Leptogenesis, DM and GWs from Discrete Symmetry Breaking

Drona Vatsyayan

27^{th} August 2024, TeVPA - Chicago

Based on:
JCAP 06 (2024) 029 [Subhaditya Bhattacharya, Niloy Mondal, Rishav Roshan, **DV**]
arXiv: 2312.15053

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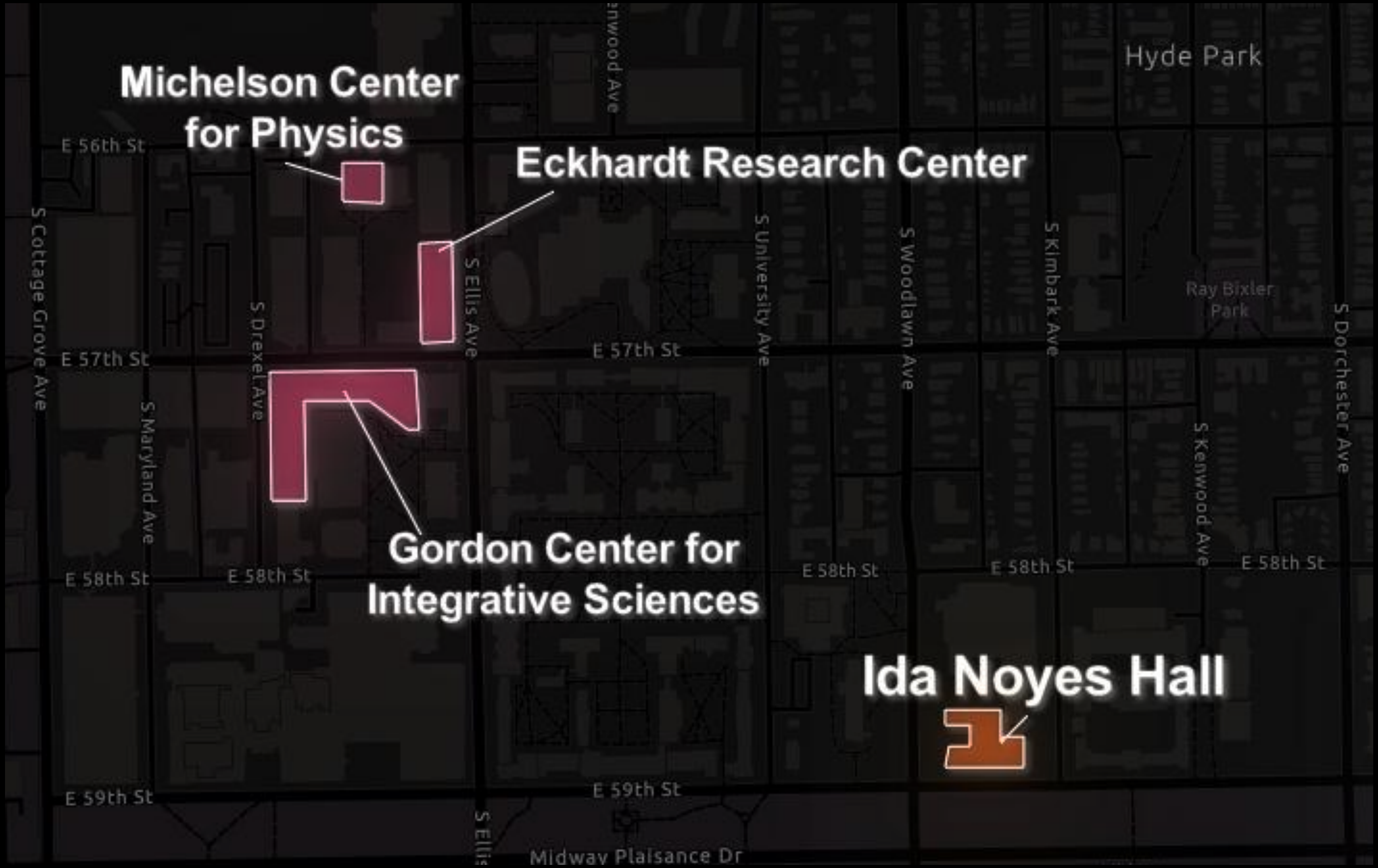
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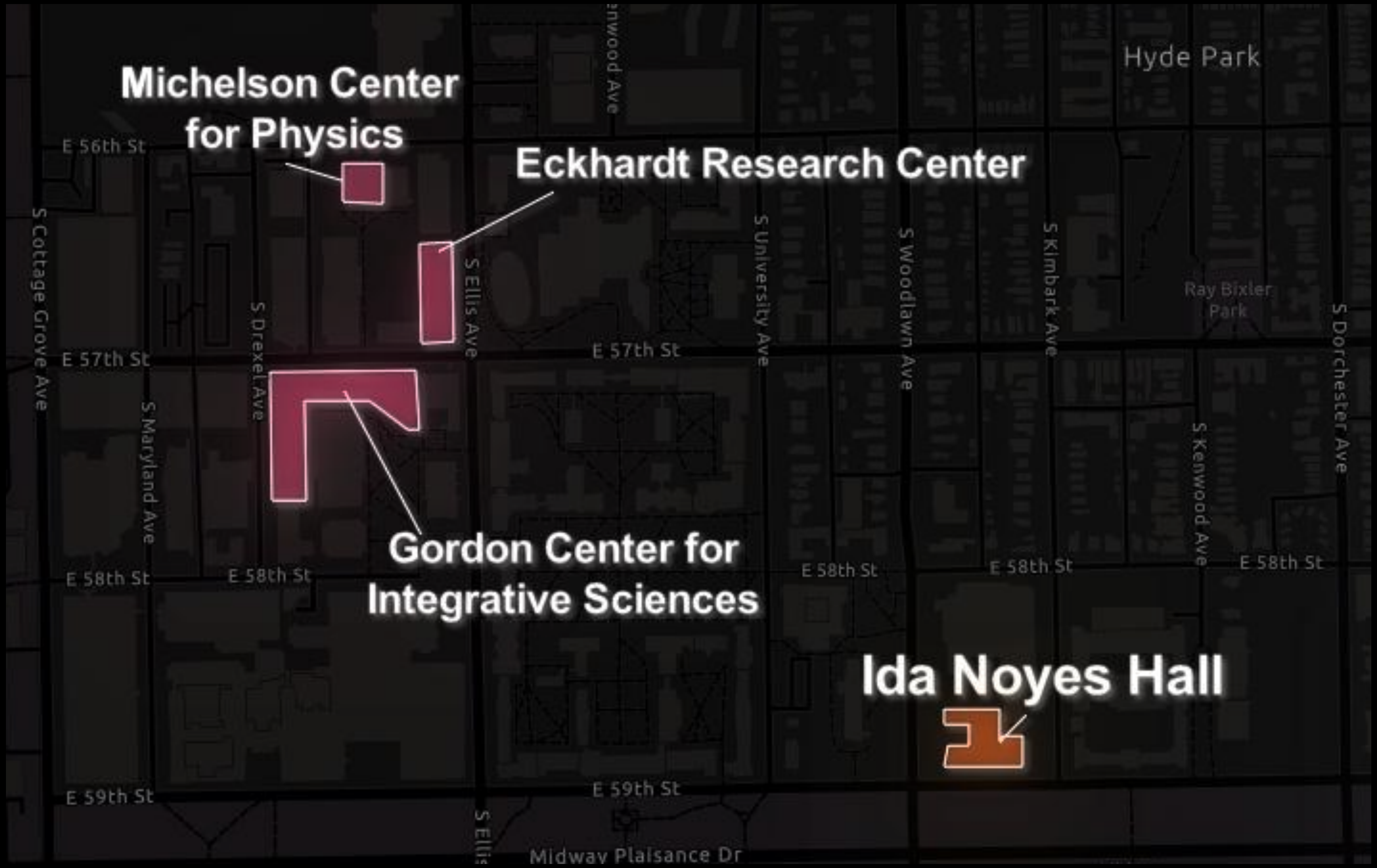
SM Problems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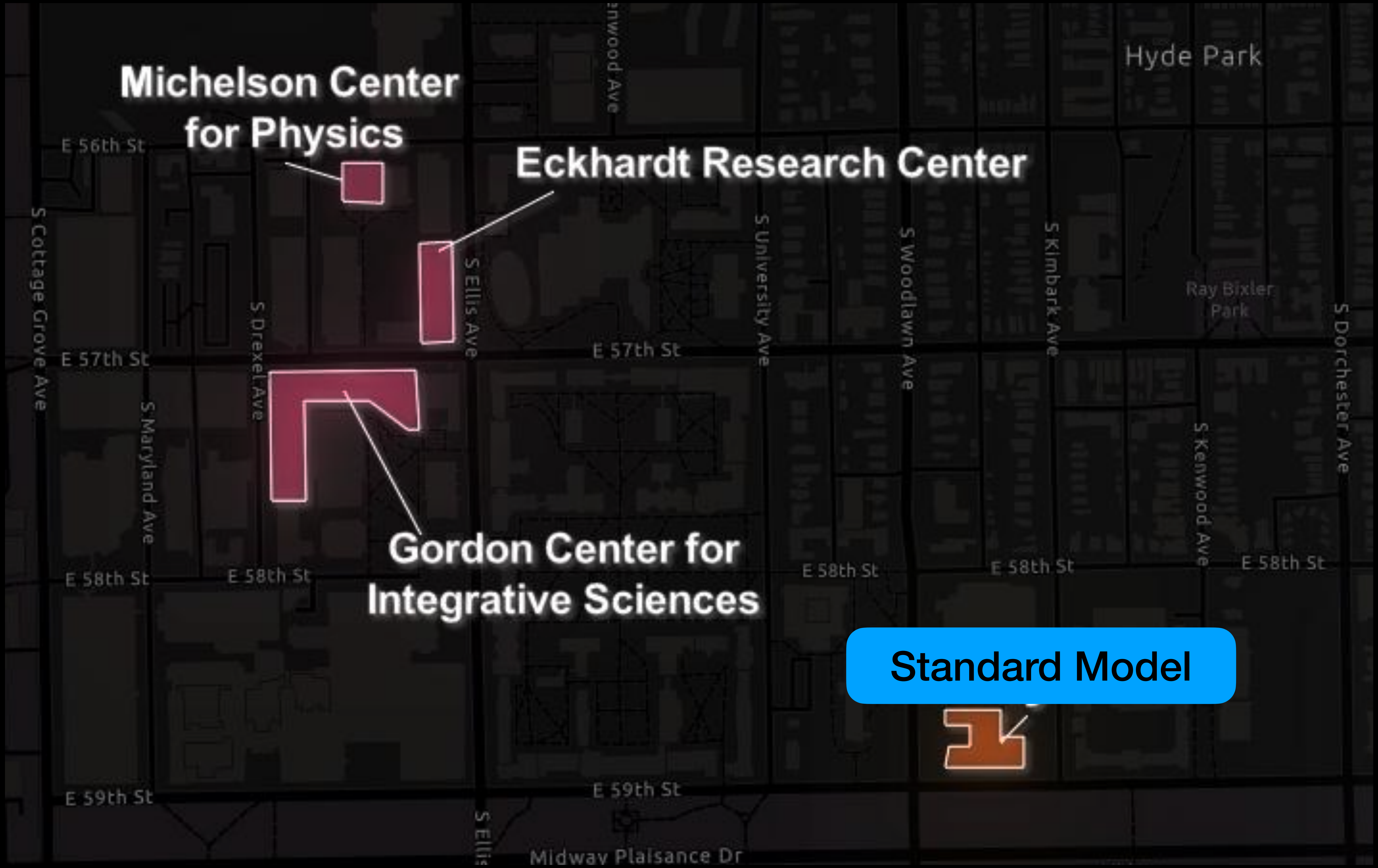
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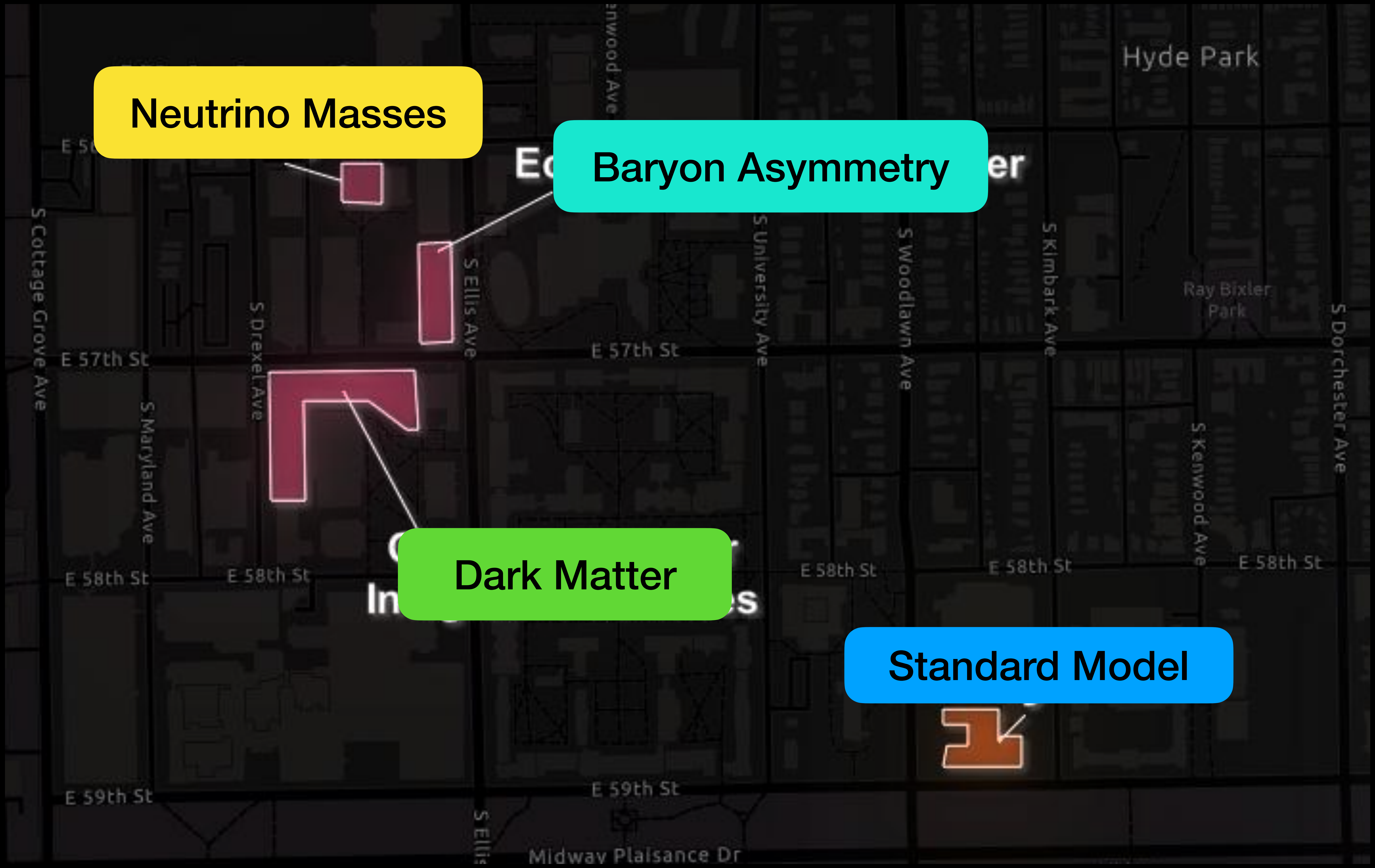

