Testing Dark Matter and Unification of Forces with Gravitational Waves

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Standard Model extension

Gauge symmetry

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

Accidental global symmetry

$$U(1)_B \times U(1)_L$$

→ **Our model:**

$$\mathrm{SU}(4) \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_X \times \mathrm{SU}(2)_\ell$$

B. Fornal, K.G, E. Pierre, accepted by PRD, arXiv:2305.12566

Embedding of Standard Model fields

Quarks are part of SU(4) quadrupelts:

$$\hat{Q}_L \equiv \left(Q_L^r \;\; Q_L^b \;\; Q_L^g \;\; \tilde{Q}_L\right)^T = (4,2,0,1)\,,$$
$$\hat{u}_R \equiv \left(u_R^r \;\; u_R^b \;\; u_R^g \;\; \tilde{u}_R\right)^T = \left(4,1,\tfrac{1}{2},1\right)\,,$$
$$\hat{d}_R \equiv \left(d_R^r \;\; d_R^b \;\; d_R^g \;\; \tilde{d}_R\right)^T = \left(4,1,-\tfrac{1}{2},1\right)$$

Leptons are part of SU(2) doublets:

$$\hat{l}_L \equiv \left(l_L \;\; \tilde{l}_L\right)^T = (1,2,-\tfrac{1}{2},2)\,,$$
$$\hat{e}_R \equiv \left(e_R \;\; \tilde{e}_R\right)^T = (1,1,-1,2)\,,$$
$$\hat{\nu}_R \equiv \left(\nu_R \;\; \tilde{\nu}_R\right)^T = (1,1,0,2)\,.$$

Symmetry breaking pattern

$$\mathrm{SU}(4) \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_X \times \mathrm{SU}(2)_\ell$$

$$\downarrow \sim 100 \text{ EeV}$$

$$\mathrm{SU}(4) \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_X$$

$$\downarrow \sim 100 \text{ TeV}$$

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \ .$$

Highlights of the model

Dark matter

→ Two dark matter particles $\tilde{\nu}'_1$ and $\tilde{u}'_1$

$$\Omega_{\mathrm{DM}} = \varepsilon\,\Omega_{\tilde{\nu}'_1} + (1-\varepsilon)\,\Omega_{\tilde{u}'_1}$$

