DARK ECHOES: FROM COLLIDER TO GRAVITATIONAL WAVES OBSERVABLES

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Fundação para a Ciência e a Tecnologia

universidade de aveiro theoria poiesis praxis

CIDMA

The SM is a tremendously successful theory that explains "boringly" well most its predictions!

However, it fails to…

- Explain neutrino masses
- Explain dark matter
- Explain CP violation and matter/anti-matter assymetry
- Explain the observed flavour structure - Flavour puzzles
- Suffers from the Higgs mass *hierarchy problem*

Current and future experimental facilities will offer new channels to search for New Physics Phenomena

LHC and future colliders

LISA and future GW observatories ⟶ Stochastic gravitational waves background (SGWB)

SGWB

✓ Superposition of unresolved astrophysical sources

✓ Cosmological origin

- ◉ Inflation
- ◉ Topological defects
- ◉ Phase transitions

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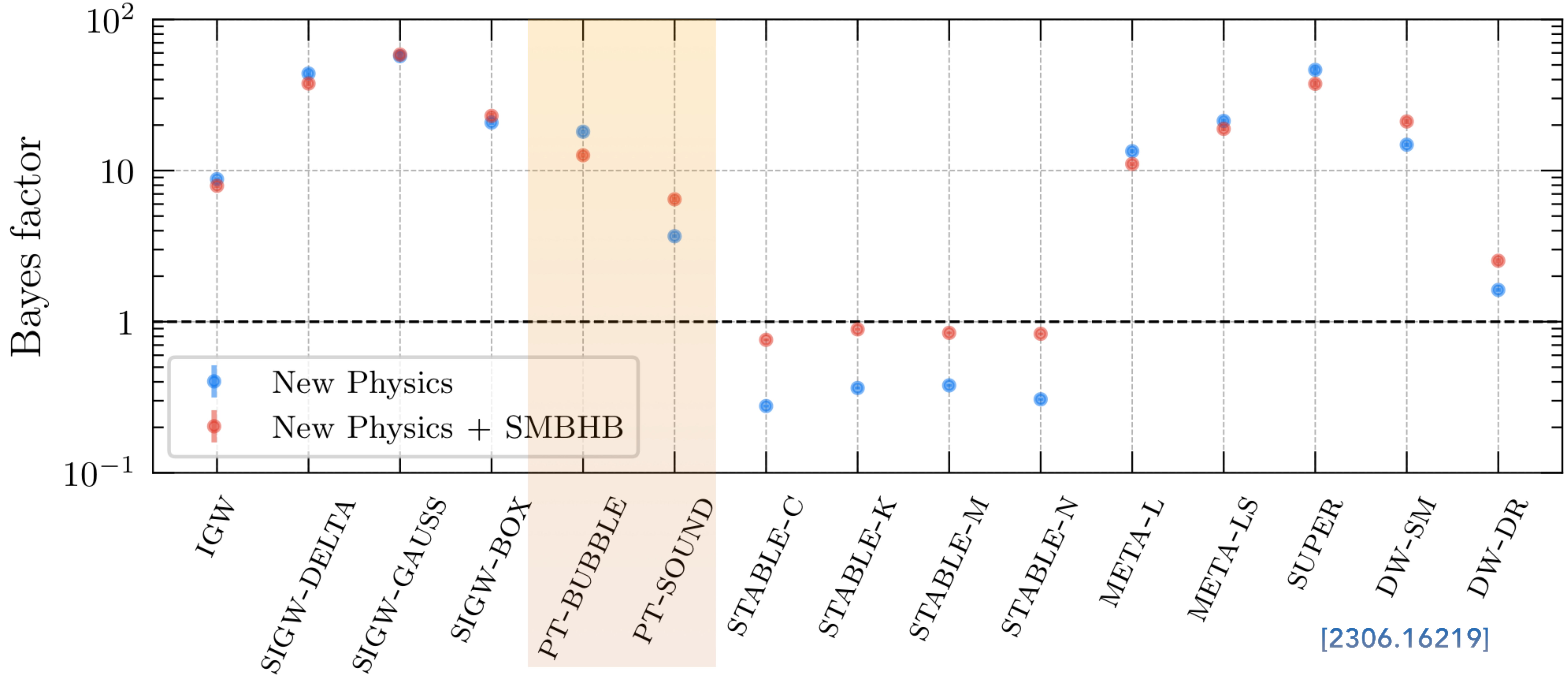
A SGWB detection can represent the first direct measurement of the Universe prior to the BBN era, a breakthrough comparable to the discovery of the CMB

NANOGrav 15-year New-Physics Signals [2306.16213]



[2306.16219]

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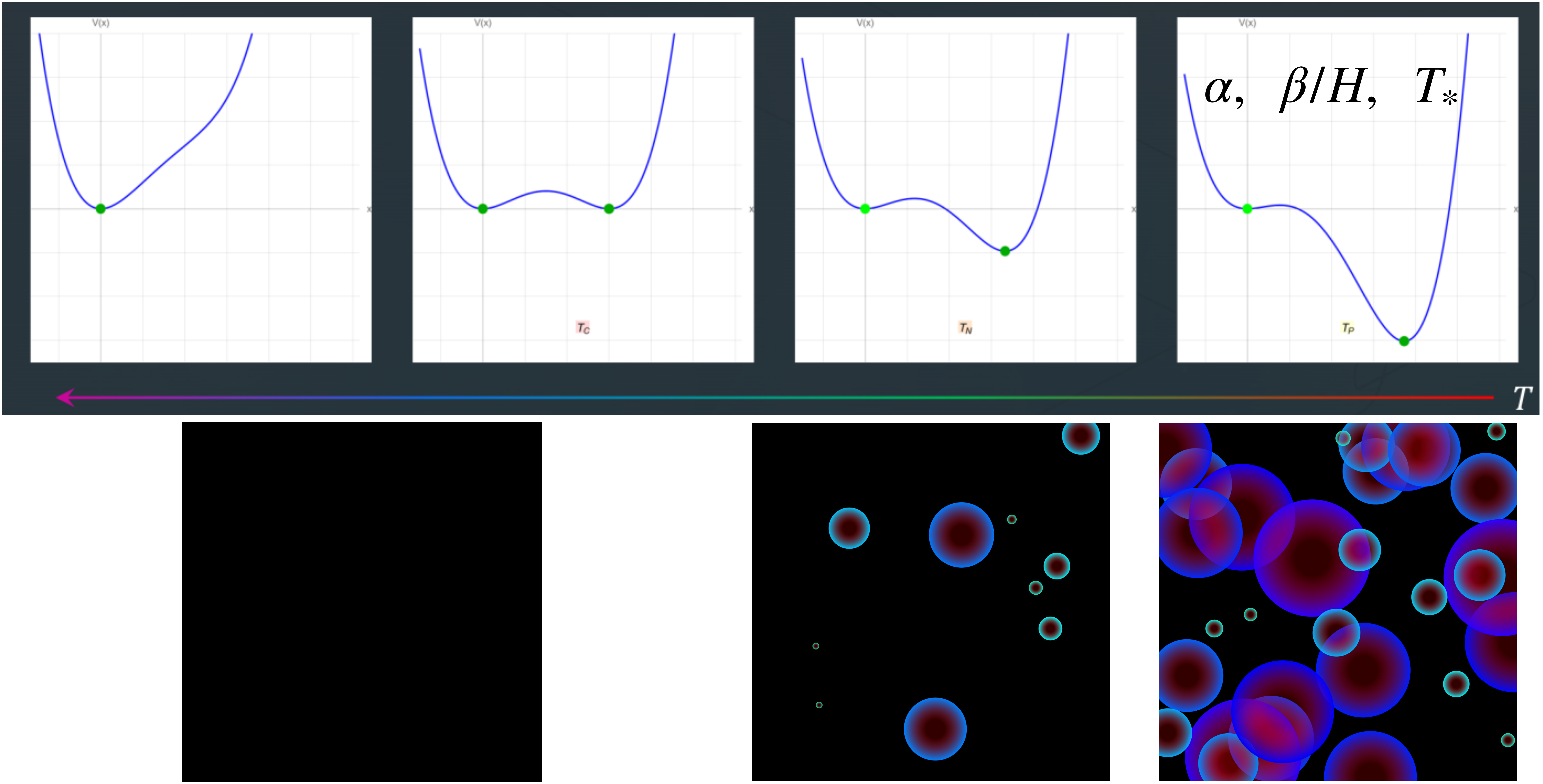
First order phase transition (FOPT)