Neutrino Masses
Baryon Asymmetry
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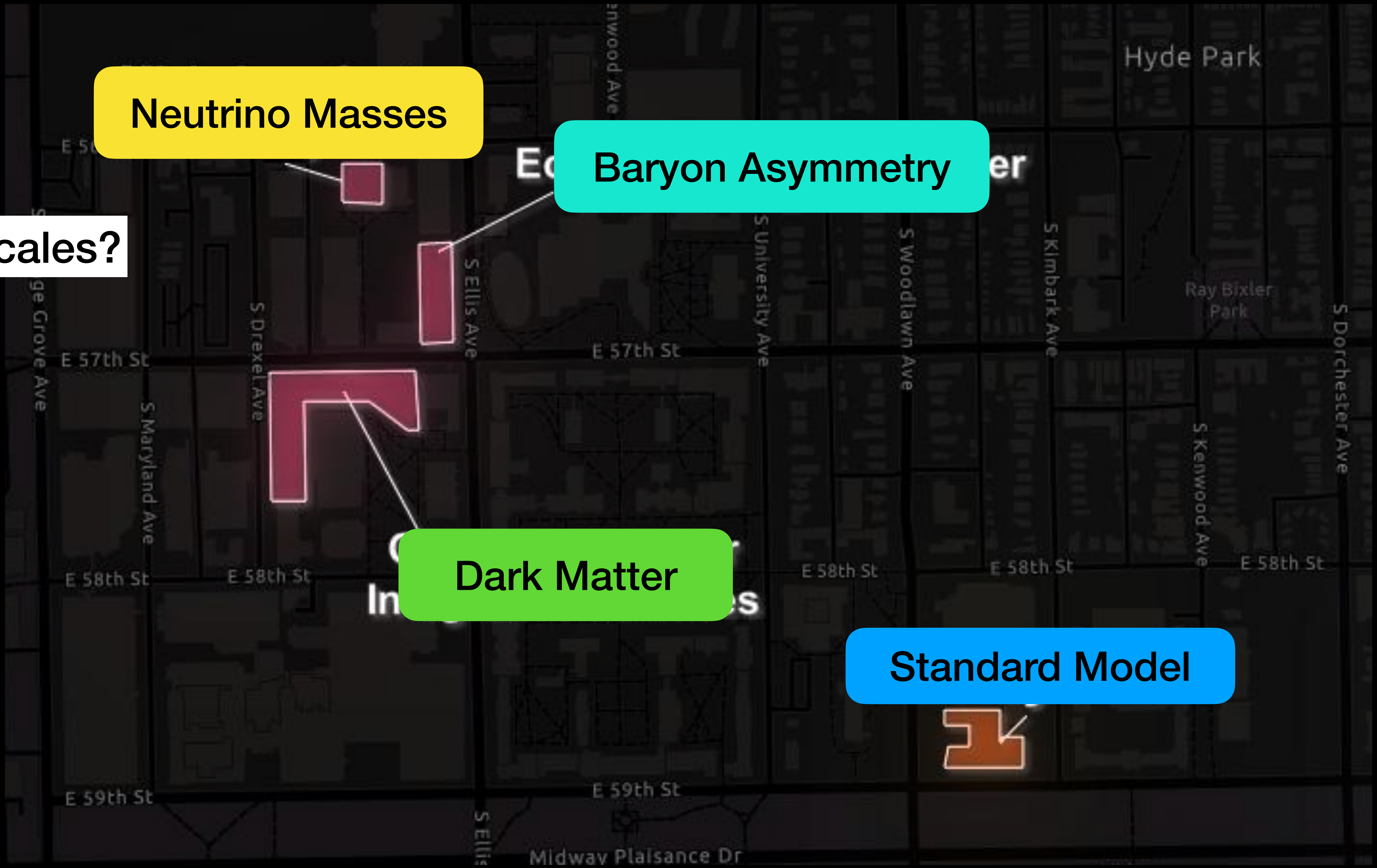
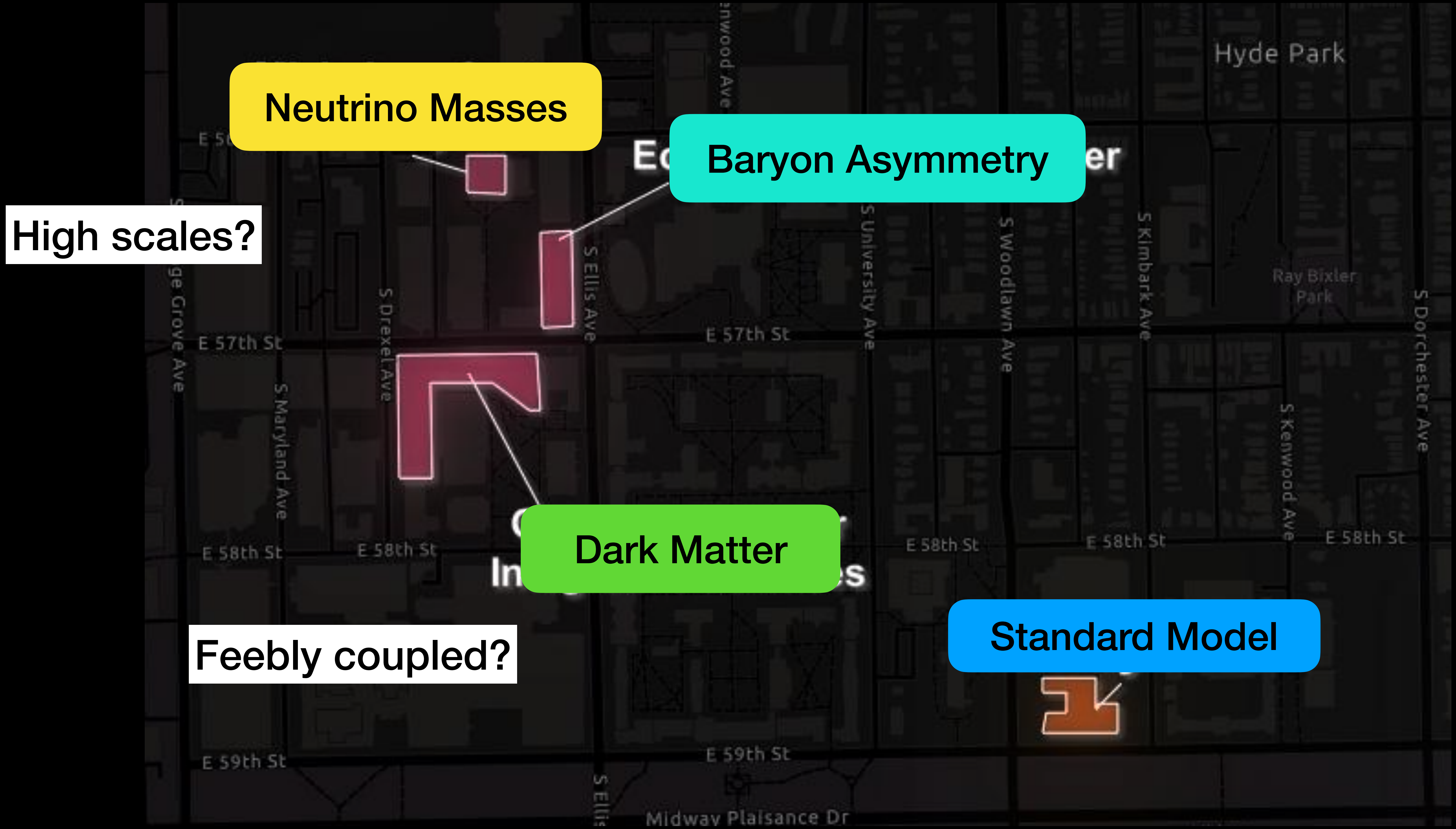
SM Problems

High scales?



SM Problems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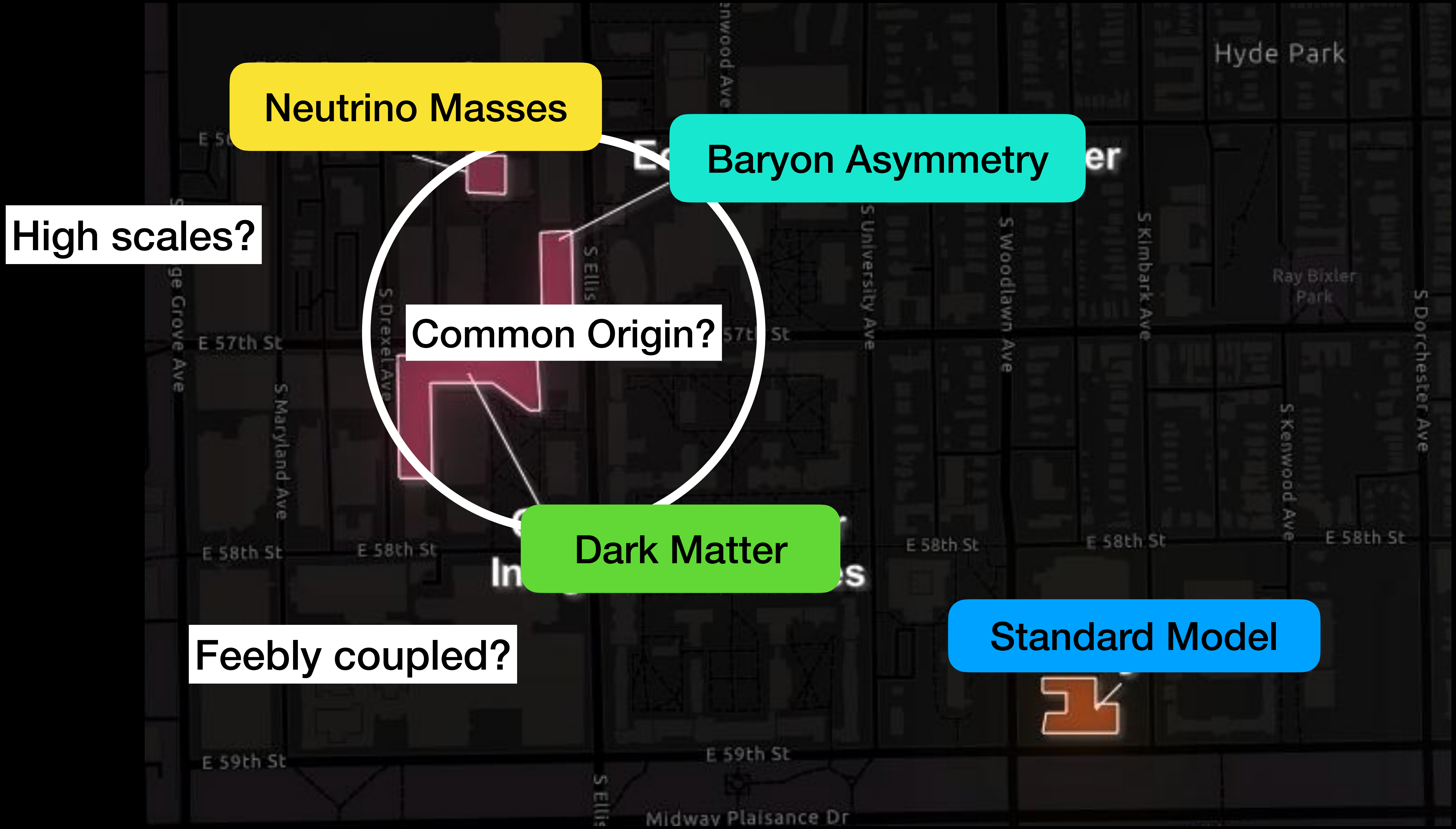

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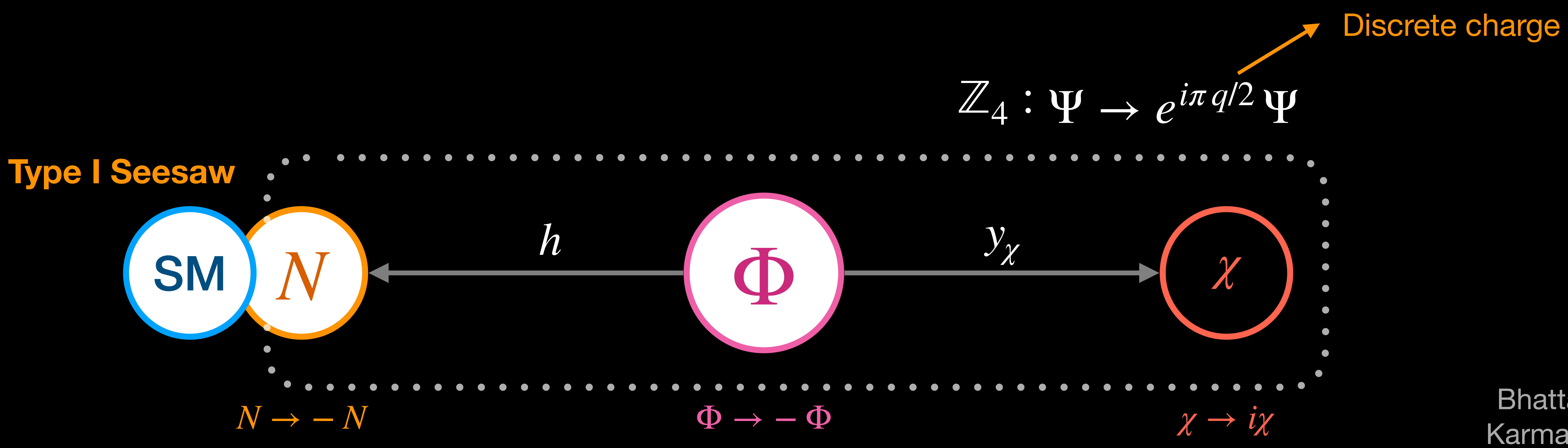
Model