Matter-antimatter asymmetry

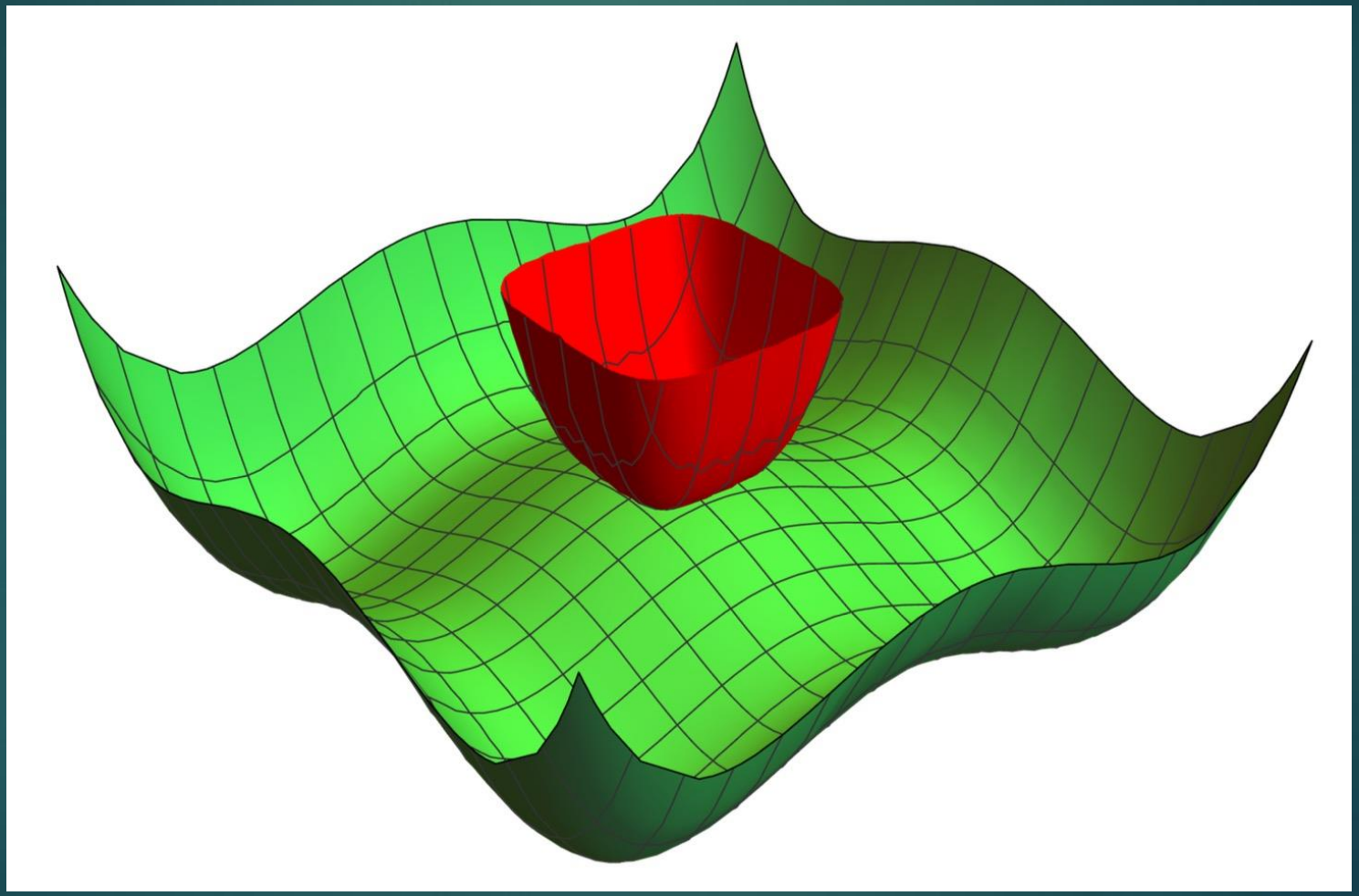
→ Through an asymmetric dark matter scenario (see talk by B. Fornal)

Neutrino masses

→ Right-handed neutrino required by anomaly cancellation

Effective potential

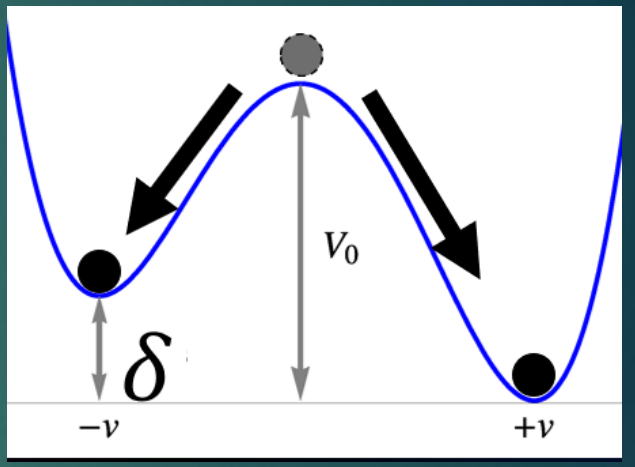
→ **SU(2) is broken by two scalars**



Domain walls

- 2D topological defects created when a discrete symmetry is spontaneously broken