(Illustration)



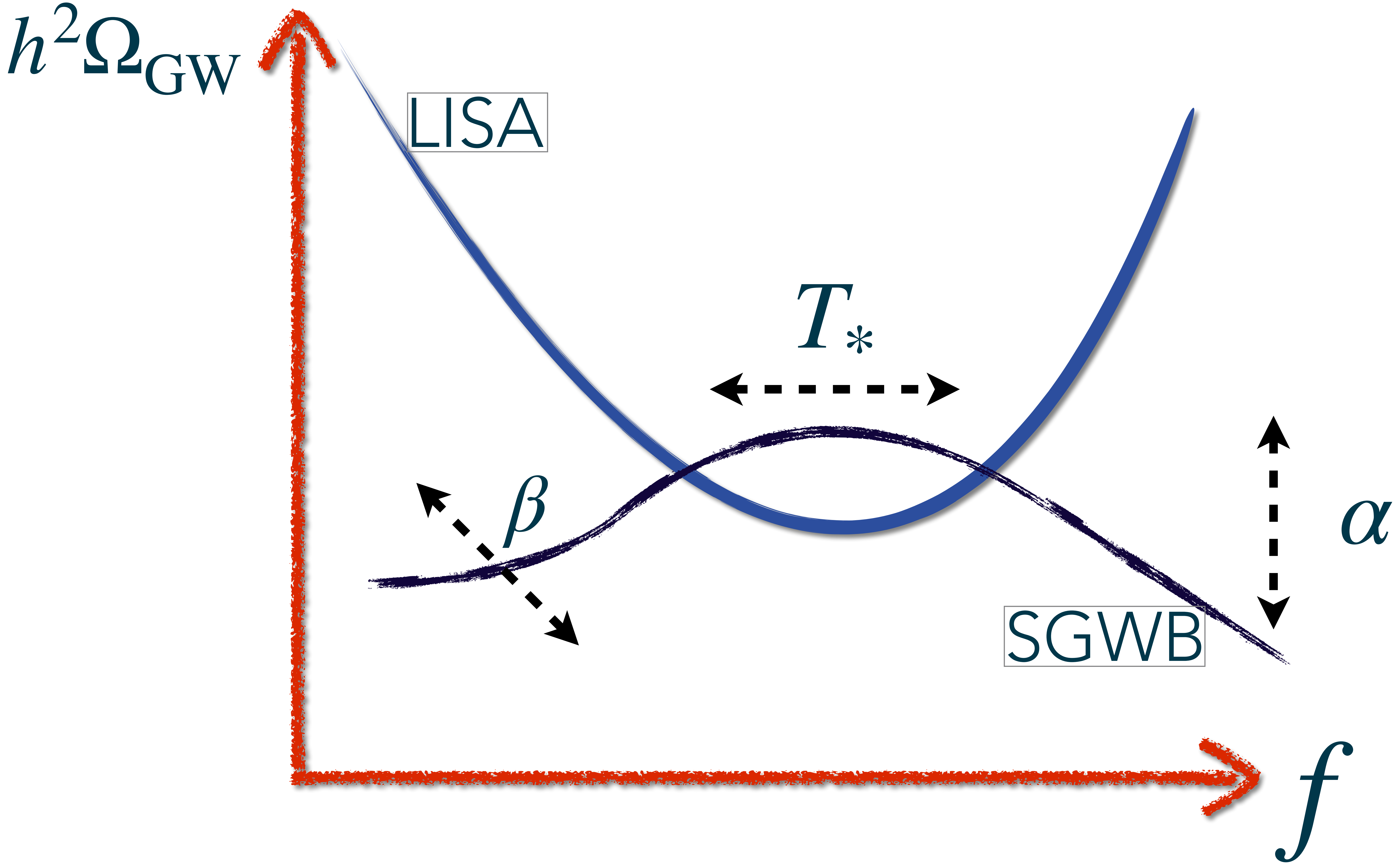
Strength
α

Inverse duration
β/H

Percolation temperature
T_*

Credit: Marco Finetti

Effect of the thermodynamic parameters on the SGWB



Case study: A non-abelian $\mathrm{SU(2)_D}$ vector dark matter model

[OUT SOON] BELYAEV, BERTENSTAM, GONÇALVES, APM, PASECHNIK, THONGYOI

[*Fermionic portal to vector dark matter from a new gauge sector*: Belyaev, Dandrea, Moretti, Panizzi, Ross, Thongyuoi, PRD 108 (2023) no. 9 095001, 2204.03510]

[*A fermion portal to a non-abelian dark sector*: Belyaev, Dandrea, Moretti, Panizzi, Ross, Thongyuoi, Front.in.Phys. 12 (2024) 1339886, 2203.04681]

$$\mathcal{L}_0 = -\frac{1}{4}(V^a_{\mu\nu})^2 + |D\mu\Phi_D|^2 - \mu_D^2\Phi_D^\dagger\Phi_D - \lambda_D(\Phi_D^\dagger\Phi_D)^2$$

Secluded sector

$$\mathcal{L}_{\rm I} = \mathcal{L}_0 - \frac{1}{4}(V^i_{\mu\nu})^2|_{B,W^i,G^i} + \bar{f}^{\rm SM} i\not{D} f^{\rm SM} + |D_\mu\Phi_H|^2 - \mu_H^2(\Phi_H^\dagger\Phi_H)^2 - \lambda_H(\Phi_H^\dagger\Phi_H)^2 - (y\bar{f}_L^{\rm SM}\Phi_H f_R^{\rm SM} + {\rm H.c.})\,.$$

Visible sector

$$\mathcal{L}_{\rm II} = \mathcal{L}_0 + \mathcal{L}_{\rm I} - \lambda_{HD}(\Phi_H^\dagger\Phi_H)(\Phi_D^\dagger\Phi_D) - (y'\bar{\Psi}_L\Phi_D f_R^{\rm SM} + {\rm H.c.}) - m_{f_D}\bar{\Psi}\Psi$$

Fermion and Higgs portals

Vector -like Fermion Mediator

$$\Psi = \begin{pmatrix} f_D \\ \psi \end{pmatrix}$$

Dark Matter

$$V_\mu^D = \begin{pmatrix} V_\mu^+ \\ V_\mu^0 \\ V_\mu^- \end{pmatrix}$$

$$m_{V^\pm} = g_D\frac{v_D}{2}$$

$$\Phi_H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \longrightarrow \langle\Phi_H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad (\text{breaking } SU(2)_L \times U(1)_Y \to U(1)_Q)\,,$$

$$\Phi_D = \begin{pmatrix} H_D^+ \\ H_D^0 \end{pmatrix} \longrightarrow \langle\Phi_D\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_D \end{pmatrix} \qquad (\text{breaking } SU(2)_D \times U(1)_{Y_D} \to U(1)_{Q_D})$$