Model

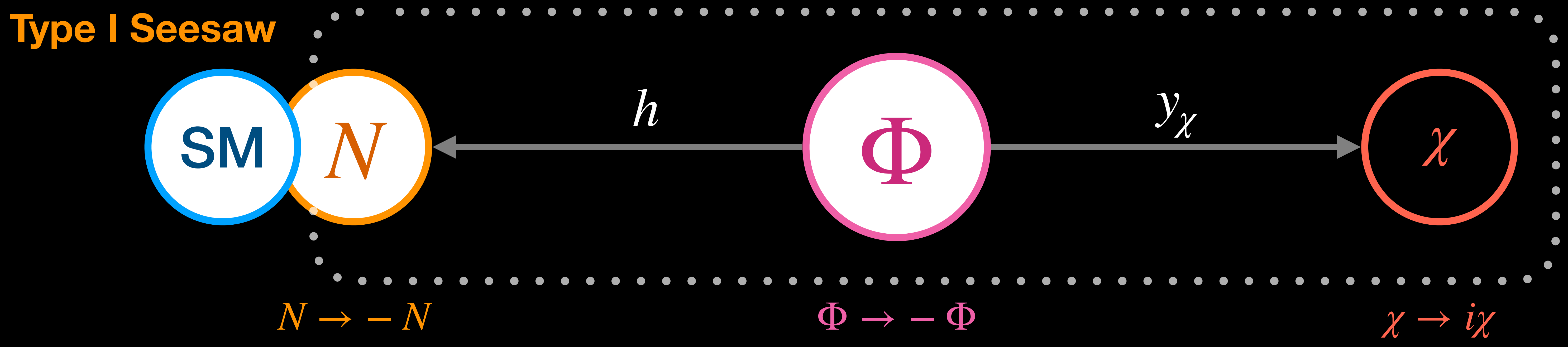


Bhattacharya, Varzielas, Karmakar, King, Sil (2019)

Model

Discrete charge

$$\mathbb{Z}_4 : \Psi \to e^{i\pi q/2}\,\Psi$$



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$\mathbb{Z}_4$ preserving $$-\mathscr{L} \supset \frac{h_{\alpha i}}{\Lambda}\,\bar{l}^{\alpha}_L \tilde{H}\Phi N^i_R + y_\chi\, \Phi \overline{\chi^c}\chi + M_{N_{ij}}\overline{N^{ci}_R} N^j_R + V(H,\Phi) + \text{h.c.}$$

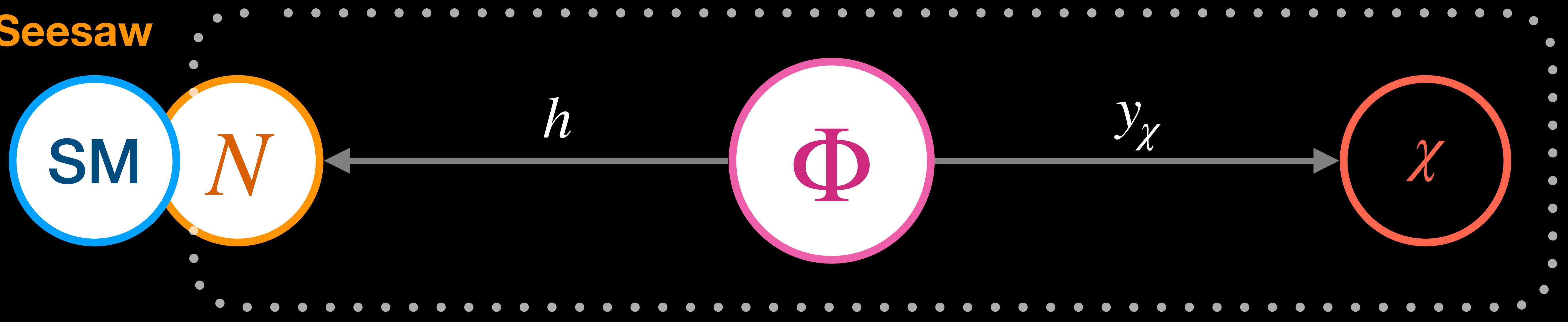
$$V(H,\Phi) = -\mu_H^2 H^\dagger H - \frac{\mu_\phi^2}{2}\Phi^2 + \lambda_H (H^\dagger H)^2 + \frac{\lambda_\phi}{4}\Phi^4 + \frac{\lambda_{H\phi}}{2}(H^\dagger H)\Phi^2$$

Model

Discrete charge

$\mathbb{Z}_4 : \Psi \rightarrow e^{i\pi q/2}\,\Psi$

Type I Seesaw



$N \rightarrow -N$ $\quad\Phi \rightarrow -\Phi$ $\quad\chi \rightarrow i\chi$

Bhattacharya, Varzielas, Karmakar, King, Sil (2019)

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ν masses;
Leptogenesis

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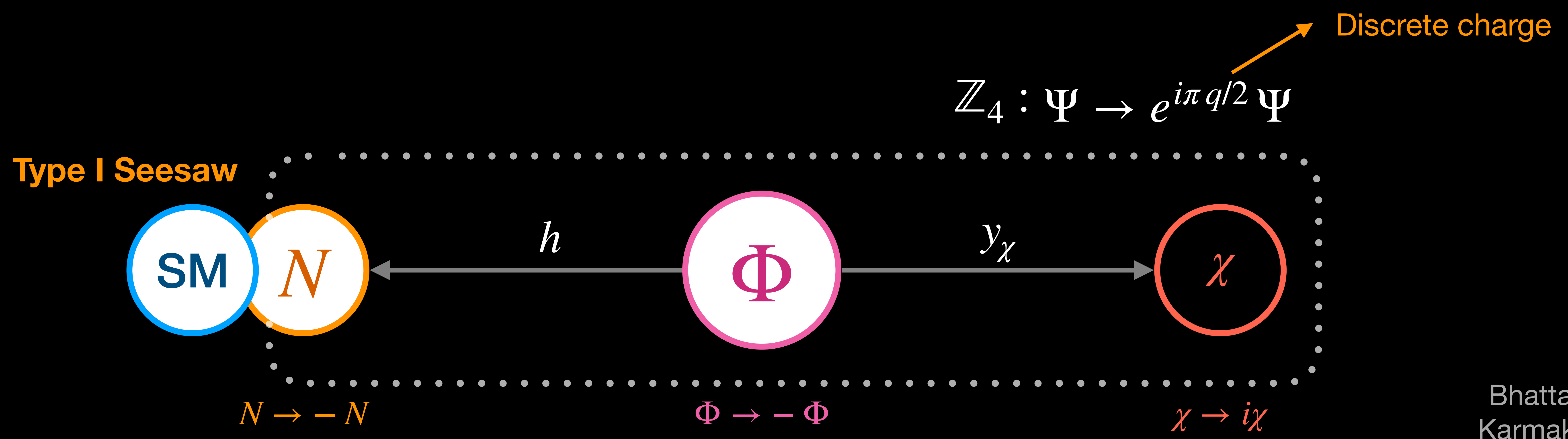
Model



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ν masses; Leptogenesis

DM mass, production

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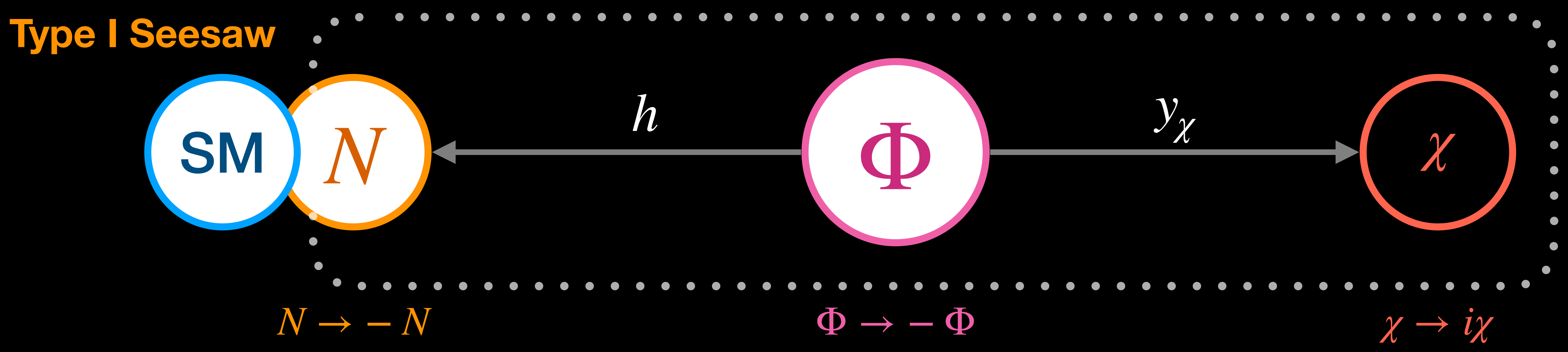
Model

Discrete charge

$$\mathbb{Z}_4 : \Psi \rightarrow e^{i\pi q/2}\Psi$$



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DM mass, production

RHN mass; violates LN

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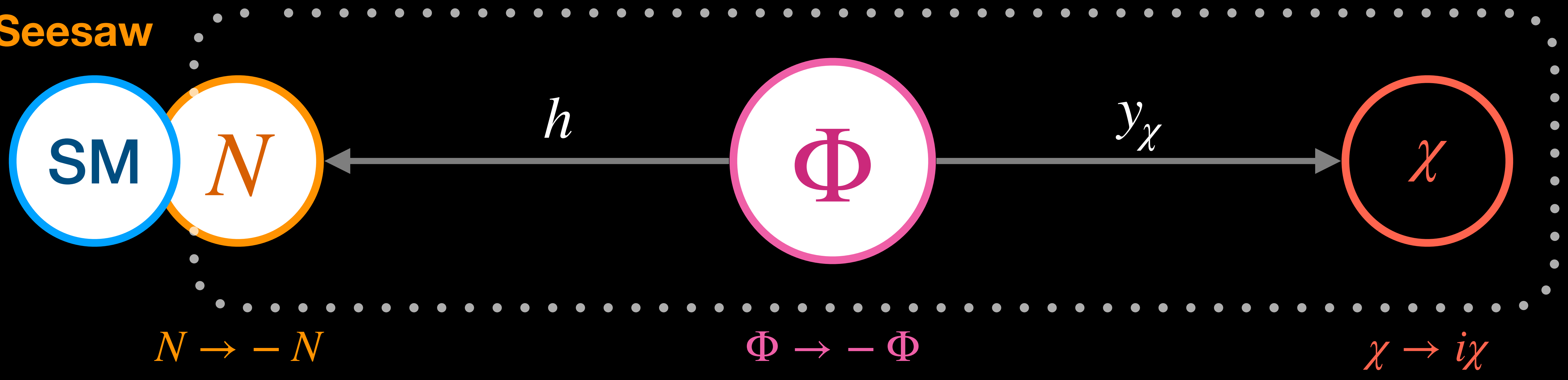
Model

Discrete charge

$$\mathbb{Z}_4 : \Psi \to e^{i\pi q/2}\Psi$$

Type I Seesaw



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ν masses; Leptogenesis

DM mass, production

RHN mass; violates LN

$\bar{l}_L\tilde{H}N$

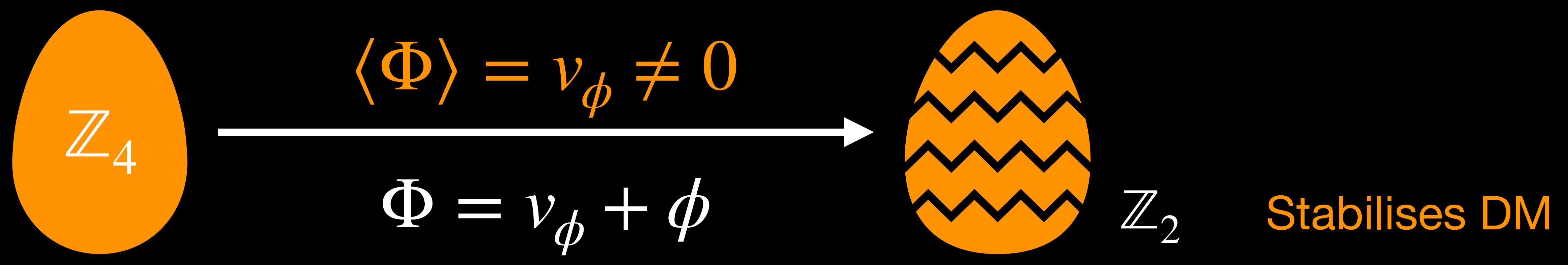
$\bar{N}^c N\Phi$

✗

$$V(H,\Phi) = -\mu_H^2 H^\dagger H - \frac{\mu_\phi^2}{2}\Phi^2 + \lambda_H (H^\dagger H)^2 + \frac{\lambda_\phi}{4}\Phi^4 + \frac{\lambda_{H\phi}}{2}(H^\dagger H)\Phi^2$$

Model

Discrete Symmetry Breaking

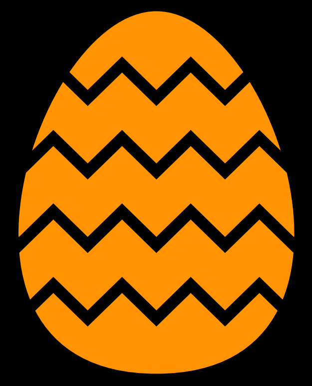


Model

Discrete Symmetry Breaking

$\langle \Phi \rangle = v_\phi \neq 0$

$\Phi = v_\phi + \phi$



$\mathbb{Z}_2$ Stabilises DM

ν masses

$$\frac{h_{\alpha i}}{\Lambda} \bar{l}_L^\alpha \tilde{H} \Phi N_R^i \to m_\nu = h h^T \frac{v_\phi^2}{\Lambda^2} \frac{v^2}{M_N} = y_\nu y_\nu^T \frac{v^2}{M_N}$$

Type I seesaw → Leptogenesis

DM mass

$$y_\chi \Phi \overline{\chi^c} \chi \to M_\chi = 100 \text{ GeV} \left(\frac{y_\chi}{10^{-10}} \right) \left(\frac{v_\phi}{10^{12}} \right)$$

TeV scale DM with feeble coupling → Large v_ϕ

Fukugita, Yanagida (1986)

Leptogenesis

Decay contribution

Sakharov (1967)

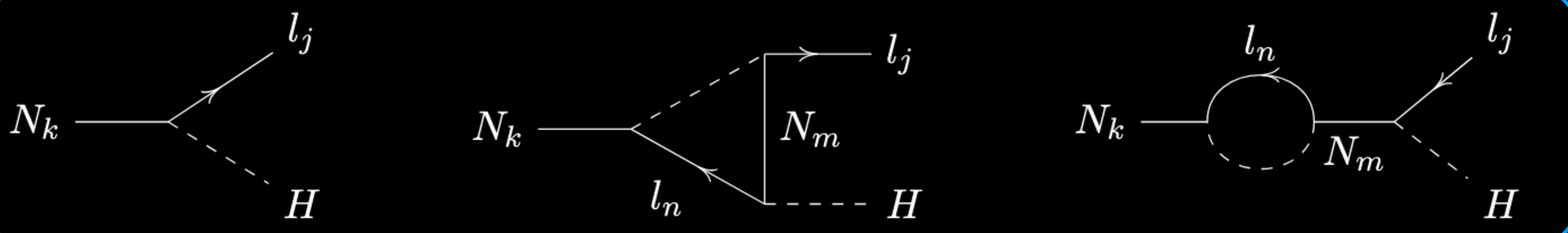
Lepton number violation: Majorana mass term

