p)$$

Area density of the DW network

SM plasma velocity

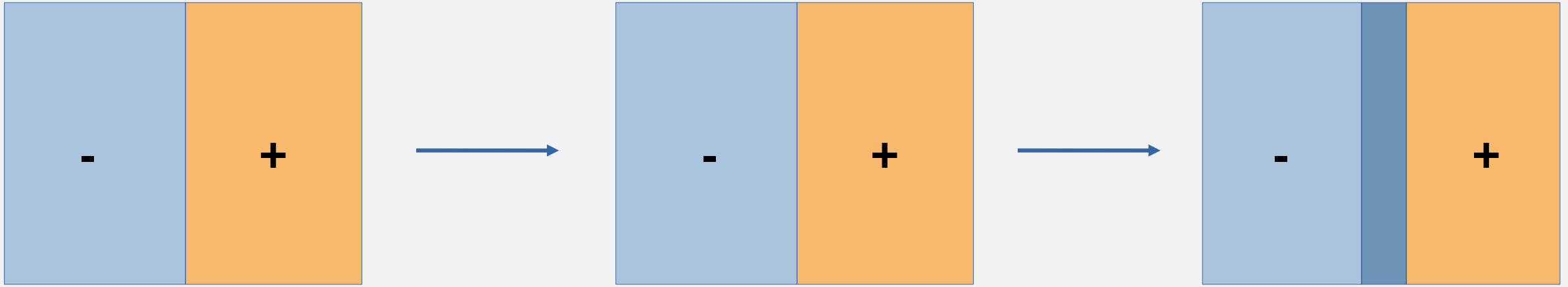
Flux of SM particles

Conversion probability

- **The energy of the SM particle is converted into dark sector mass**. Therefore, SM plasma particles with energies higher than the temperature or the mediator mass can still produce dark sector particles M_S. **Important advantage compared to standard Freeze-in where the mediator mass is converted into dark sector energy.**

- **For very high masses $M_S >> T$**, the flux of SM particles with energy $E > M_S$ is exponentially suppressed and the mechanism is turned-off.