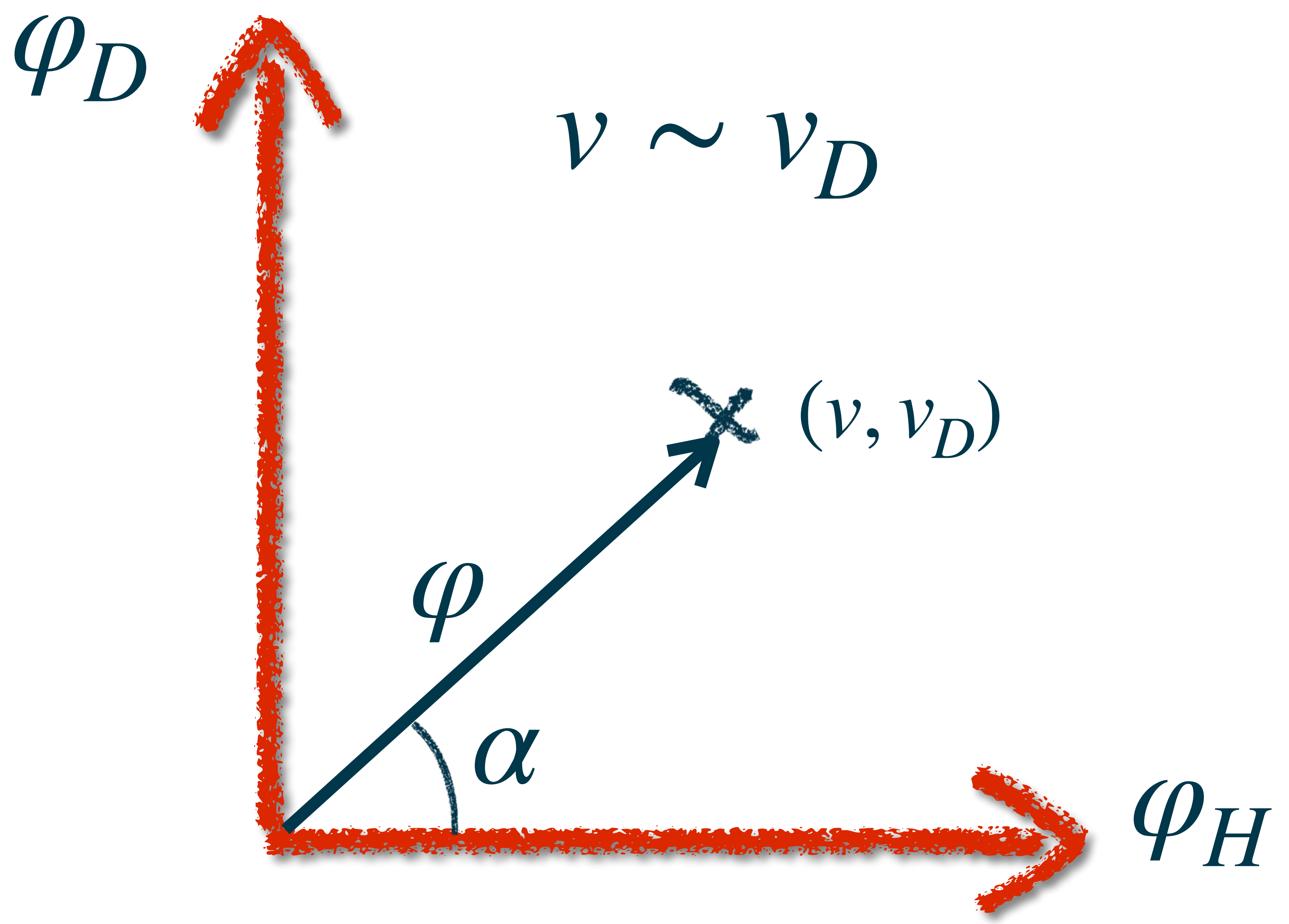
Scenario I: Completely decoupled dark sector

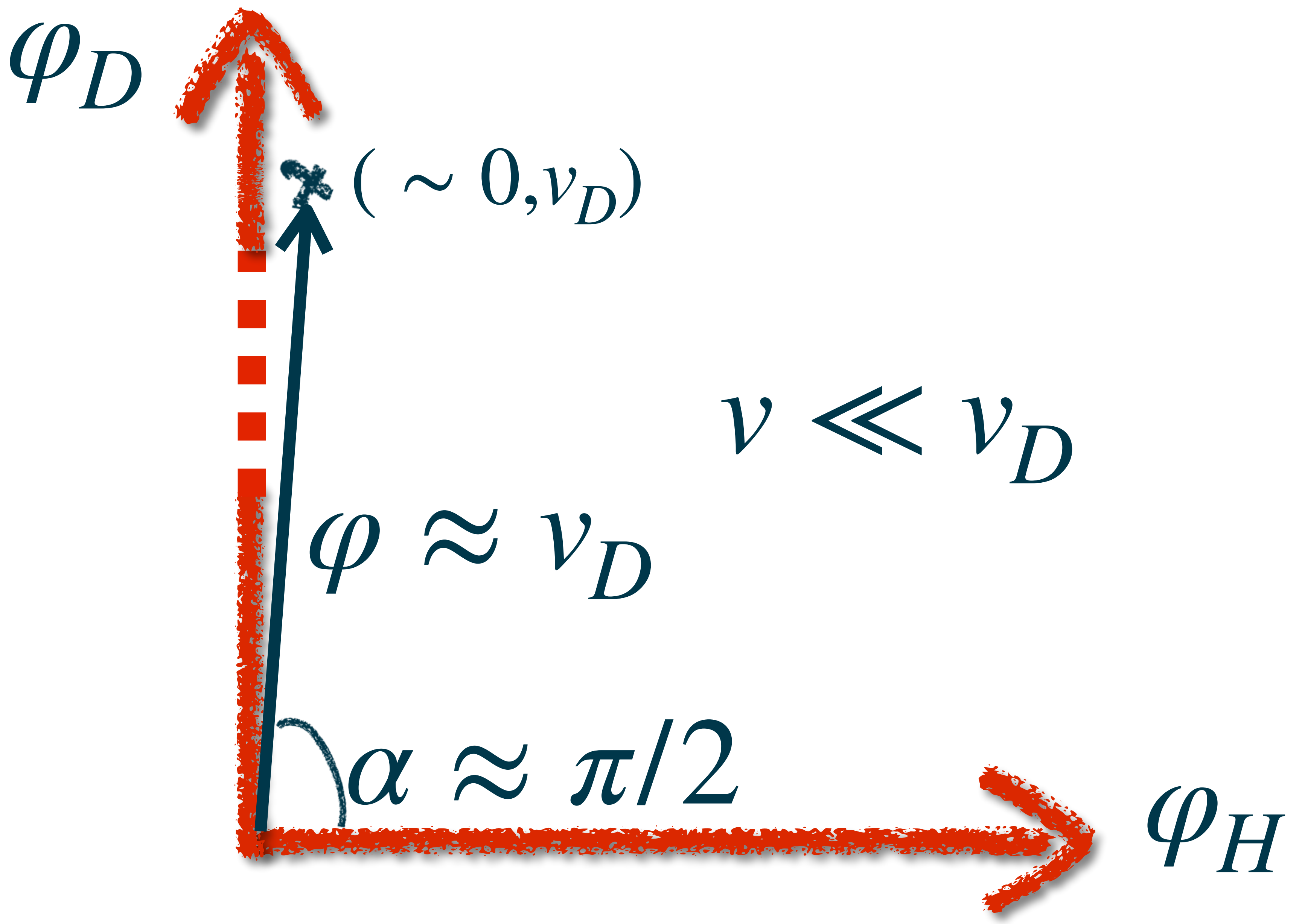
$$\mathcal{L}_0 = -\frac{1}{4}(V^a_{\mu\nu})^2 + |D\mu\Phi_D|^2 - \mu_D^2\Phi_D^\dagger\Phi_D - \lambda_D(\Phi_D^\dagger\Phi_D)^2$$