CP violation: Complex Yukawas y_ν

Departure from equilibrium: Out-of equilibrium decays

CP Asymmetry in N decays

$$\varepsilon_{D_i} \equiv \frac{\Gamma(N_i \to lH) - \Gamma(N_i \to \bar{l}\bar{H})}{\Gamma(N_i \to lH) + \Gamma(N_i \to \bar{l}\bar{H})}$$



$$\varepsilon_{D_1} = \frac{3}{16\pi} \sum_{m \neq 1} \frac{1}{\sqrt{x}} \frac{\mathrm{Im}[(y_\nu^\dagger y_\nu)^2_{1m}]}{(y_\nu^\dagger y_\nu)_{11}} \text{ for } x \gg 1$$

Hierarchical case

Lepton asymmetry → Baryon asymmetry via EW sphalerons: $Y_B = C_{sp} Y^\infty_{\Delta L}$

Leptogenesis

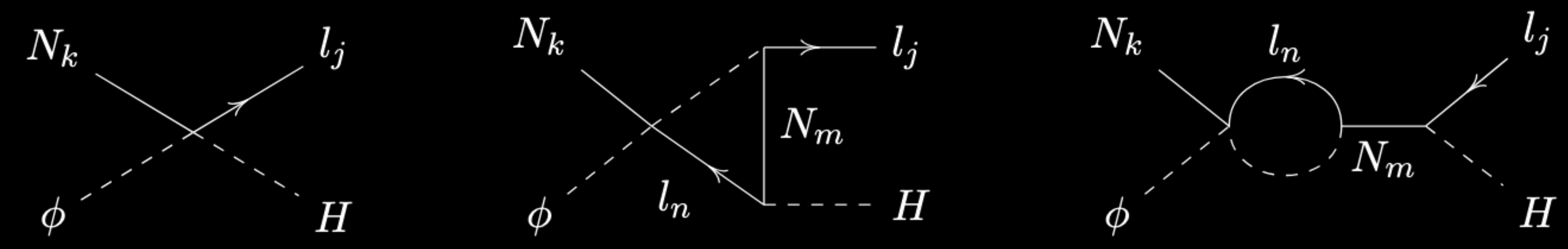
Scattering contribution

$\frac{h_{\alpha i}}{\Lambda} \bar{l}_L^{\alpha} \tilde{H} \Phi N_R^i \rightarrow$ New contribution to leptogenesis: CP asymmetry, washout

CP Asymmetry in scatterings

$$\varepsilon_{S_i} \equiv \frac{\gamma(N_i\phi \rightarrow l\bar{H}) - \gamma(N_i\phi \rightarrow \bar{l}H)}{\gamma(N_i\phi \rightarrow l\bar{H}) + \gamma(N_i\phi \rightarrow \bar{l}H)}$$

$\gamma_s \propto v_\phi^{-2}$



$$\varepsilon_{S_1} \approx \frac{2}{16\pi} \sum_{m \neq 1} \frac{1}{\sqrt{x}} \frac{\mathrm{Im}[(y_\nu^\dagger y_\nu)^2_{1m}]}{(y_\nu^\dagger y_\nu)_{11}} \quad (\text{for } \tilde{s} \gg M_{i,m} \text{ and } x \gg 1)$$

High energy limit

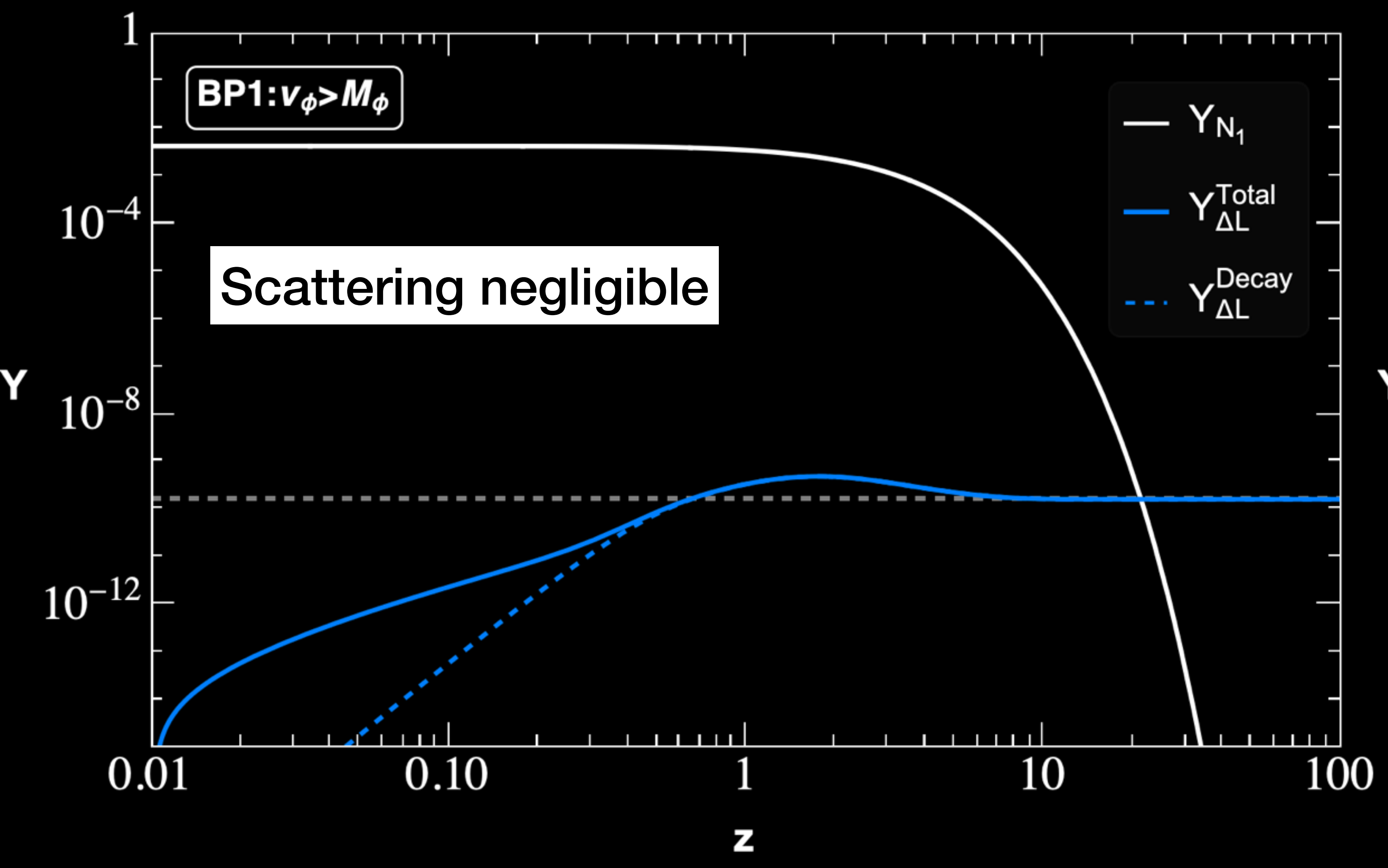
Scattering contributions can be important!

Leptogenesis

Numerical Solutions

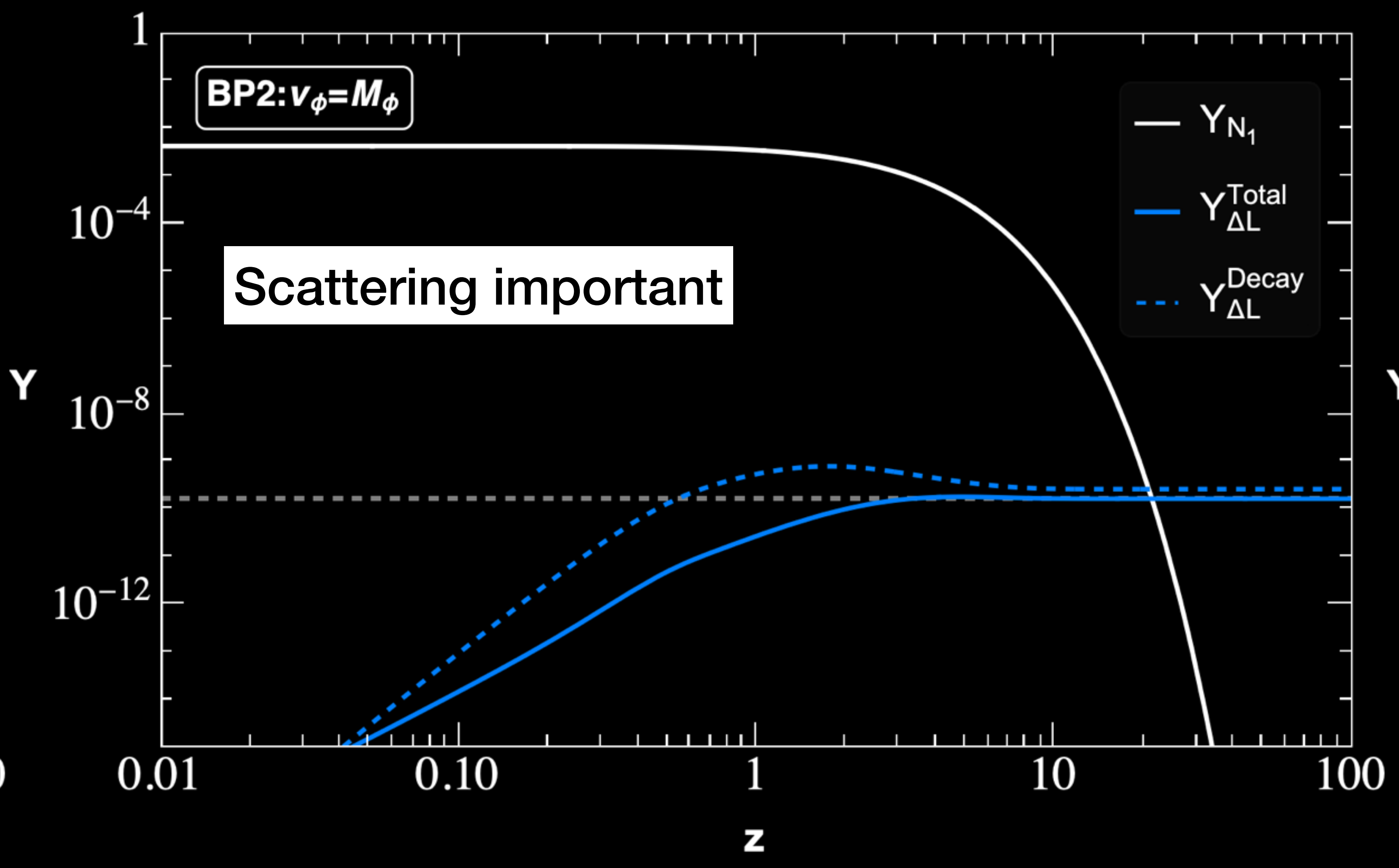
$v_\phi \gg M_\phi$

Scatterings source asymmetry initially but are subdominant later



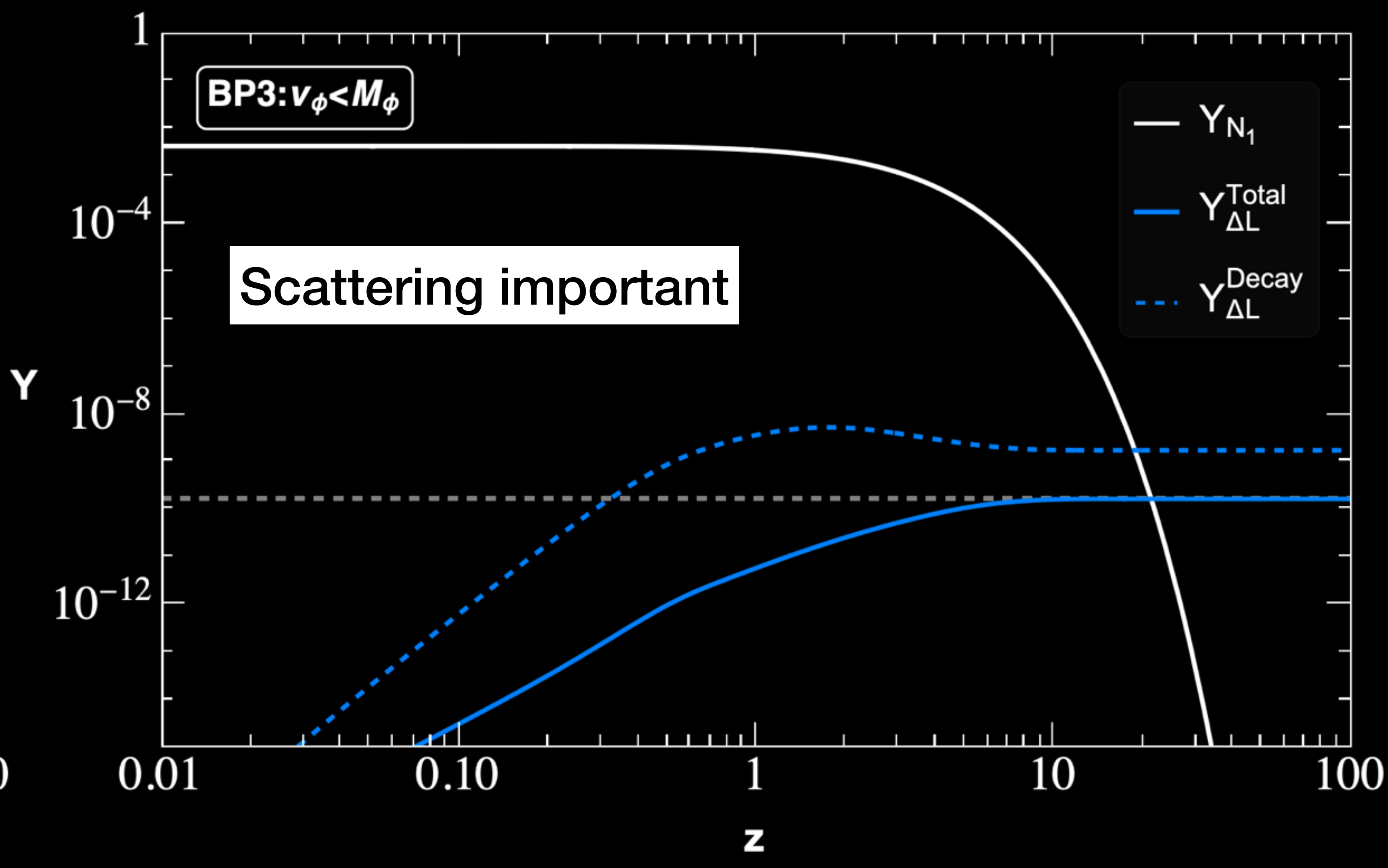
$v_\phi \sim M_\phi$

Scattering contribution is larger →
Mild washout of decay asymmetry



$v_\phi < M_\phi$

Scattering contribution is quite large→
Strong washout of decay asymmetry



If $v_\phi \ll M_\phi$, scatterings will lead to too strong washout → Cannot match observations