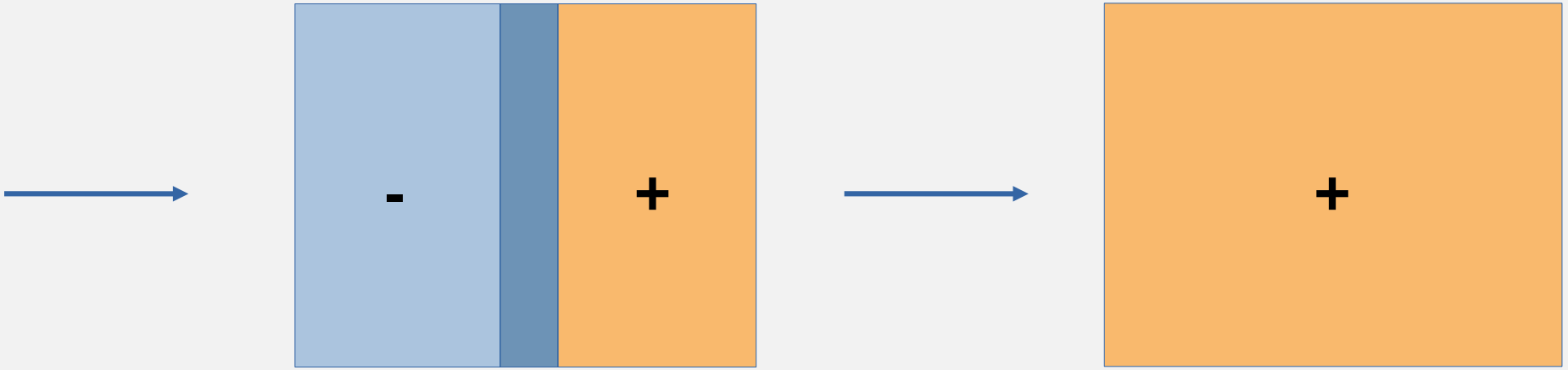
Key timelines for the mechanism



Domain walls form at T_f

Effective mass $M_+(0)<0$ at T^+_c

The condensate forms inside the wall at T_{onset}



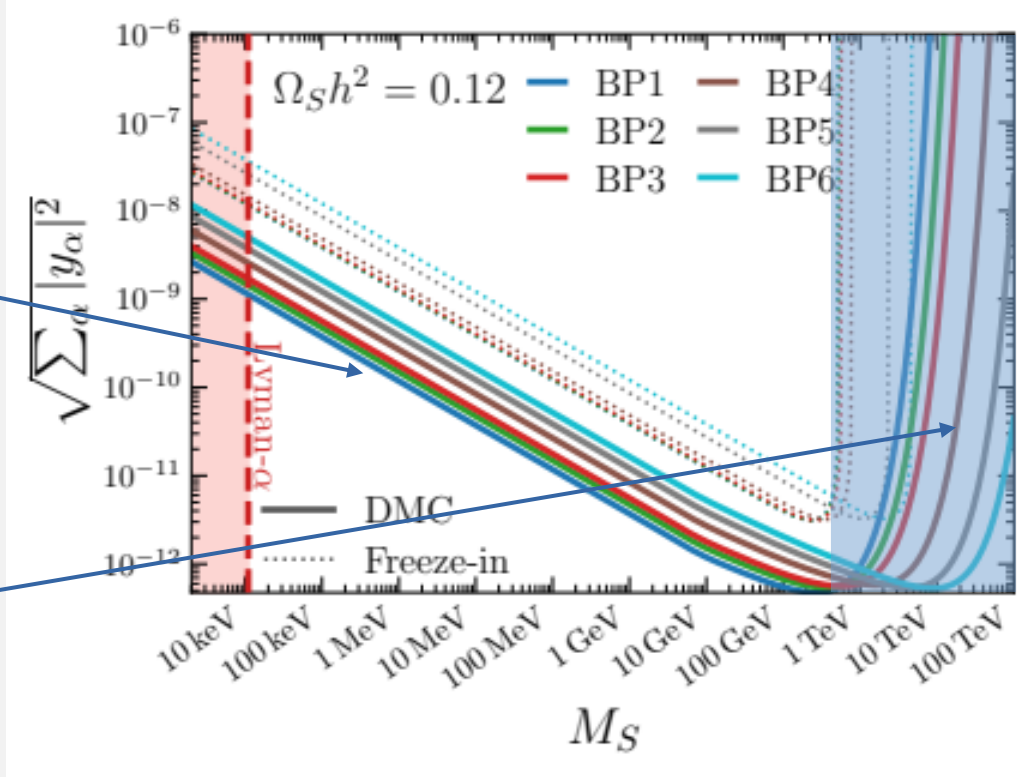
Mechanism active for $T < T_{onset}$

Domain walls annihilate and the mechanism shuts-off

Results and advantages vs. Standard Freeze-In

- For relativistic SM-leptons and dark sector, the relic abundance follows a $(1/y_\alpha)^4$ curve

For dark particles heavier than the temperature/mediator mass, the yield drops since the flux of SM-leptons with $E_\alpha > M_S$ is small (but non-zero).
The correct abundance is obtained at the expense of larger Yukawa couplings.

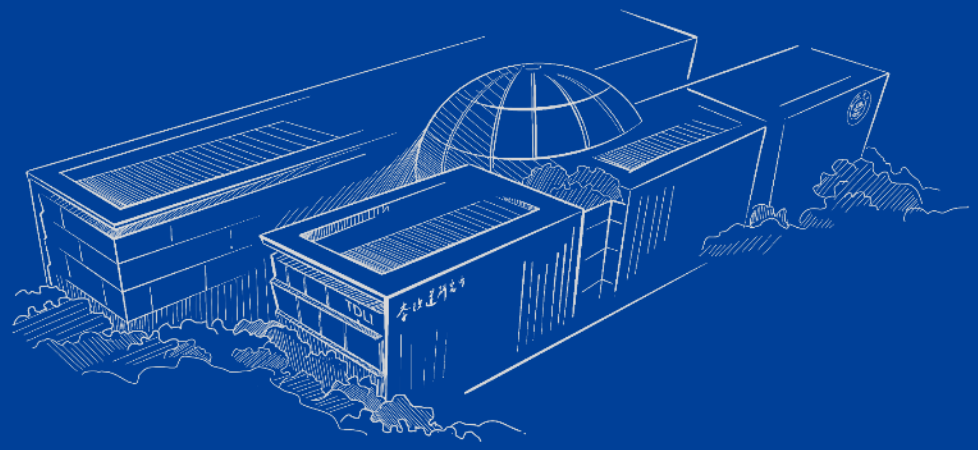


For all dark sector masses, this mechanism yields a larger abundance of dark sector. However, the advantage of the mechanism is in producing a much larger yield of heavy dark sector particles heavier than the mediator mass, a regime where Freeze-in cannot compete!