Secluded sector

$$\mathcal{L}_\mathrm{I} = \mathcal{L}_0 - \frac{1}{4}(V^i_{\mu\nu})^2|_{B,W^i,G^i} + \bar{f}^{\mathrm{SM}} i\not{D} f^{\mathrm{SM}} + |D_\mu\Phi_H|^2 - \mu_H^2(\Phi_H^\dagger\Phi_H)^2 - \lambda_H(\Phi_H^\dagger\Phi_H)^2 - (y\bar{f}_L^{\mathrm{SM}}\Phi_H f_R^{\mathrm{SM}} + \mathrm{H.c.})\,.$$

Visible sector





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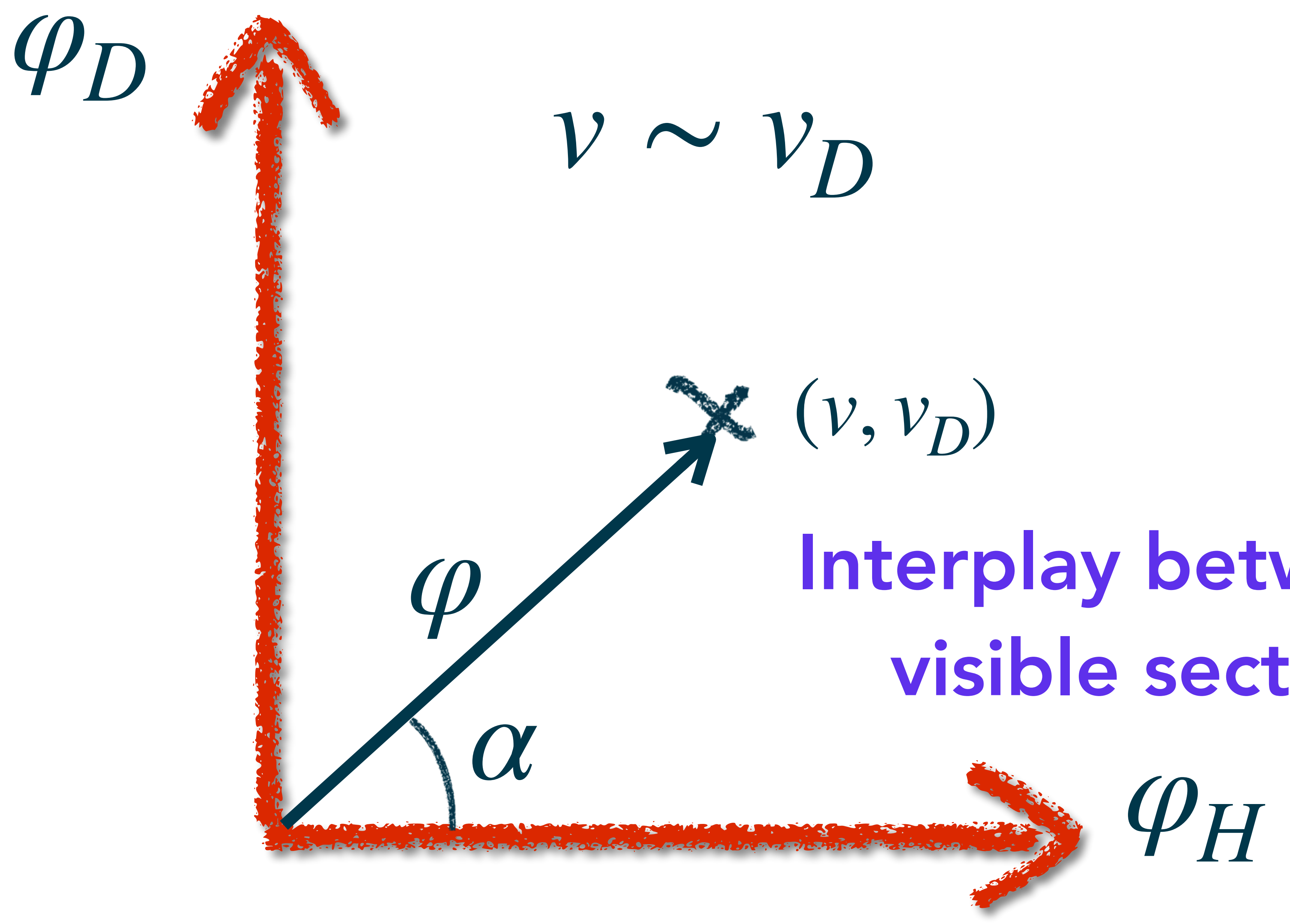
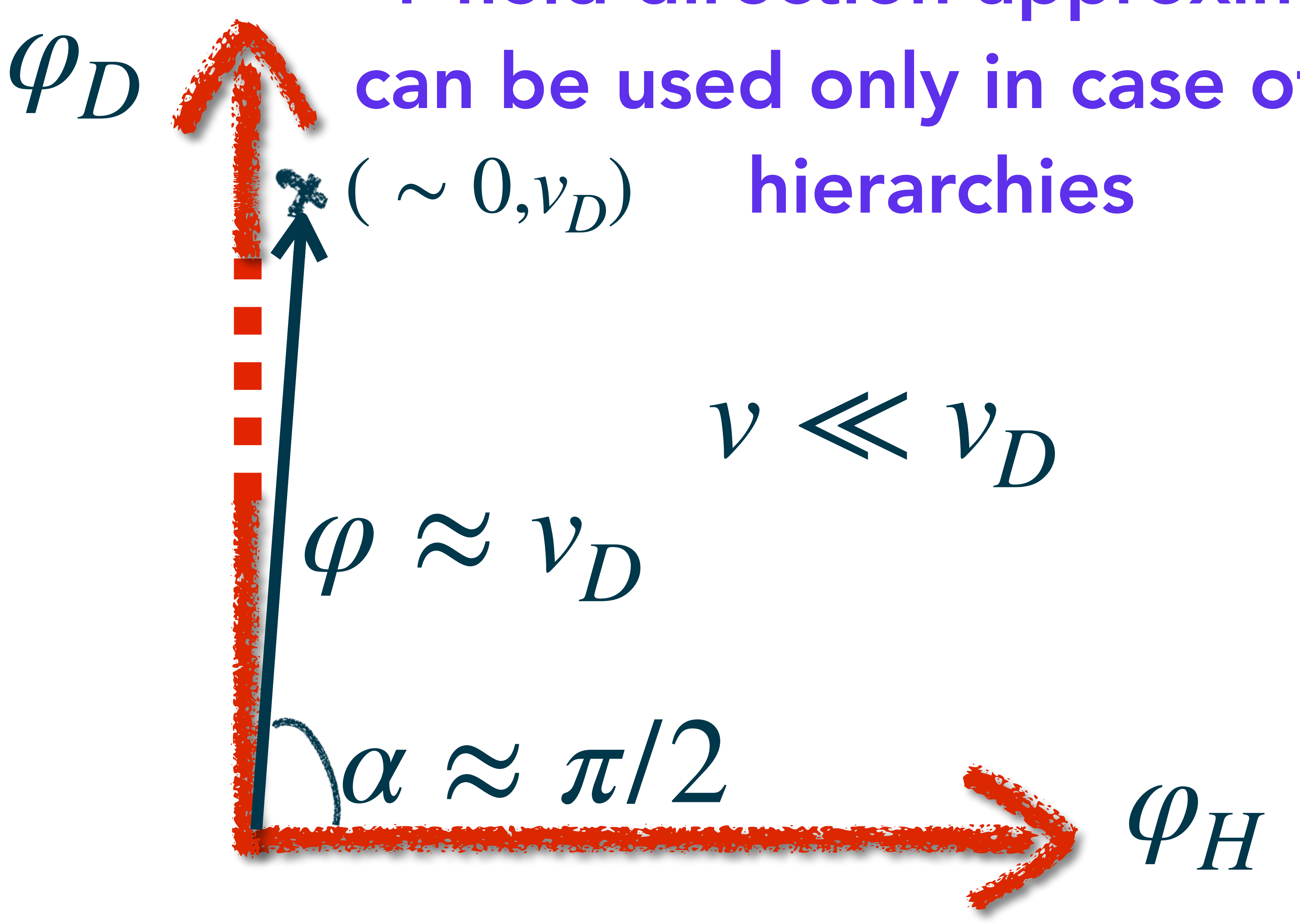
Visible sector