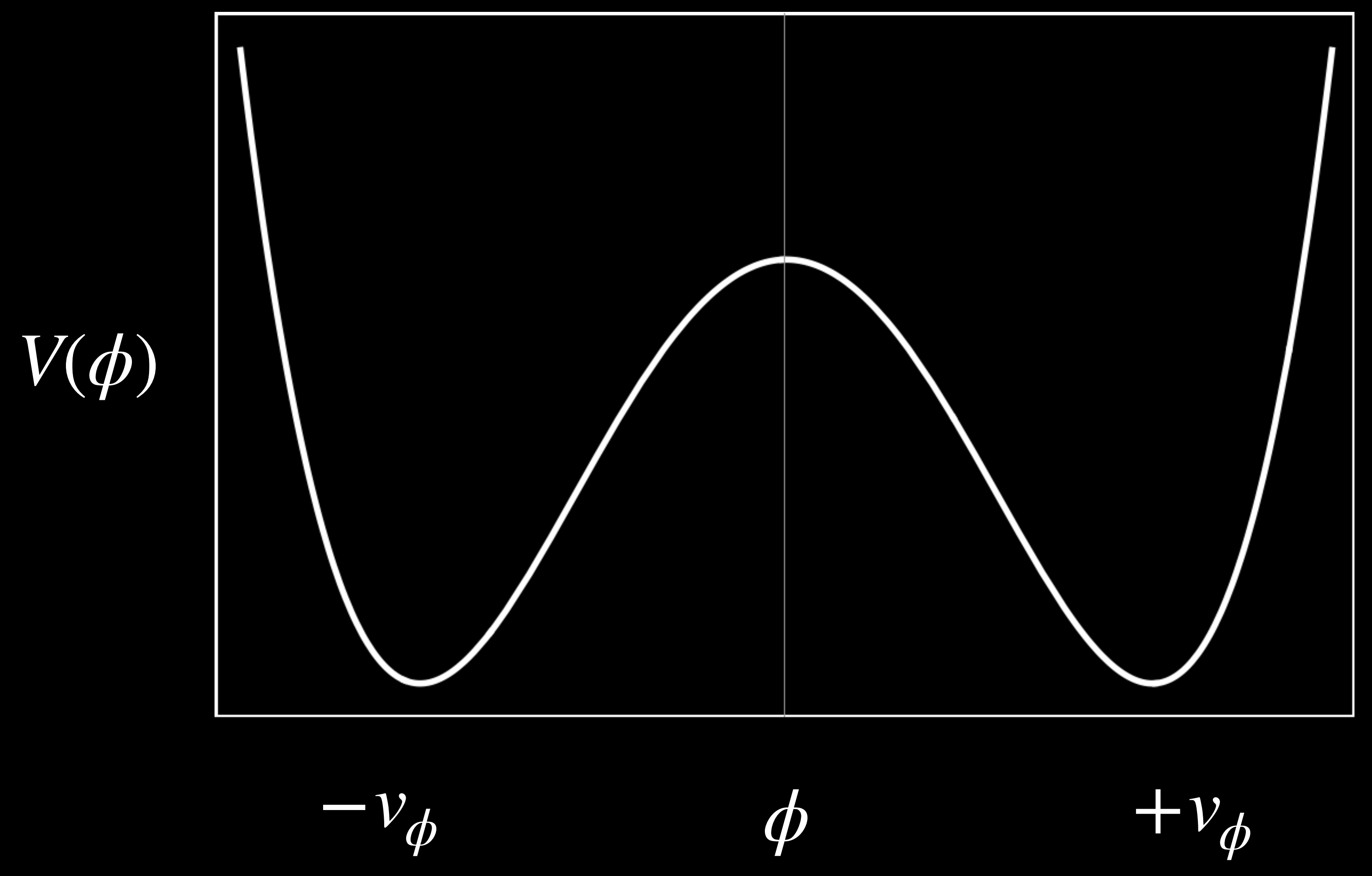
Domain Walls

From Discrete Symmetry Breaking

Domain Walls

From Discrete Symmetry Breaking

$\langle \Phi \rangle = \pm\, v_\phi \to \mathbb{Z}_4$ discrete symmetry
spontaneously broken to remnant $\mathbb{Z}_2$

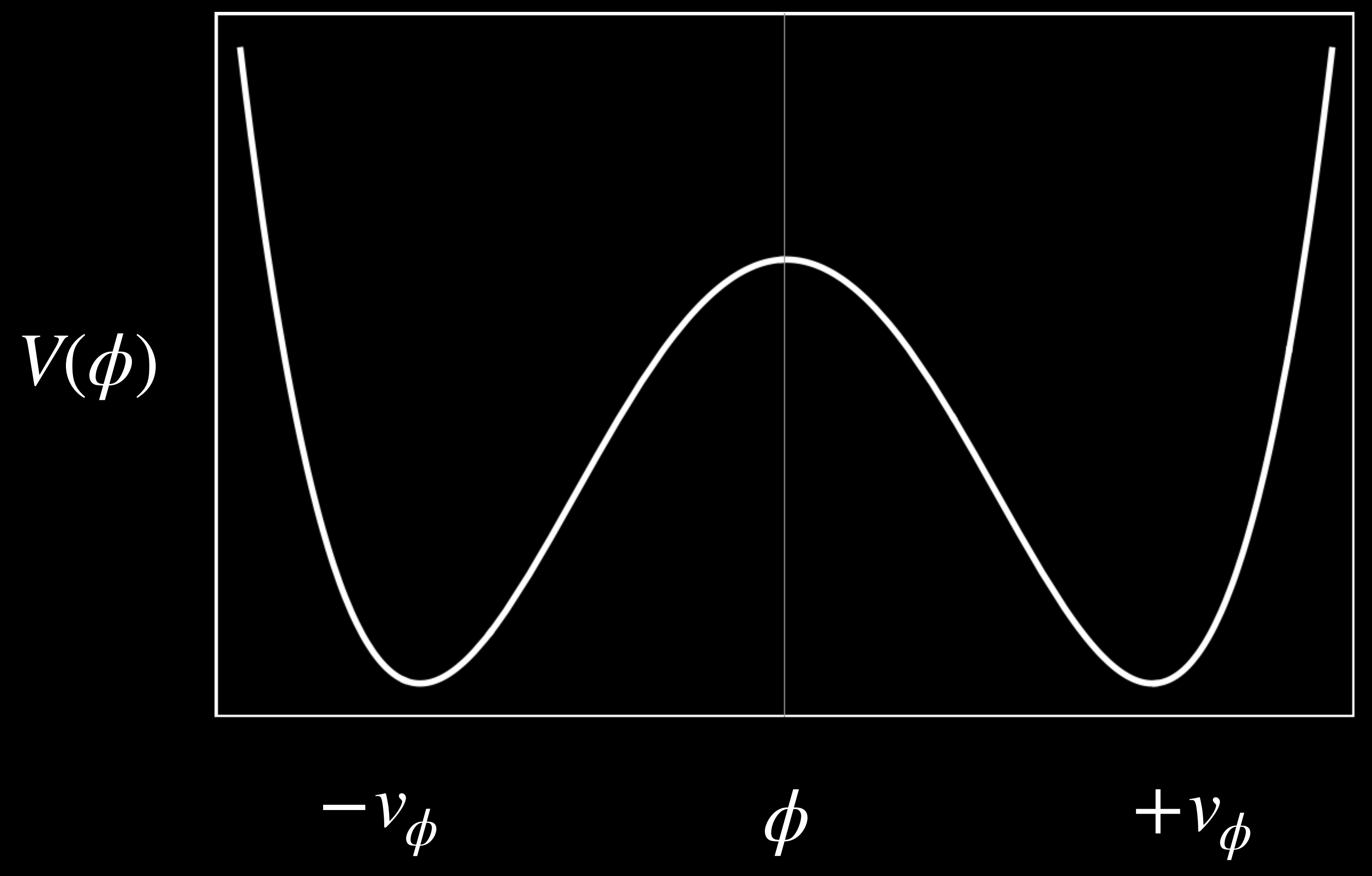


Formation of two different domains: $+v_\phi$ **and** $-v_\phi$

Domain Walls

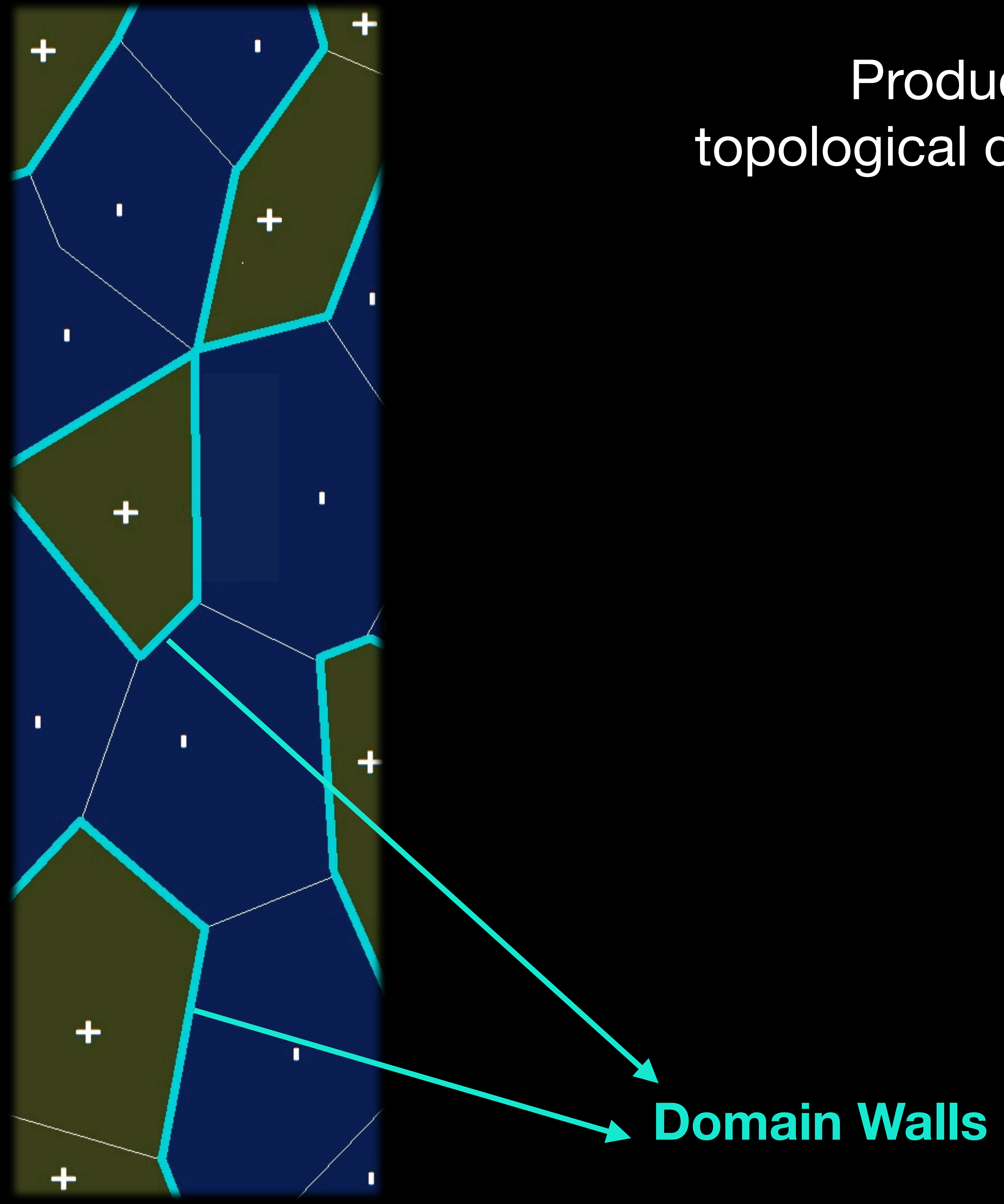
From Discrete Symmetry Breaking

$\langle \Phi \rangle = \pm v_\phi \rightarrow \mathbb{Z}_4$ discrete symmetry spontaneously broken to remnant $\mathbb{Z}_2$



Formation of two different domains: $+v_\phi$ and $-v_\phi$

Kibble (1976)