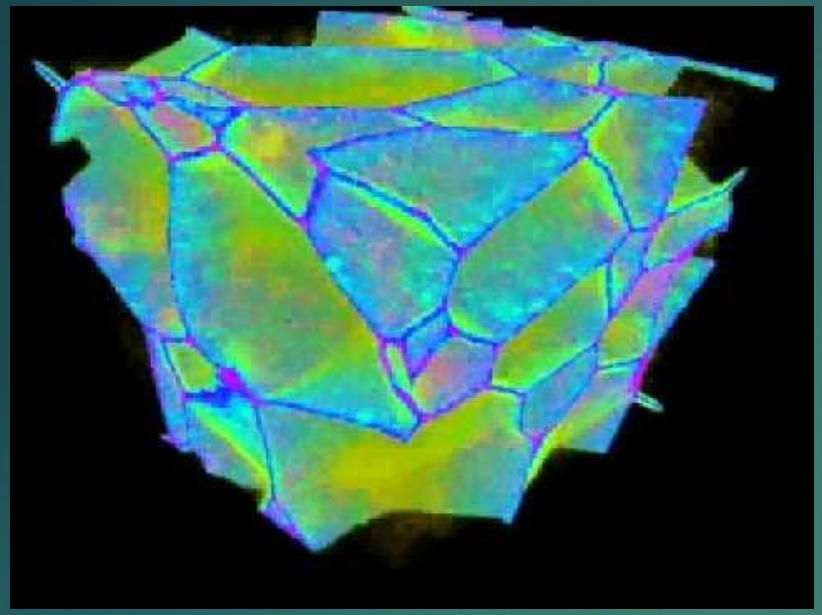
- DWs exist around boundaries of regions corresponding to different vacua



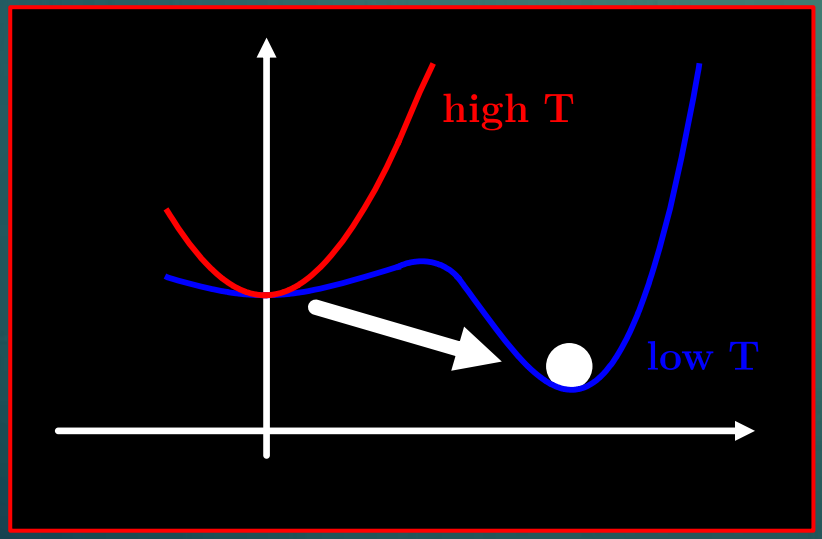
- Characterized by tension $\sigma \sim v^3$ and potential bias $\Delta\rho$

- For nonzero potential bias DWs are unstable and annihilate emitting gravitational waves