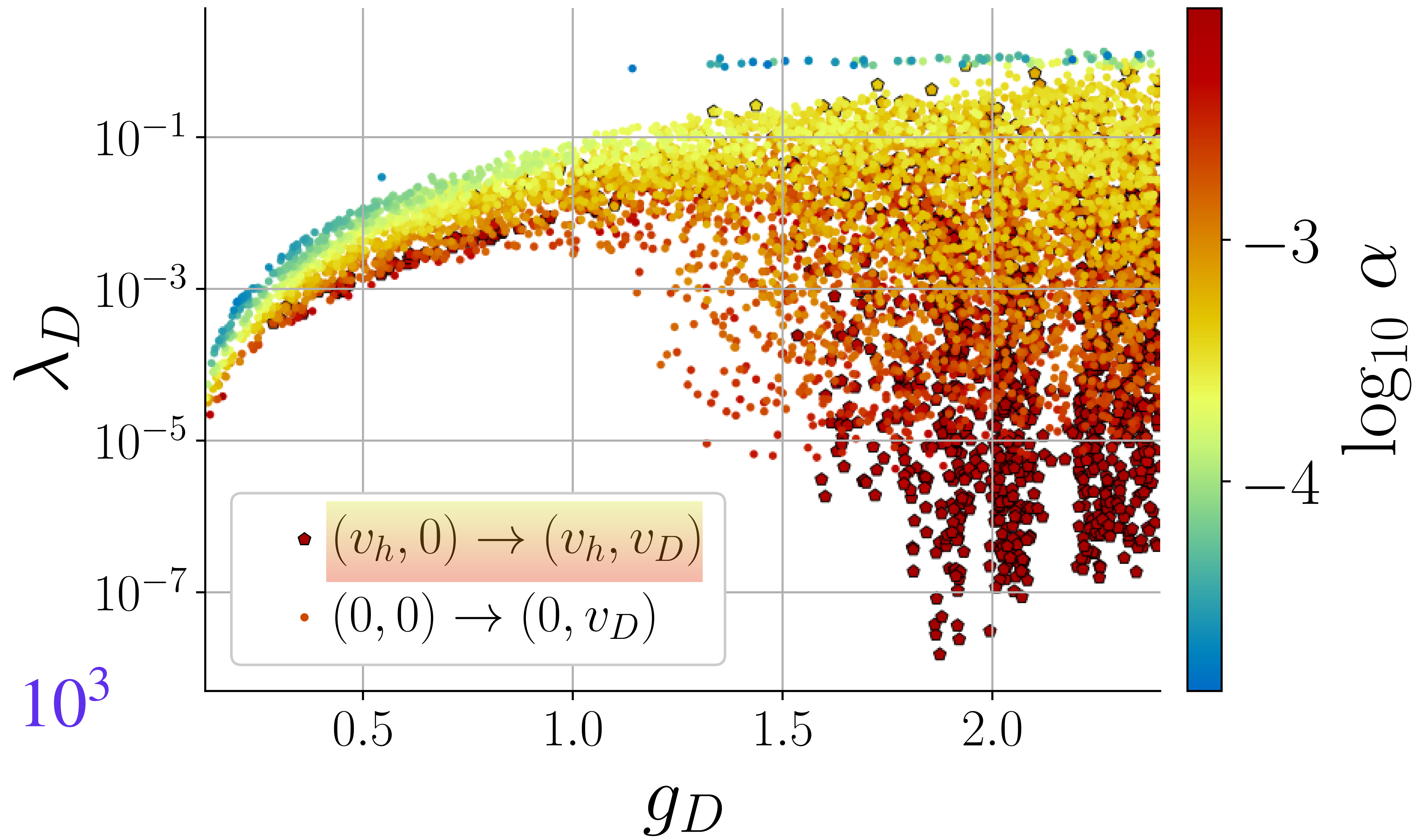


Interplay between dark and visible sectors in FOPT



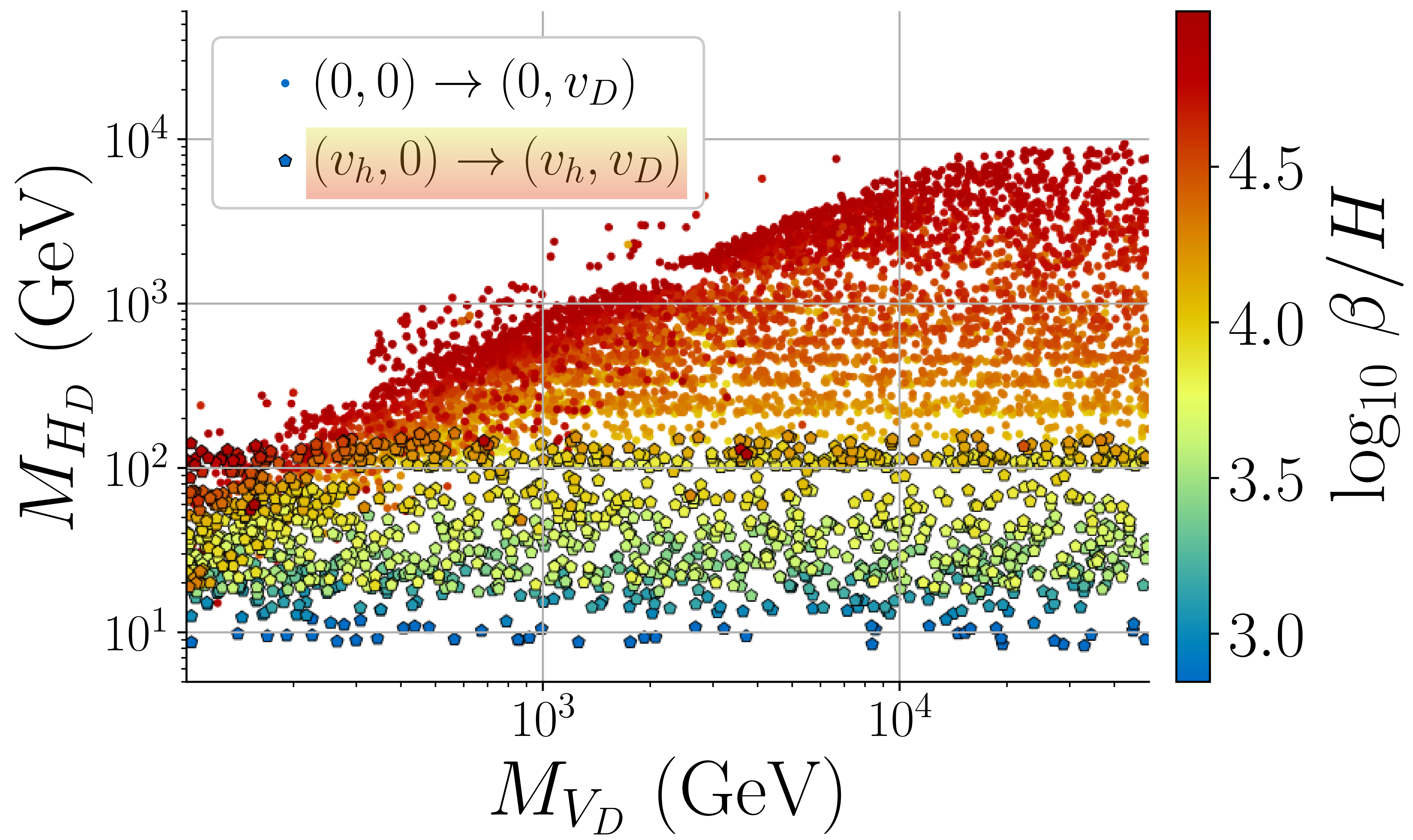
1-field direction approximation can be used only in case of large hierarchies