Production of DWs (sheet-like topological defects) from their boundaries

Domain Walls

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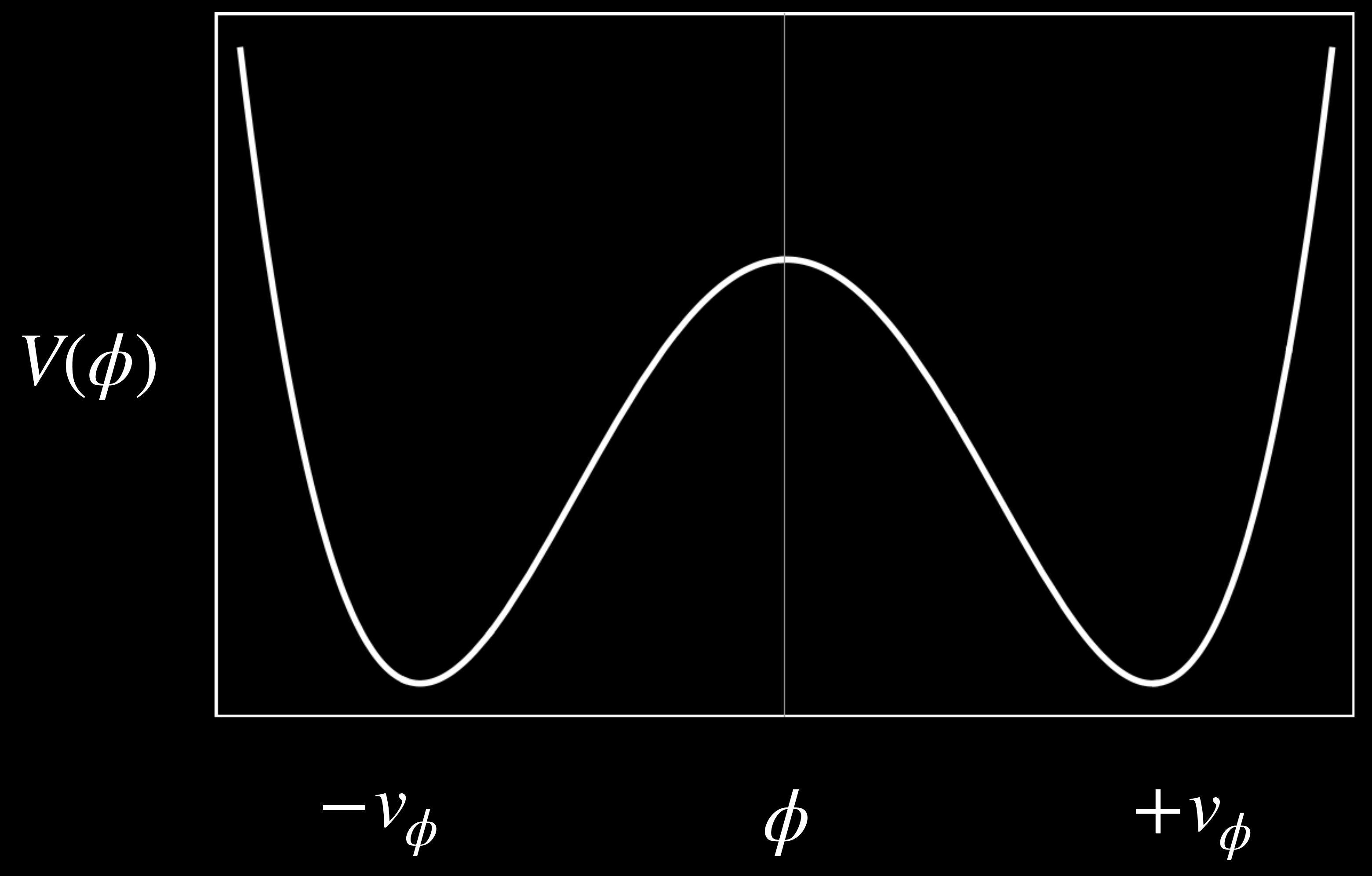

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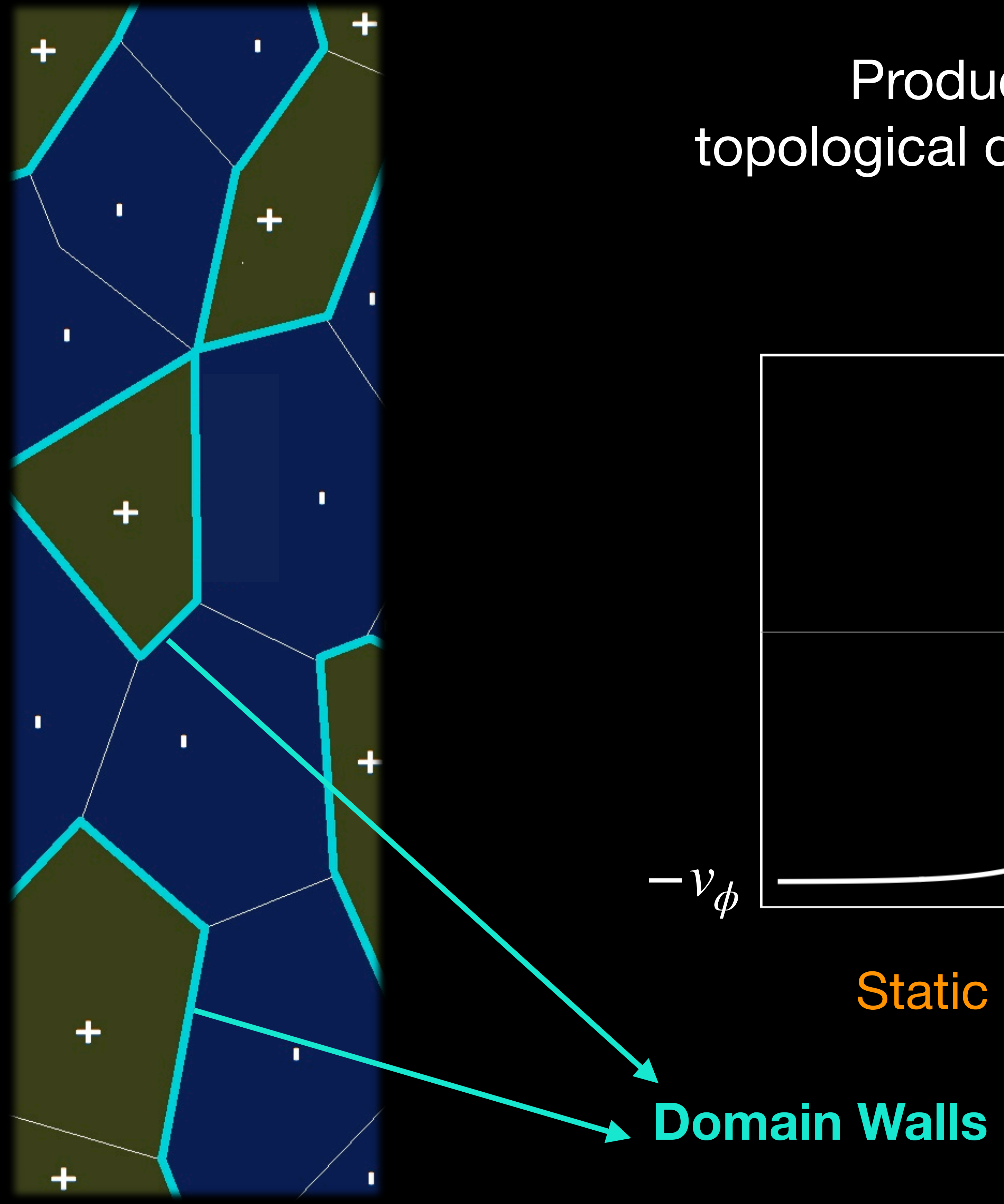

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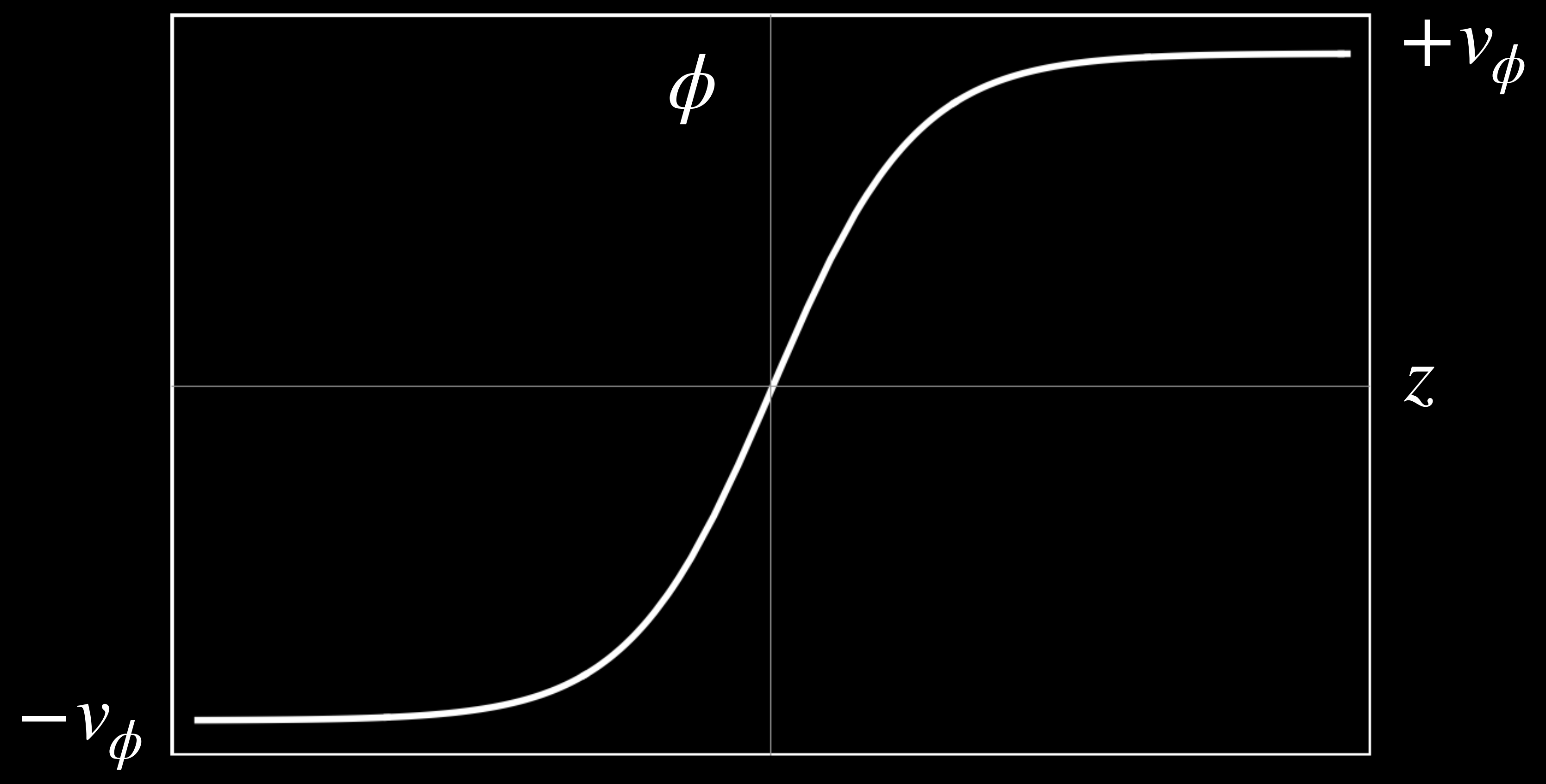

Static Planar DW configuration

Domain Walls

Biased Potential

Domain Walls

Biased Potential

Problem DWs: Stable configuration → Long-lived; $\rho_{\rm DW} \sim a^{-1}$ → Cosmological catastrophe

Domain Walls

Biased Potential

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Make DWs unstable → Introduce bias in the potential **Solution**

Vilenkin (1981); Gelmini, Gleiser, Kolb (1989); Larsson, Sarkar, White (1997)

Domain Walls

Biased Potential

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Soft $\mathbb{Z}_4$ breaking terms: $\Delta V = \mu \Phi^3 + \mu_{\phi H} \Phi H^\dagger H + \ldots$

$$V_{\rm bias} = \mu v_\phi^3 + \mu_{\phi H} \frac{v_\phi v^2}{2}$$

Domain Walls

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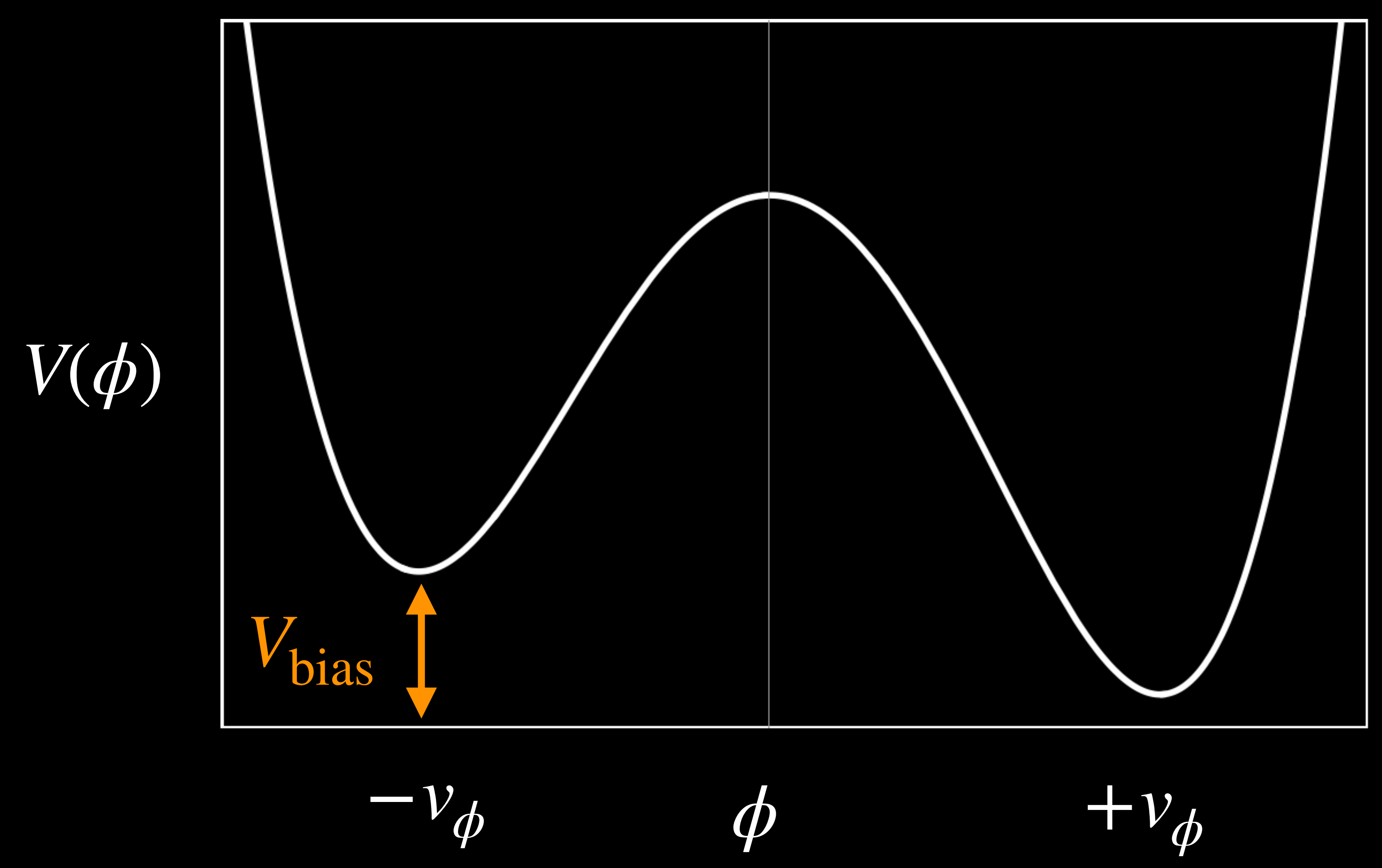

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$$V_{\text{bias}} = \mu v_\phi^3 + \mu_{\phi H}\frac{v_\phi v^2}{2}$$