Early Universe gravitational waves in the model



Domain walls from SU(2) breaking



First order phase transition from SU(4) breaking

Gravitational wave signal from domain walls

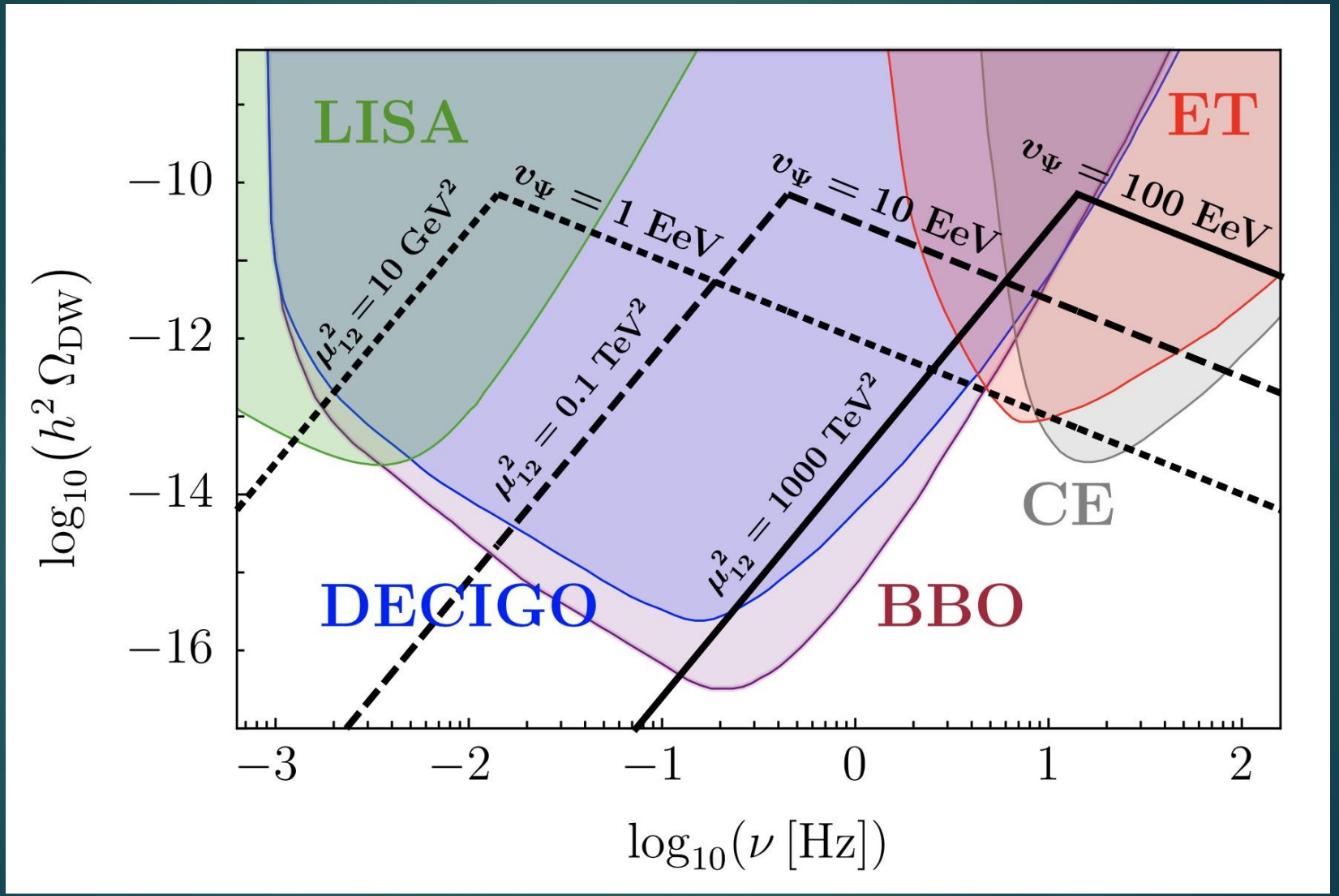
→ **Numerical simulations yield**

$$h^2\Omega_{\rm DW}(\nu) \approx 7\times 10^{-21}\left(\frac{g_*}{100}\right)^{-\frac{1}{3}}\left(\frac{\sigma}{\rm EeV^3}\right)^4\left(\frac{\rm PeV^4}{\Delta\rho}\right)^2 \times\left[\left(\frac{\nu}{\nu_d}\right)^3\theta(\nu_d-\nu)+\left(\frac{\nu_d}{\nu}\right)\theta(\nu-\nu_d)\right]$$