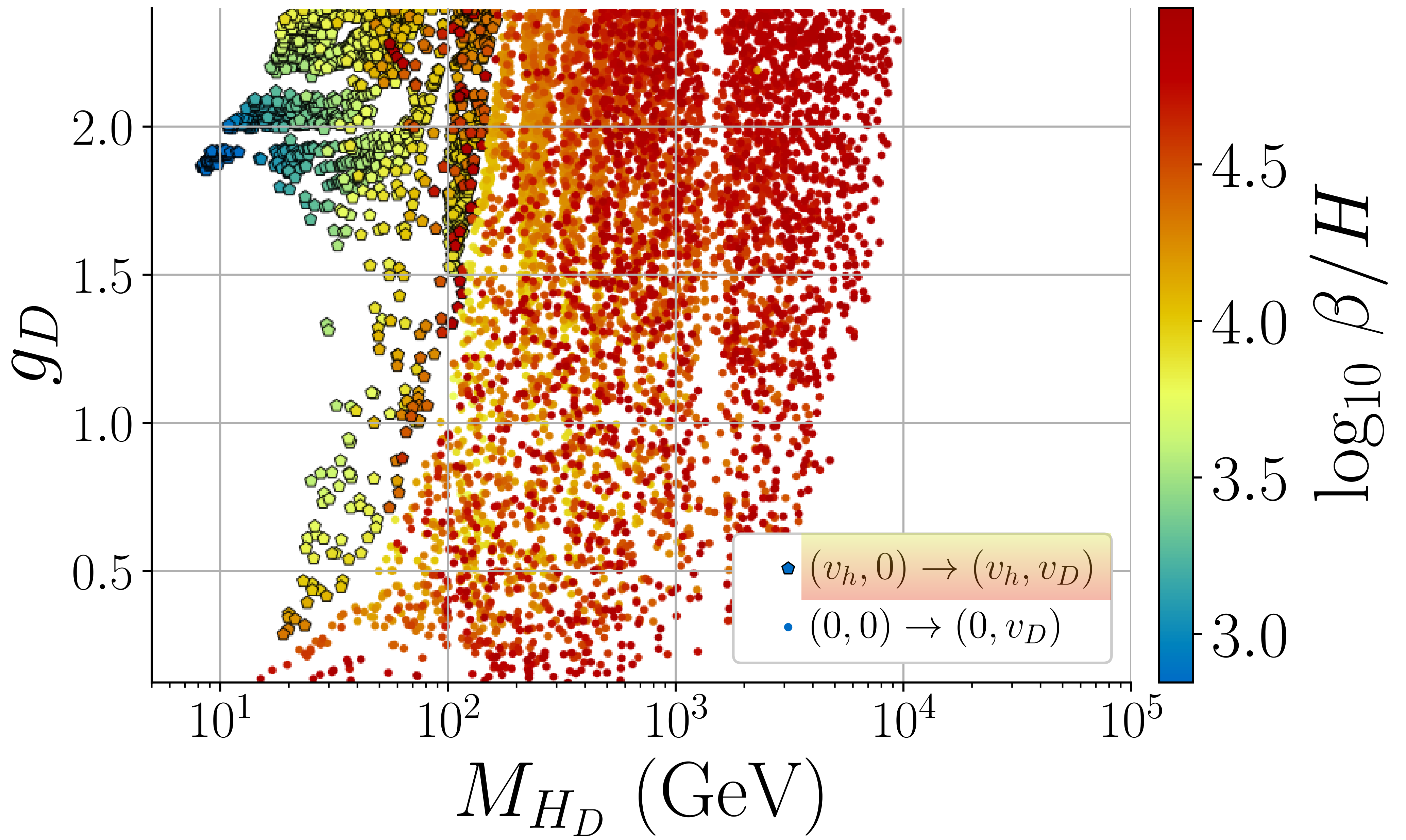
Parameter space scans for $\lambda_{HD} = y' = 0$



Observable SGWB for:

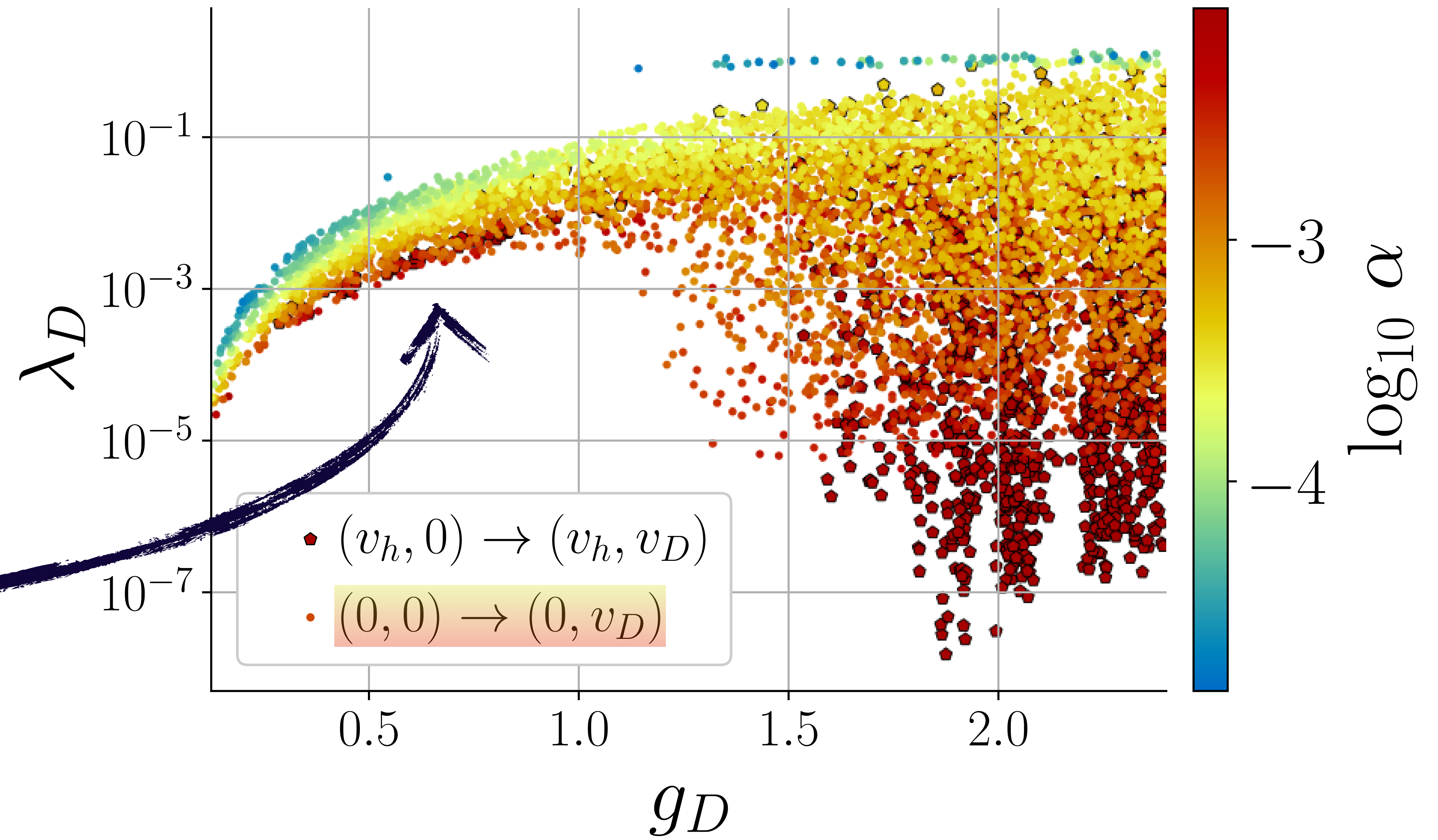
$M_{H_D} \sim \mathcal{O}(10\text{ GeV})$ $\quad g_D \approx 1.8$ $\quad \alpha \approx 10^{-2}$ $\quad \beta/H \lesssim 10^3$