V_{bias} → Vacuum degeneracy uplifted → False Vacuum region shrinks

Domain Walls

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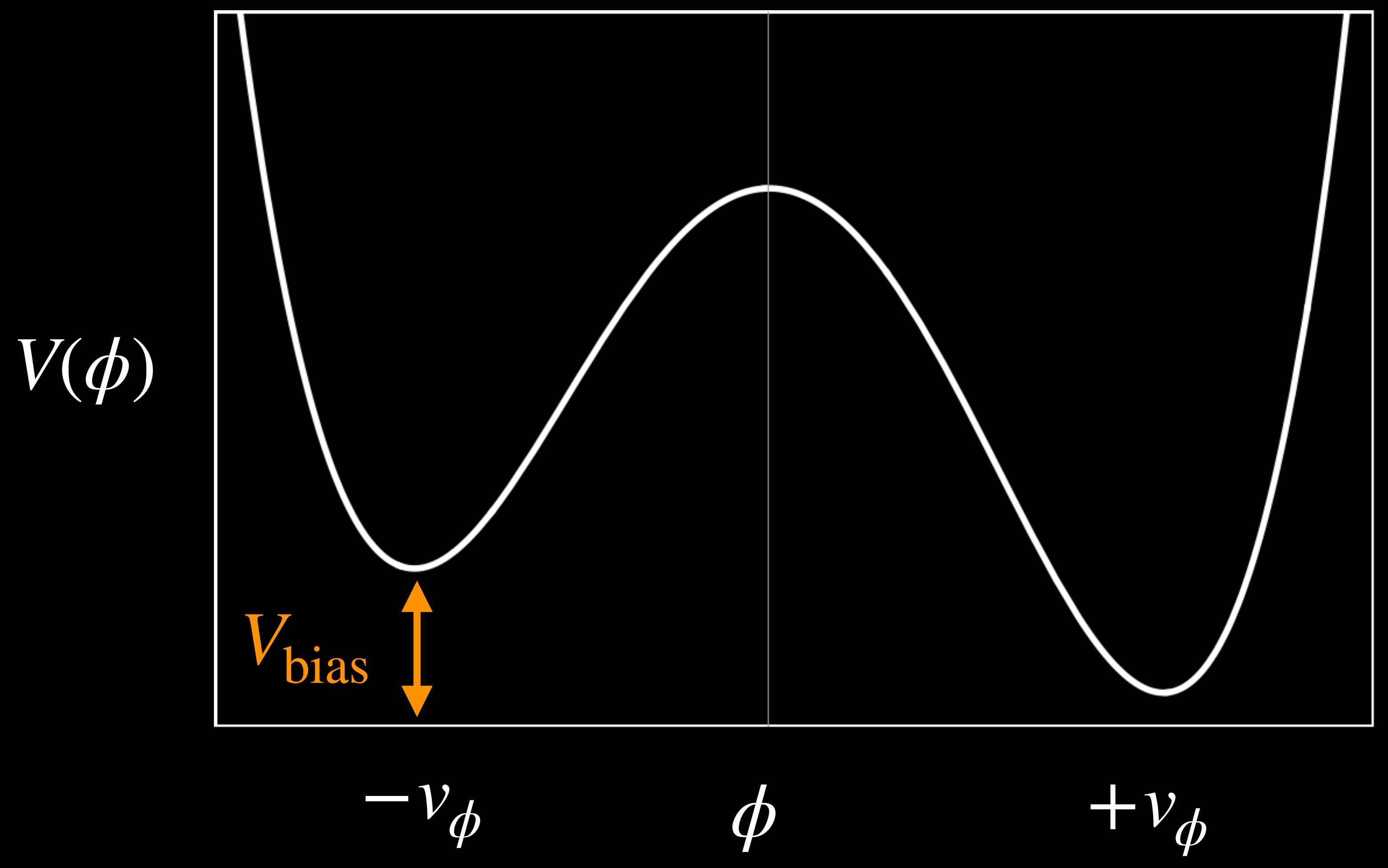

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$V_{\rm bias}$ → Vacuum degeneracy uplifted → False Vacuum region shrinks

Volume pressure force: $p_V \sim V_{\rm bias} > p_T$ (Tension force) → Collapse and annihilation of DWs → Production of GWs

Gravitational Waves

From DW annihilations

Peak frequency

$$f_p \simeq 1.4 \times 10^{-5}\ \text{Hz} \times \left(\frac{1.41}{\mathscr{A}}\right)^{1/2} \left(\frac{10^7\ \text{GeV}}{\sigma^{1/3}}\right)^{3/2} \left(\frac{V_{\text{bias}}}{10^7\ \text{GeV}^4}\right)^{1/2}$$

Area parameter

Surface tension $\sigma = \frac{2}{3}\sqrt{2\lambda_\phi v_\phi^3}$

Peak energy density

$$\Omega_p h^2 \simeq 1.49 \times 10^{-10} \times \left(\frac{\tilde{\epsilon}_{\text{GW}}}{0.7}\right) \left(\frac{\mathscr{A}}{1.41}\right)^4 \left(\frac{\sigma^{1/3}}{10^7\ \text{GeV}}\right)^{12} \left(\frac{10^7\ \text{GeV}^4}{V_{\text{bias}}}\right)^2$$

Efficiency factor

Broken power-law spectrum

$$\Omega_{\text{GW}} h^2 = \Omega_p h^2 \frac{(a+b)^c}{\left(b x^{-a/c} + a x^{b/c}\right)^c}$$

$a = 3\,, b \sim c \sim 1$

Gravitational Waves

From DW annihilations

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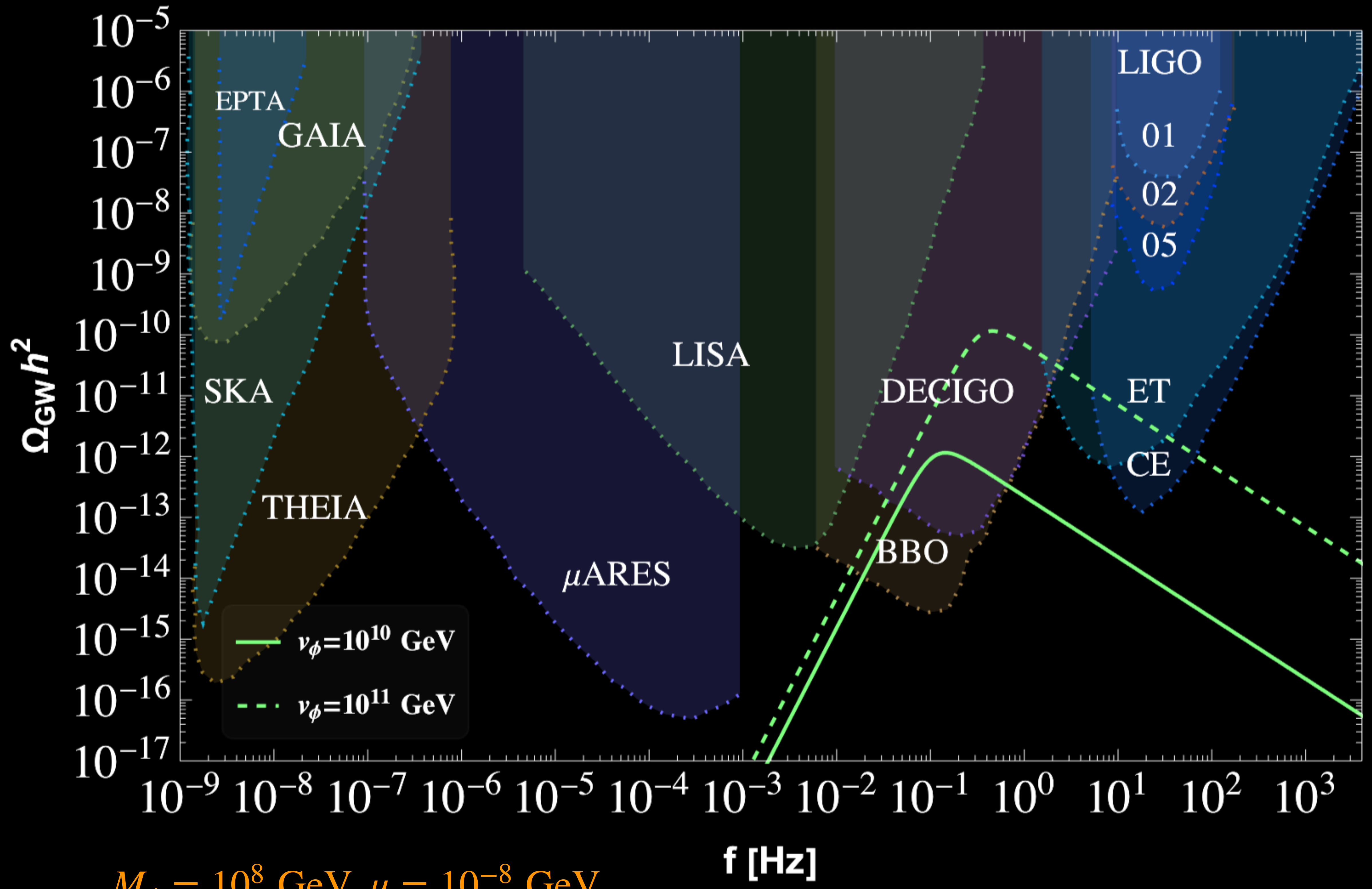
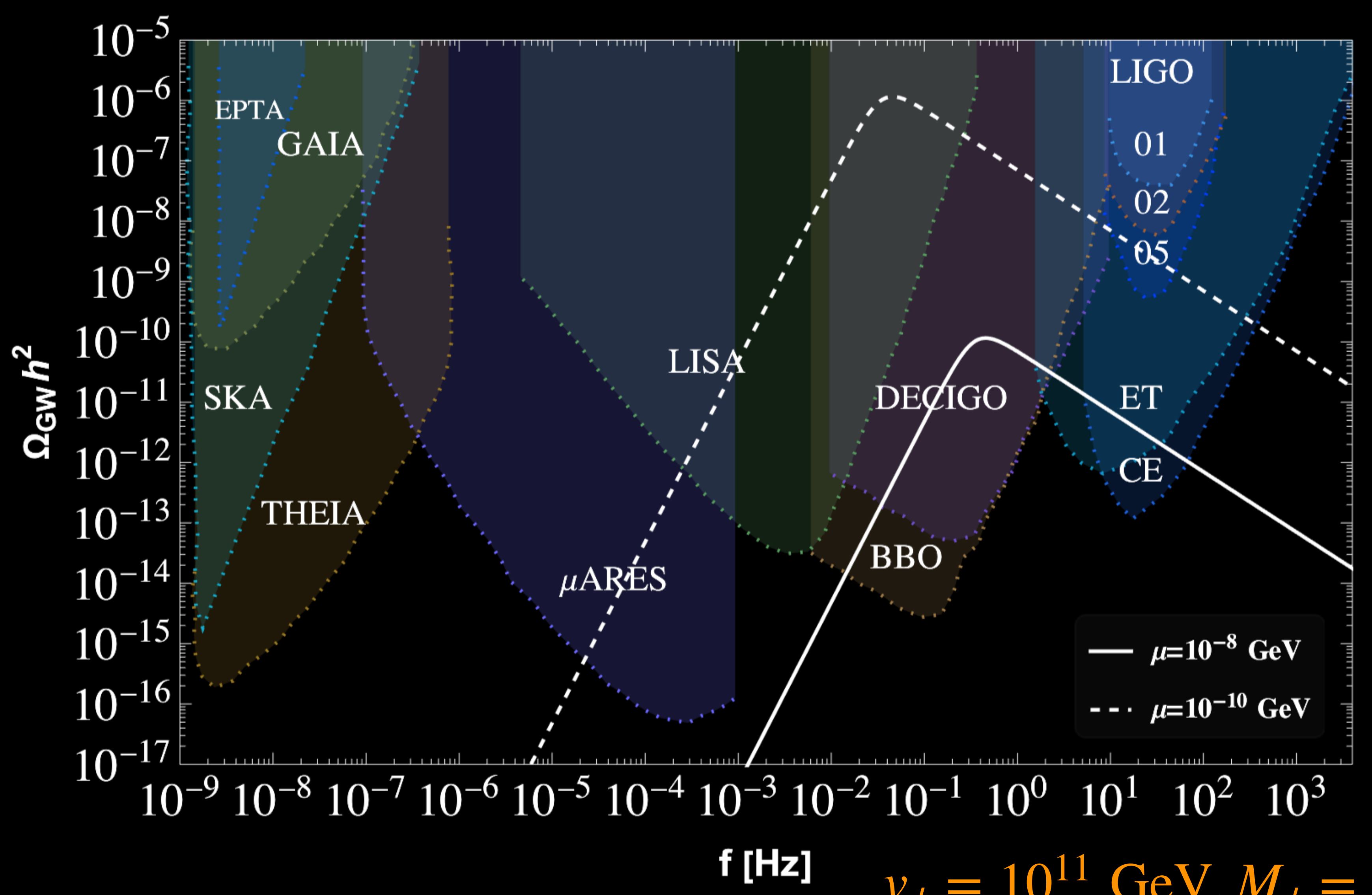
Sakkara (2017); Roshan, White (2024)