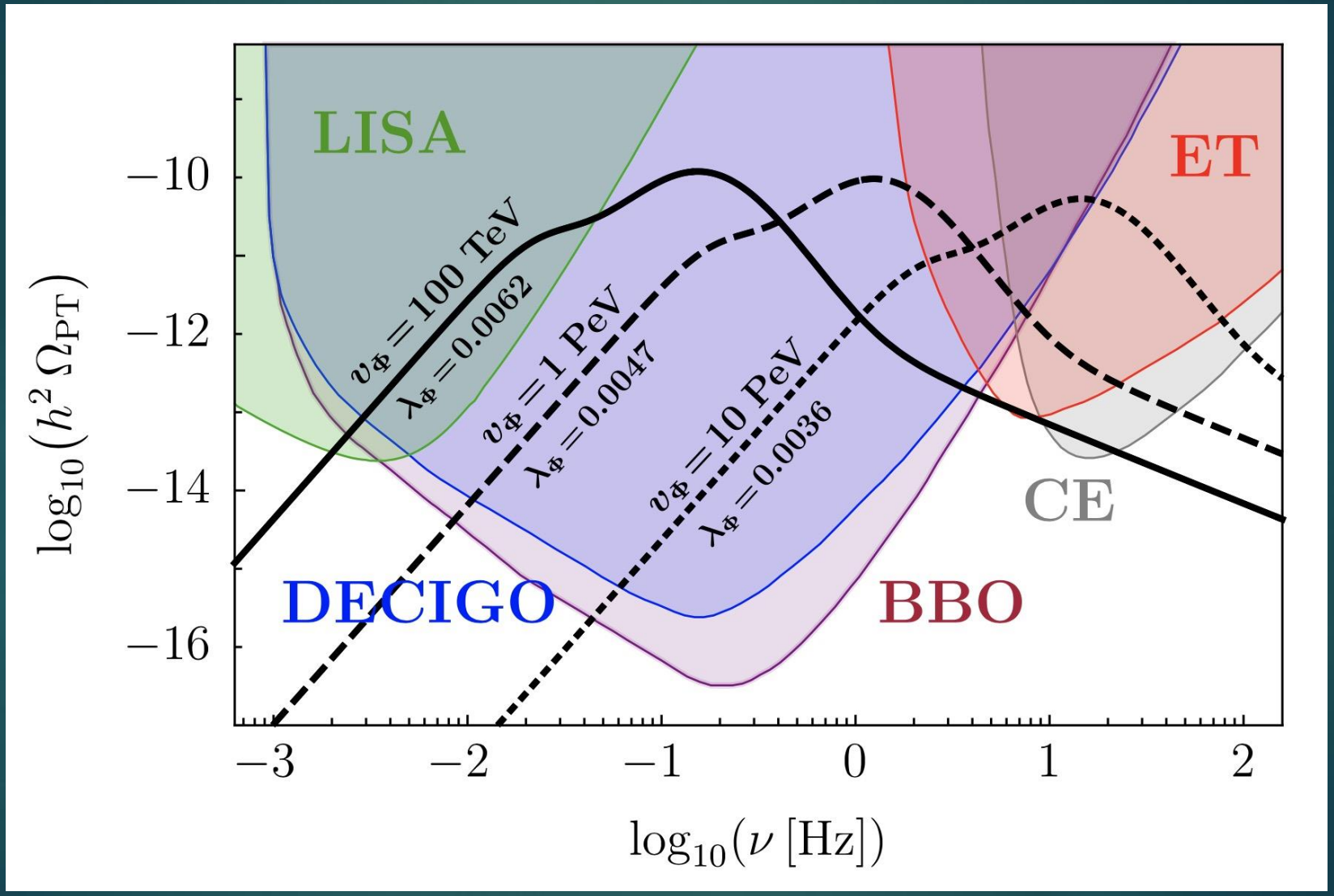
with peak frequency

$$\nu_d \approx (4.5\ {\rm Hz})\sqrt{\frac{\rm EeV^3}{\sigma}\frac{\Delta\rho}{\rm PeV^4}}\,.$$