Take away message

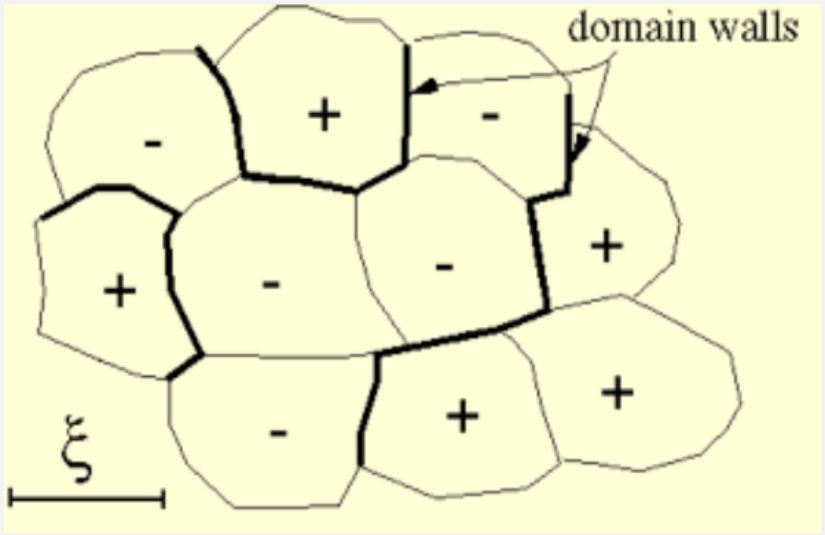
- Domain walls can induce a localized condensate for the scalar mediator between the SM and the dark sector.
- This localized condensate leads to a mixing portal between the SM and the dark sector. SM particles hitting the wall can be converted into the dark sector.
- The mechanism can be more competitive than Freeze-In for the same parameter points. With the clear advantage for producing dark sector particles which are much heavier than the mediator mass.

谢谢！



Backup

Area density of the domain walls



$$\mathcal{A}(T) = \mathcal{A}_0 \; T^2/T_f^2$$

Initial area density at formation time

Evolution due to scaling

- We use the maximum possible value for $A_0 = 1/\xi_0 \approx 1/m_\sigma$
- Friction and effects of the bias term need to be taken into account for a precise calculation of the area density evolution.
- **Requires numerical simulations.**

Benchmark points

TABLE II. Full parameter set for benchmarks BP1–BP6, all satisfying the thin-wall requirement (wall width $< 5/v_\sigma$) both at $T = 0$ and at $T_{\rm eval} = 0.9\,T_{\rm onset}$. The in-core condensate v_+ is obtained by solving the coupled scalar equations of motion at each temperature. Note that BP5 and BP6 share the same quartics and differ only in v_σ, yielding the same $\mathcal{S}$ to better than 1%. Masses in GeV.

	v_σ	m_{h+}	λ_σ	$\lambda_{\sigma+}$	λ_+	$v_+(0)$	$v_+(T_{\rm eval})$	T_c	$T_{\rm onset}$	$T_{\rm eval}$	$\mathcal{S}(0)$
BP1	300	523	1.82	5.31	12.0	172	104	350	263	237	0.62
BP2	500	542	1.16	2.26	5.0	276	152	660	463	417	0.78
BP3	800	579	0.74	1.16	3.0	388	208	1119	762	685	0.90
BP4	2000	789	0.74	0.49	1.0	638	167	3329	2545	2291	1.12
BP5	5000	2399	0.86	0.96	3.0	3021	1308	7575	5691	5122	1.018
BP6	10000	4747	0.86	0.96	3.0	6086	2643	15150	11449	10304	1.025

$$\mathcal{S}(0) = \int dx\, v_+(x) \approx v_+(0)\delta_{dw}$$

Relativistic limit

$$\dot{n}_S + 3Hn_S = \mathcal{A}(T)\, v_{\rm lep} \sum_\alpha \frac{g_{\rm dof}}{2\pi^2} \int_{M_S}^{\infty} dp\, \frac{p^2}{e^{p/T}+1}\, P_{\ell_\alpha \to S}(p)$$

For relativistic SM thermal bath particles and of relativistic dark matter $E_S >> M_S$

$$P_{l_\alpha \to S} \approx \tanh^2(\underbrace{y_\alpha v_+(0)\delta_{dw}}_{\mathbf{k_\alpha}})$$

In this case, the Boltzmann equation simplifies to:

$$\dot{n}_S + 3Hn_S = \mathcal{A}(T)\, v_{\rm lep}\, n_\ell(T) \sum_\alpha \tanh^2\big(k_\alpha(T)\big)$$

Relativistic limit

Formation temperature of the DW

$$M_S \simeq 10\ \mathrm{keV} \left(\frac{1}{\gamma_w}\right) \left(\frac{T_c}{400\ \mathrm{GeV}}\right)^2 \left(\frac{1\ \mathrm{TeV}}{m_\sigma^0}\right)$$

$$\times \left(\frac{0.10}{\mathcal{S}^2}\right) \frac{\ln 172}{\ln(T_{\mathrm{onset}}/T_{\mathrm{ann}})} \left(\frac{1.25 \times 10^{-9}}{\sqrt{\sum_\alpha |y_\alpha|^2}}\right)^2$$

$$\times \frac{g_{*s}\sqrt{g_*}}{(106.75)^{3/2}}.$$

Factor used to account for deviations from the maximum initial area density.