Gravitational Waves

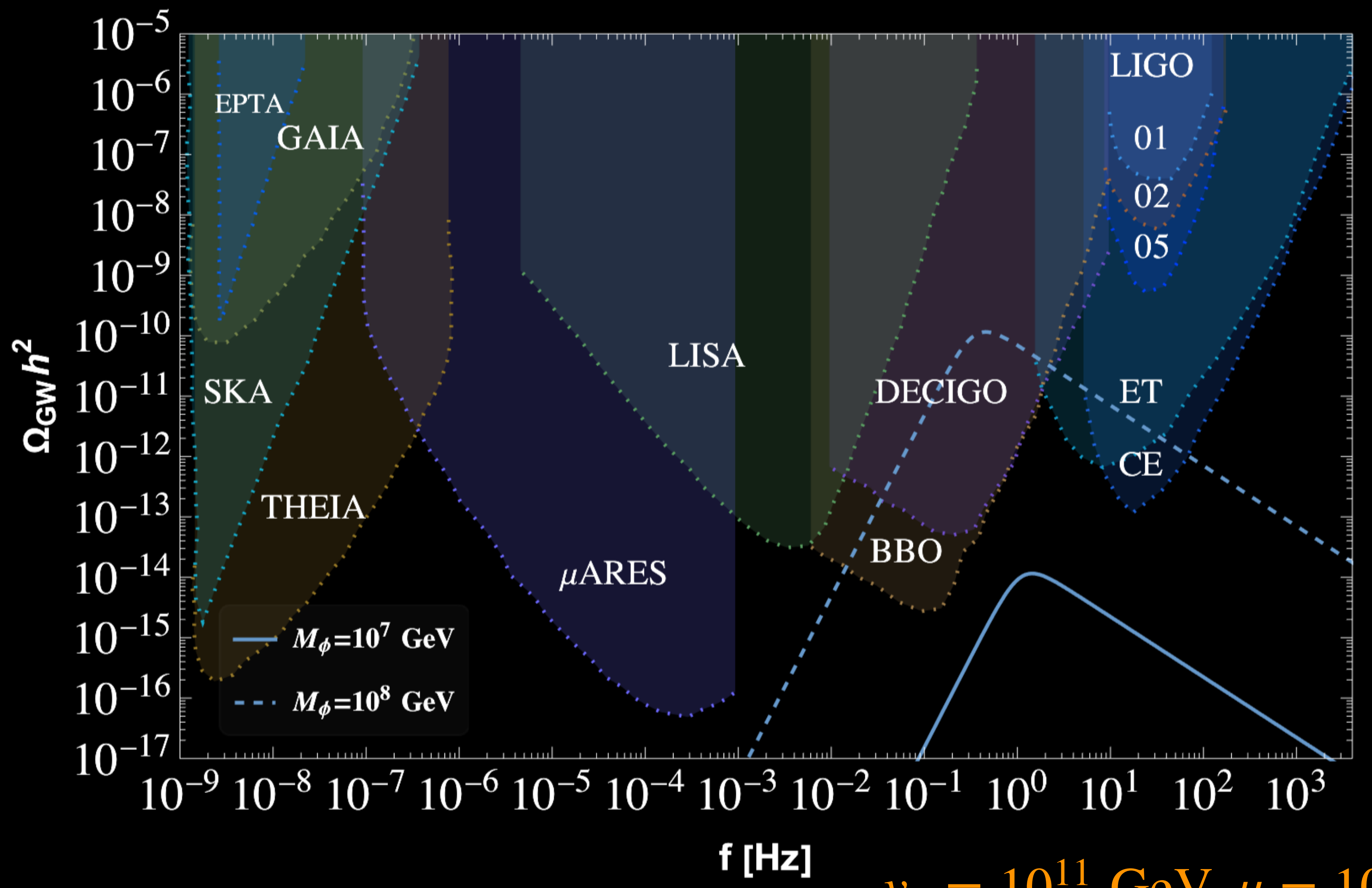
Spectrum



$M_\phi = 10^8$ GeV, $\mu = 10^{-8}$ GeV



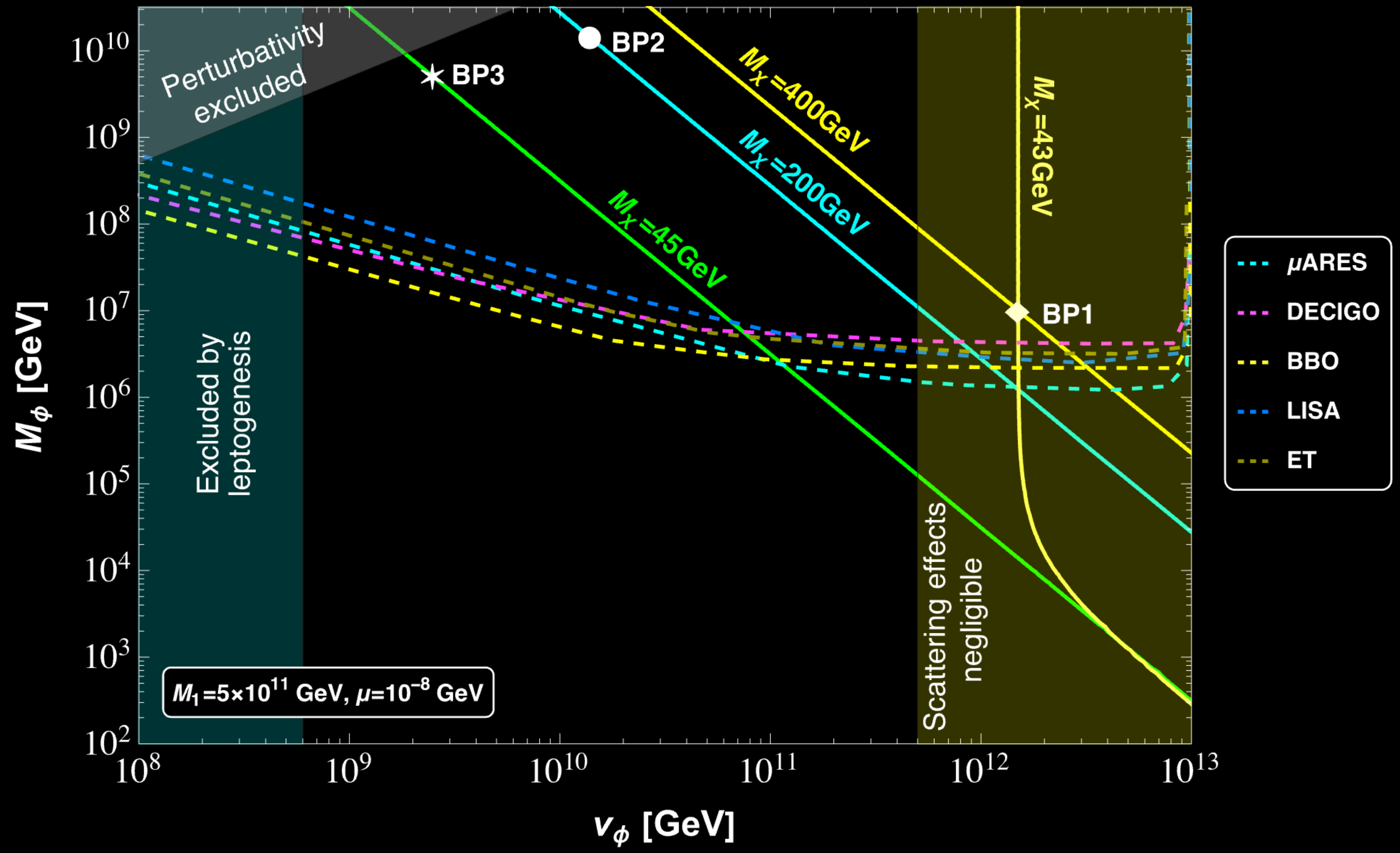
$v_\phi = 10^{11}$ GeV, $M_\phi = 10^8$ GeV



$v_\phi = 10^{11}$ GeV, $\mu = 10^{-8}$ GeV

Wrapping it up

Parameter Space



$\mathbb{Z}_4$ symmetry to connect type-I seesaw and FIMP DM → Requires very large v_ϕ

Effective interaction → New scattering contribution to leptogenesis, more washout

Spontaneous $\mathbb{Z}_4$ breaking → Domain wall problems

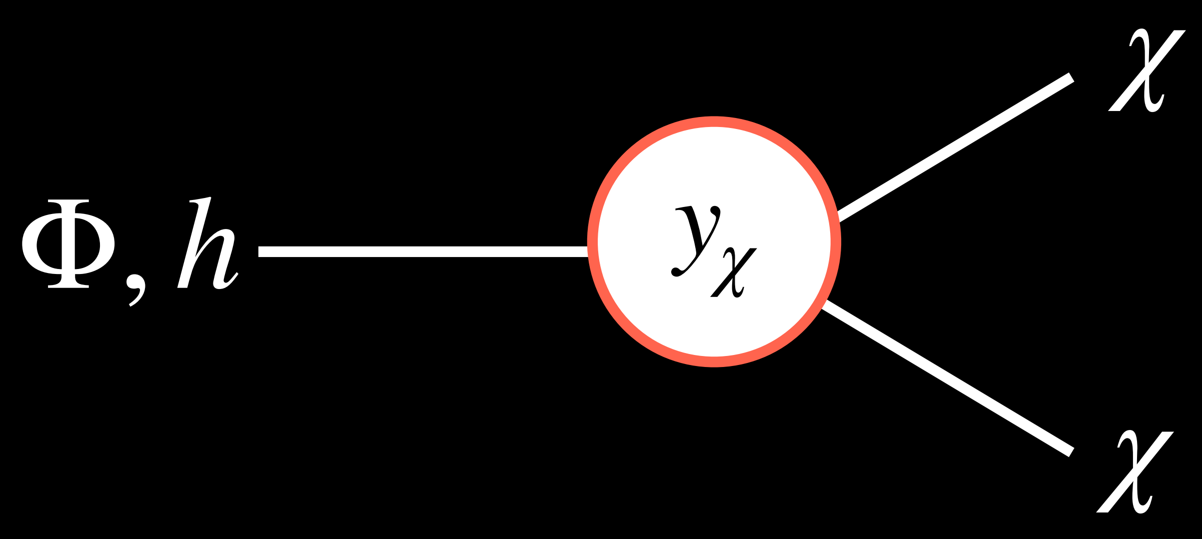
Softly break $\mathbb{Z}_4$ → DWs collapse producing gravitational waves

GW detectors → Probe discrete symmetry breaking scale

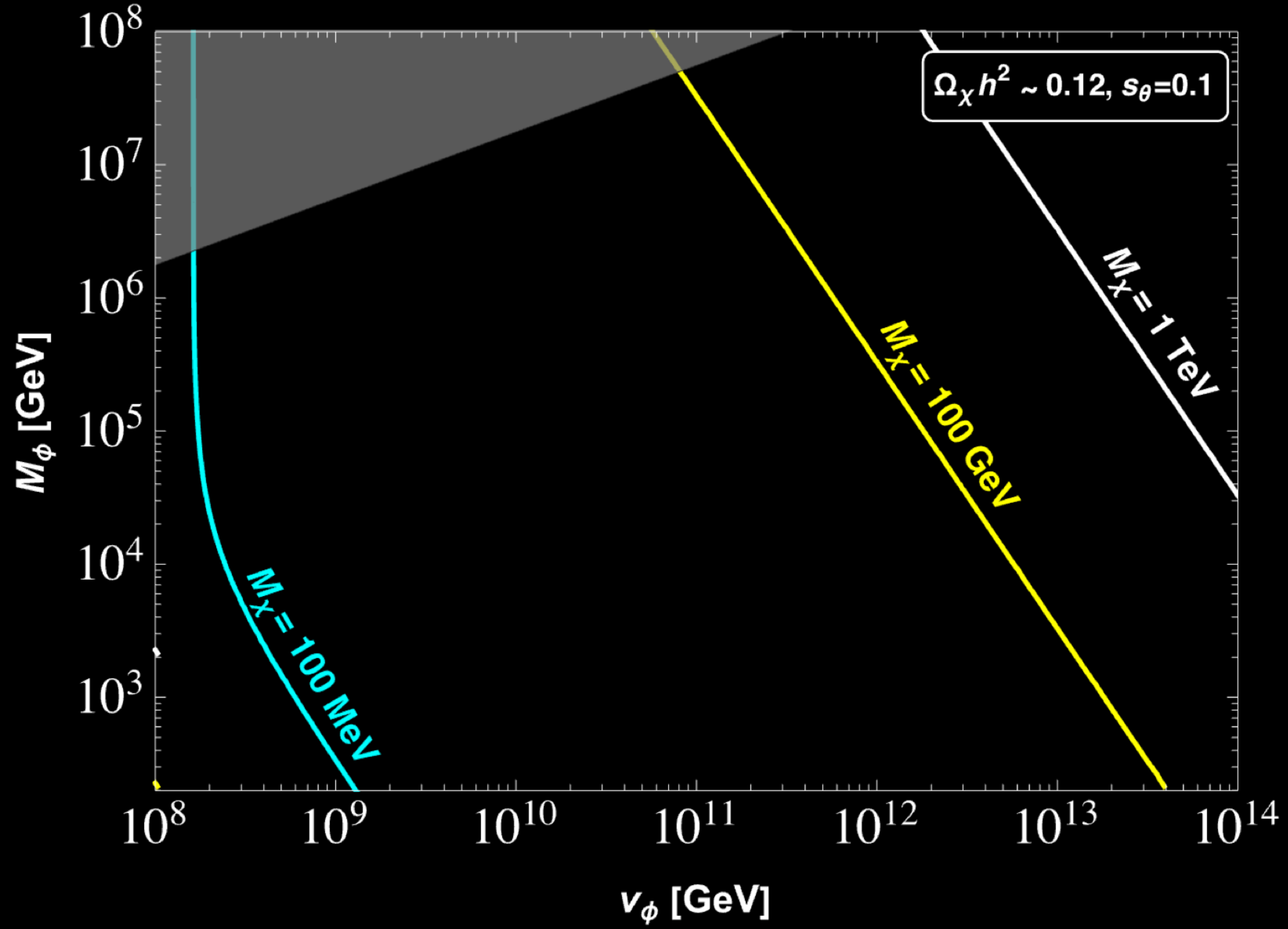
Backup

Dark Matter

Freeze-in



$$\Omega_\chi h^2 \approx 10^{27} \frac{g_\phi}{g_s\sqrt{g_\rho}} \left(\frac{M_\chi}{\text{GeV}}\right) \frac{\Gamma_{\phi\to\chi\chi}}{M_\phi^2}$$



CP Asymmetry

Scattering contribution

$$\gamma(N_i\phi \to lH) = \frac{T}{512\pi^6}\frac{(y_\nu^\dagger y_\nu)_{ii}}{v_\phi^2}\int \mathrm{d}\tilde{s}\, \frac{\sqrt{\lambda(\tilde{s}, M_\phi^2, M_i^2)}/4}{\sqrt{\tilde{s}}}\, K_1\left(\frac{\sqrt{\tilde{s}}}{T}\right)(\tilde{s} + M_i^2 - M_\phi^2)\pi$$

$$\varepsilon_{S_1} = -2\sum_{m\neq 1}\frac{\mathrm{Im}[(y_\nu^\dagger y_\nu)^2_{1m}]}{(y_\nu^\dagger y_\nu)_{11}}\frac{\int \mathrm{d}\tilde{s}\sqrt{\lambda(\tilde{s},\, M_\phi^2,\, M_1^2)}/(4\sqrt{\tilde{s}})\, K_1\left(\sqrt{\tilde{s}}/T\right)\, \int \mathrm{Im}\{\mathscr{A}_0^*\mathscr{A}_1\}d\Omega}{\int \mathrm{d}\tilde{s}\sqrt{\lambda(\tilde{s},\, M_\phi^2,\, M_1^2)}/(4\sqrt{\tilde{s}})\, K_1\left(\sqrt{\tilde{s}}/T\right)\, \int \left|\mathscr{A}_0\right|^2 d\Omega}$$

$$\mathrm{Im}\{\mathscr{A}_0^*\mathscr{A}_1\} = -\frac{M_i^2}{32\pi}\sqrt{x}\,\left\{1 - (1+x')\ln\left[\frac{1+x'}{x'}\right]\right\} - \frac{\tilde{s}}{64\pi}\left(\frac{\sqrt{x}}{1-x}\right)$$

$$\left|\mathscr{A}_0\right|^2 = (M_i^2 - M_\phi^2 + \tilde{s})/4$$