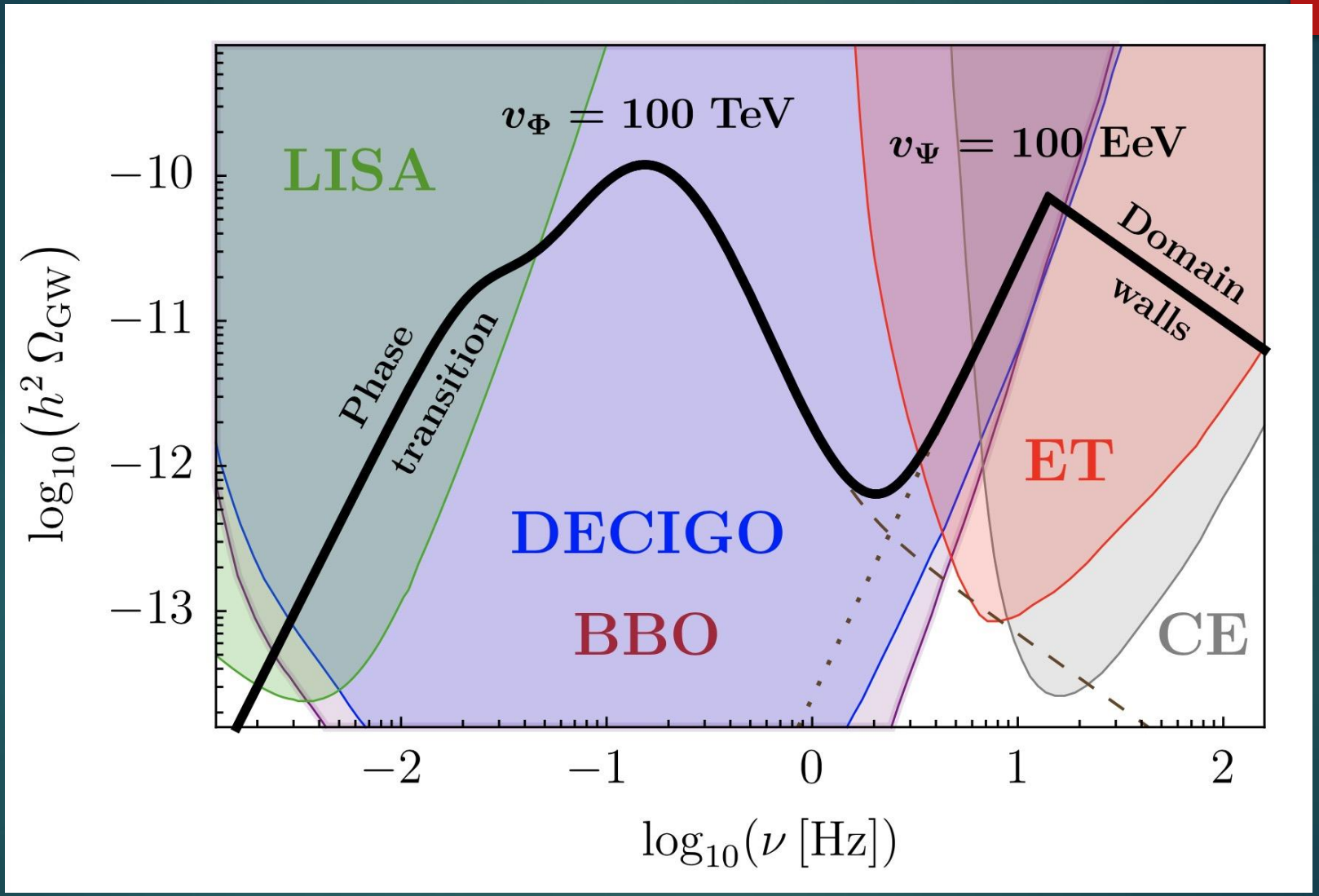
Gravitational waves from domain walls



Gravitational waves from phase transition