Constraints on the mass of h^+

In order for the condensate to form, the mass of h^+ has to fall between:

$$\frac{1}{2}\left(2\lambda_{\sigma+}v_\sigma^2 - \sqrt{\lambda_+}v_\sigma m_\sigma\right) < m_{h^+}^2 < \frac{2}{3}\lambda_{\sigma+}v_\sigma^2$$

Limit to ensure the stability of the neutral vacuum, otherwise a minimum with $v_+ \neq 0$ exists and is lower than the minimum where $v_+ = 0$

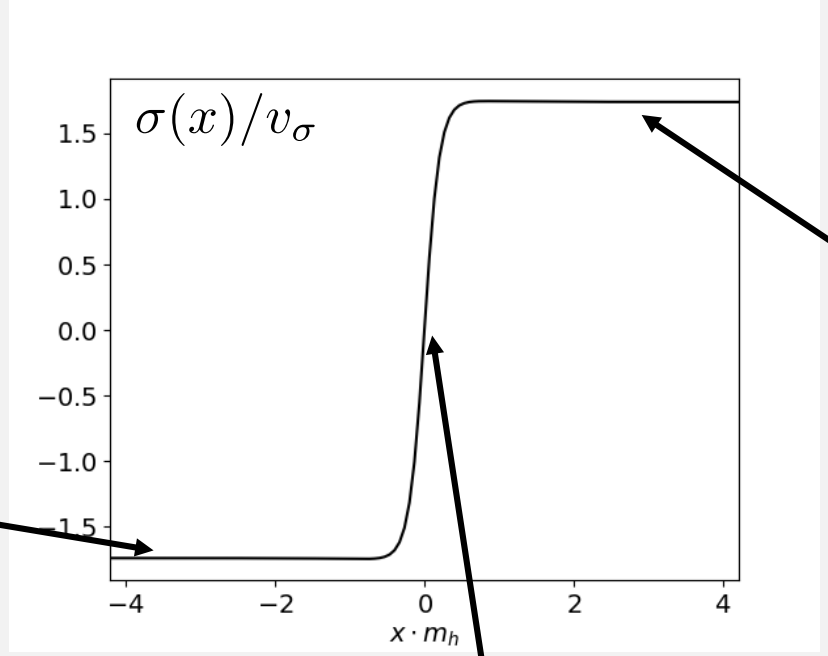
Limit needed to make sure the kinetic energy of the condensate does not cause the instability of the solution.

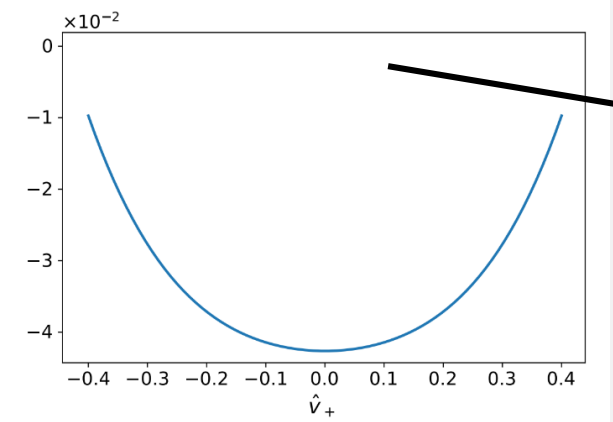
Further experimental constraints on the mass of h^+ due to long-lived charged particles at colliders:

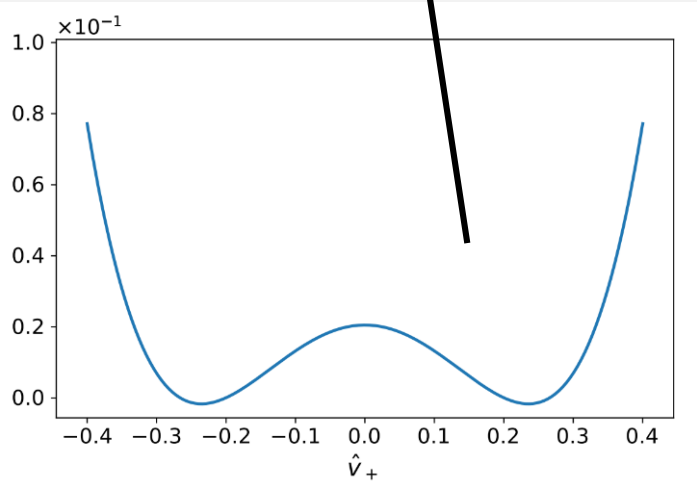
$$m_{h^+} > 500 \text{ GeV}$$

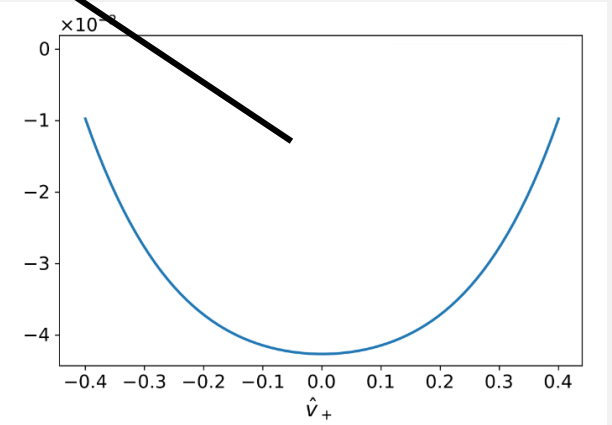
See Appendix 2608.12468

Inside the wall, the scalar potential in the v_+ direction has a non zero minimum.

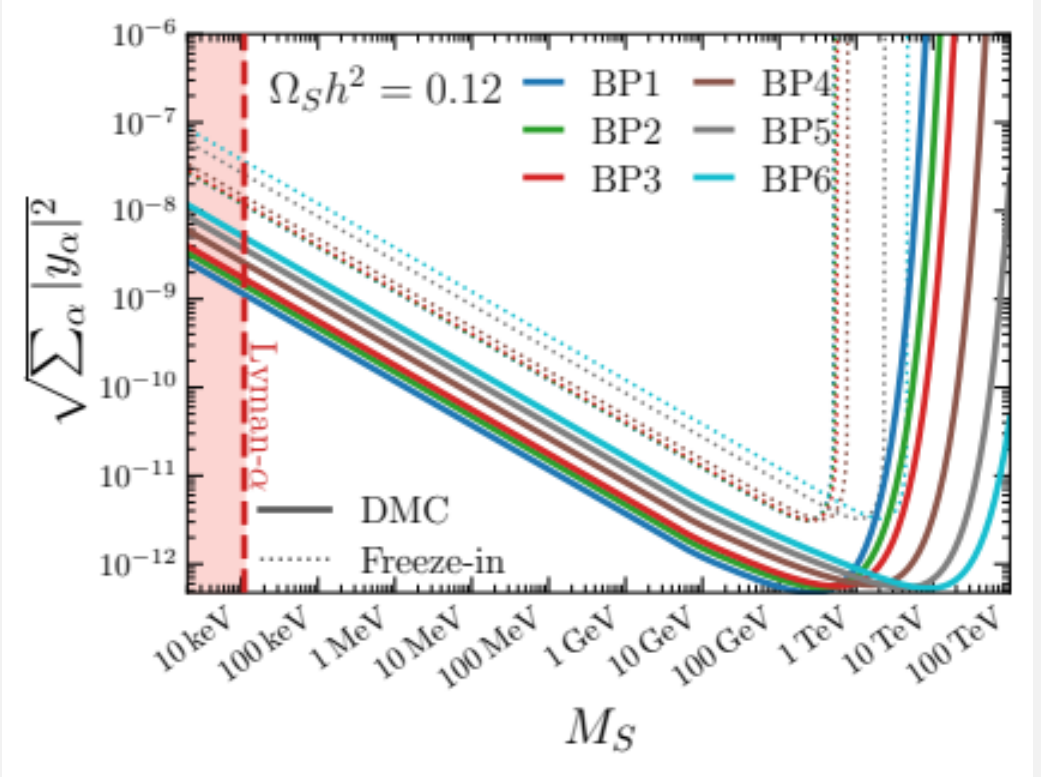








Key result

- **Main result: The mechanism yields the correct dark matter abundance with smaller SM-Mediator-Dark sector coupling compared to standard Freeze-In.**

- The **maximum mass** of the produced dark sector is set by the **maximum energy** of the SM particle and **not** the mass of the **mediator particle**!