Novel GW signal: Domain walls + phase transition



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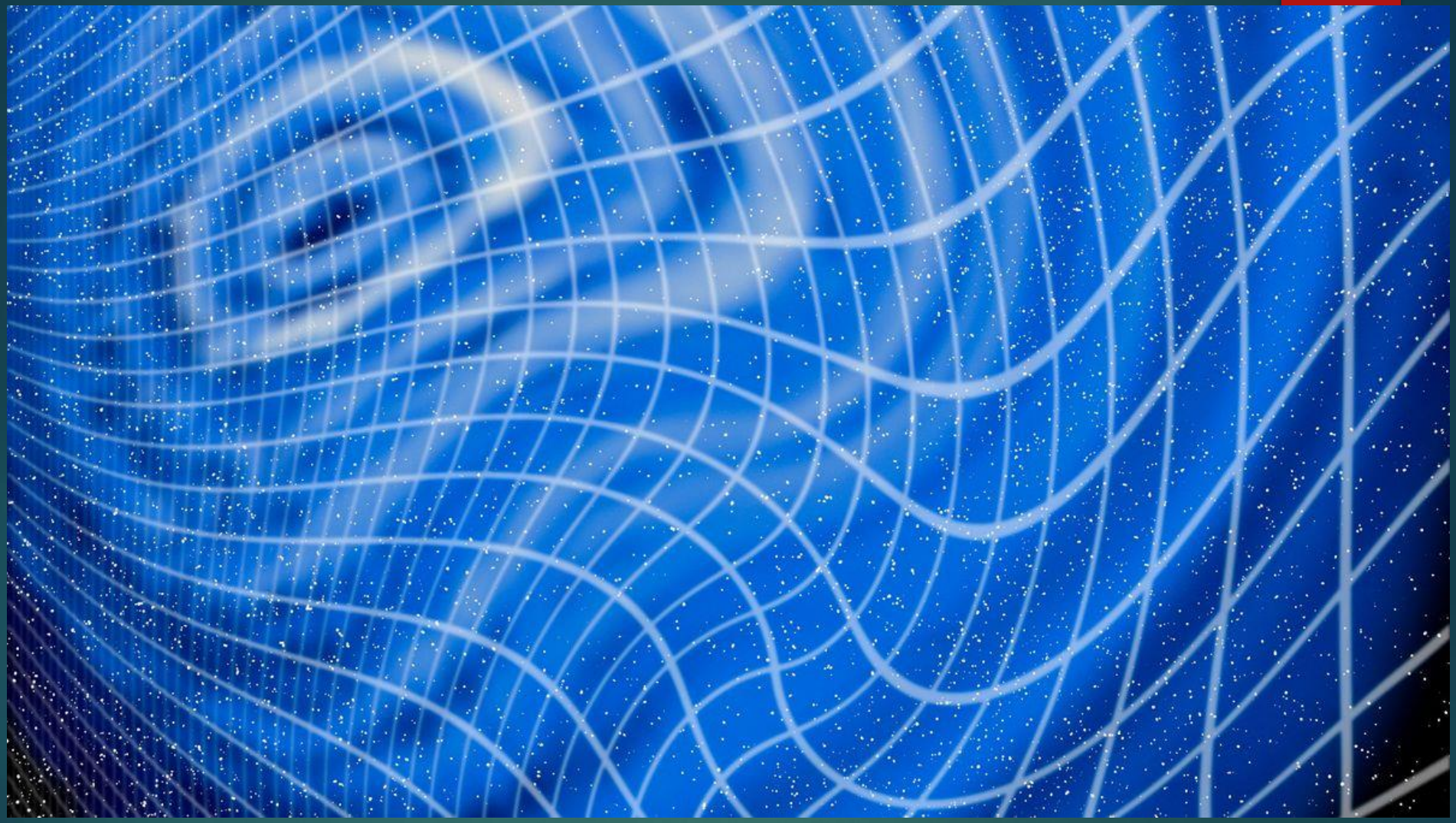

Thank you!