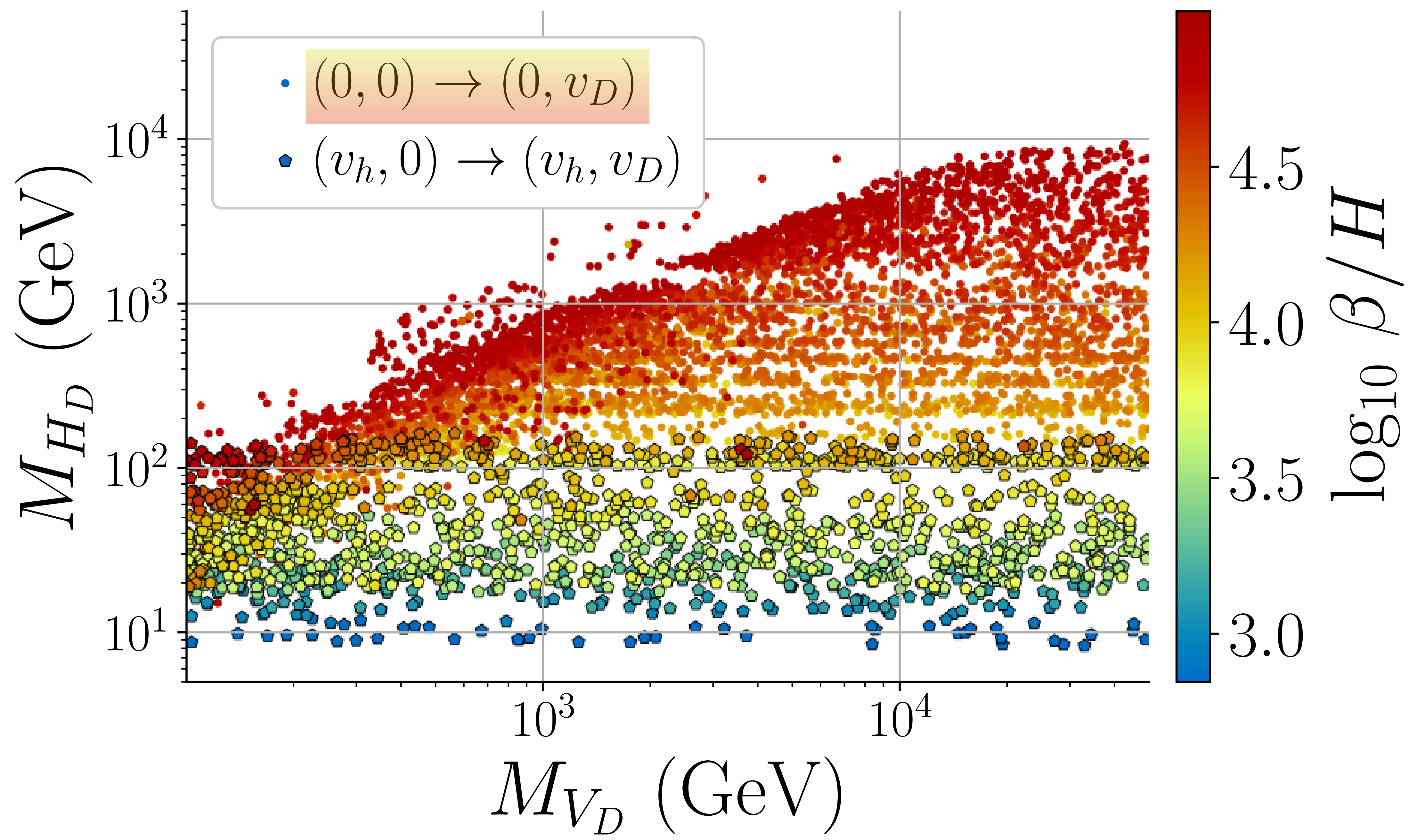


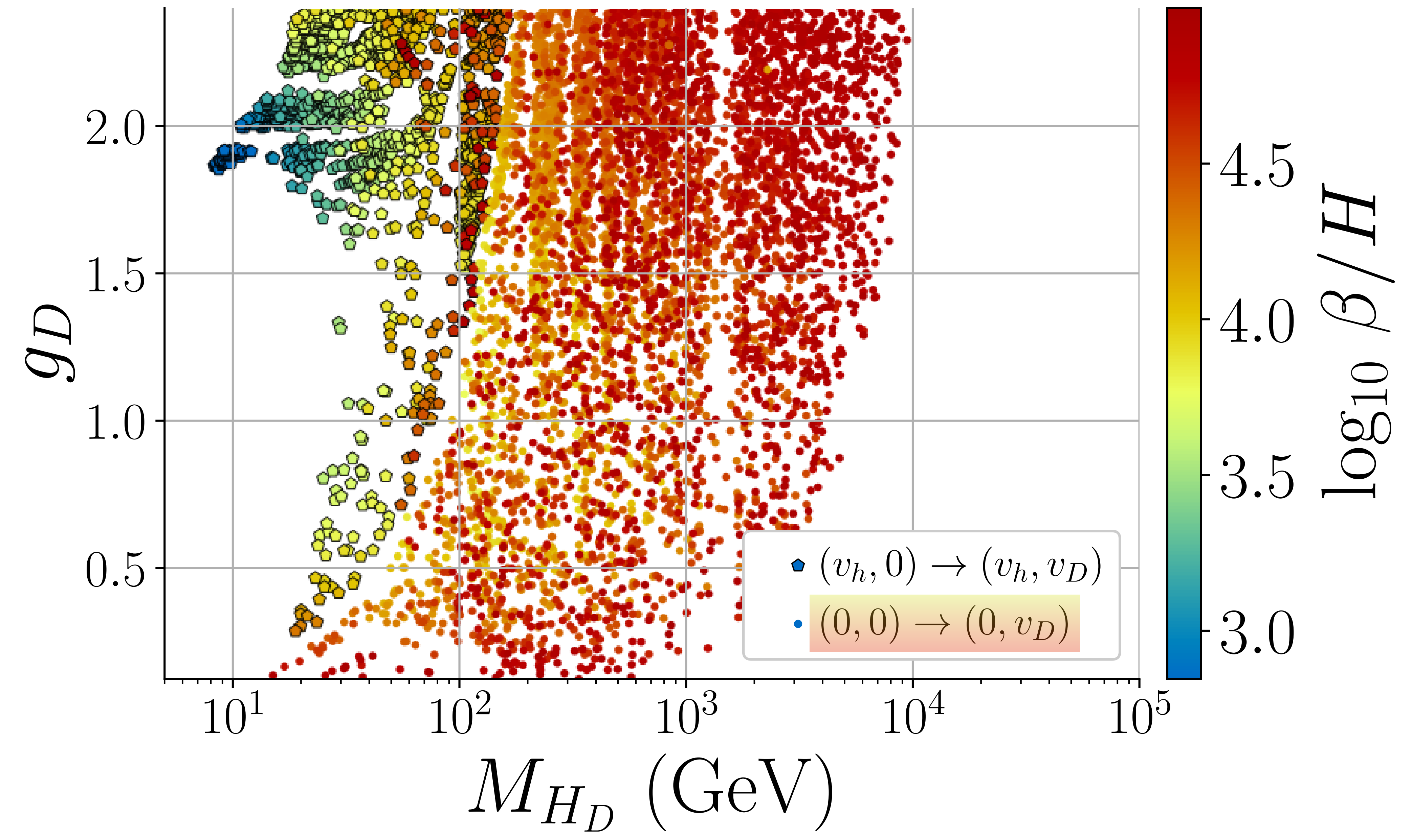


Parameter space scans for $\lambda_{HD} = y' = 0$

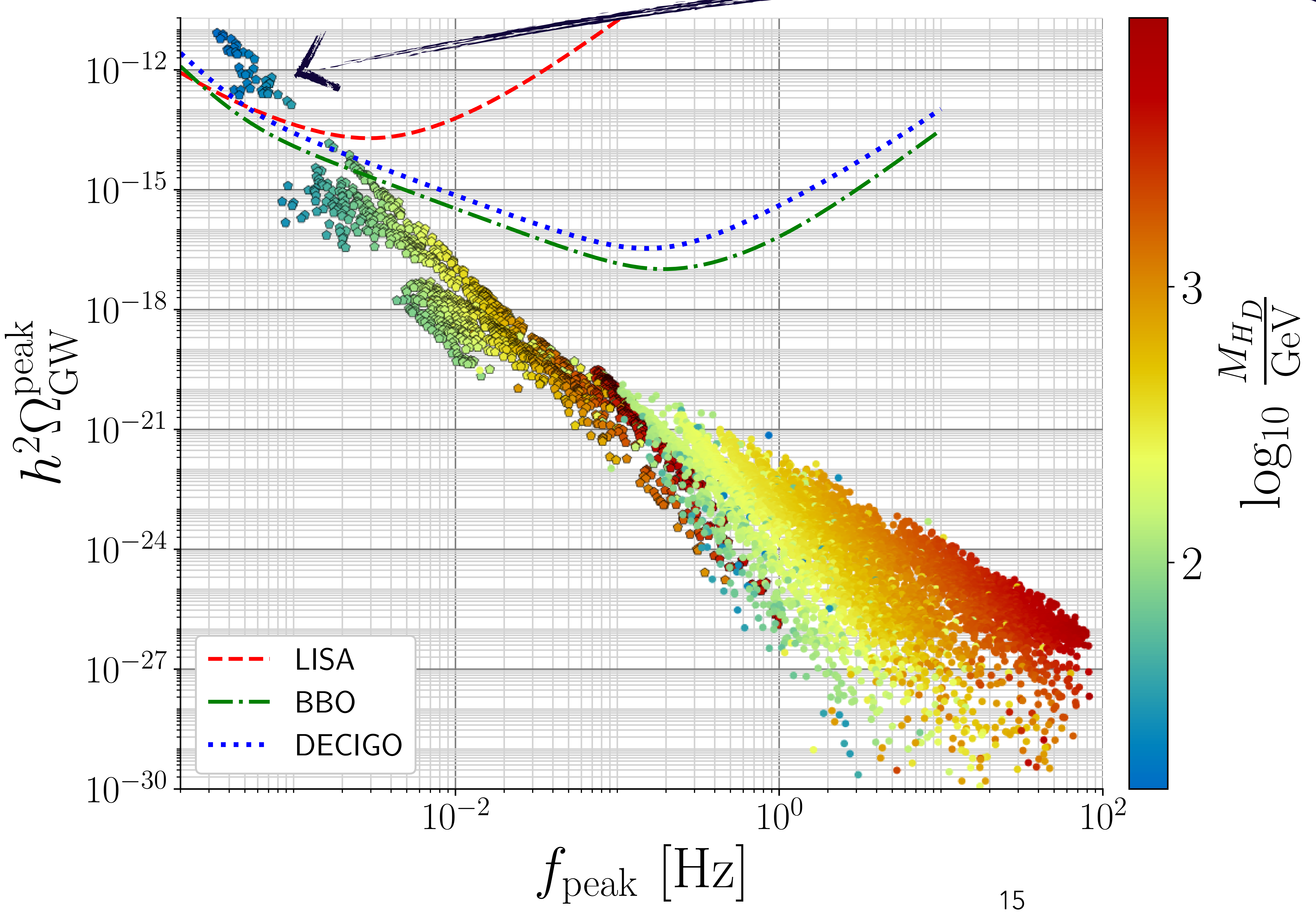
Dark sector FOPT are stronger for larger $\frac{g_D^3}{\lambda_D}$







LISA, BBO and DECIGO peak integrated sensitivity curves



Observable SGWB for dark Higgs mass smaller than 100 GeV and SNR up to 80 at LISA

[K. Schmitz, JHEP 01 (2021 097), 2002.04615]

Scenario II: Include fermion and Higgs portals

$$\mathcal{L}_{\rm II} = \mathcal{L}_0 + \mathcal{L}_{\rm I} - \lambda_{HD}(\Phi_H^\dagger \Phi_H)(\Phi_D^\dagger \Phi_D) - (y' \bar{\Psi}_L \Phi_D f_R^{\rm SM} + {\rm H.c.}) - m_{f_D} \bar{\Psi}\Psi$$

Fermion and Higgs portals

M_{V_D} (GeV)	M_{H_D} (GeV)	g_D	m_{f_D} (GeV)	m_F (GeV)	$\sin\theta_S$	
$[10, 10\ 000]$	$[10^{-3}, 10\ 000]$	$[10^{-8}, 4\pi]$	$[1500, 5000]$	$[1500, 10\ 000]$	$[-0.2, 0.2]$	$\lambda_H,\ \lambda_D,\ \lambda_{HD}$ $v_D = 2M_{V_D}/g_D$ $\mu_H^2,\ \mu_D^2$ $y_t,\ y'$

Scenario II: Include fermion and Higgs portals

Explanation of DM and observability of SGWB (LISA and/or future facilities)

Sensitivity of colliders to the scalar potential

$-0.2 < \kappa_{hhh}^{\mathrm{HL-LHC}} < 2.6$

$0.7 < \kappa_{hhh}^{\mathrm{HE-LHC}} < 1.3$

LHC data will further constrain the available parameter space with possible impact on SGWB predictions

Take home message

1. SGWB from dark SU(2) gauge theory are explored.

2. We have studied both Higgs and VL fermion portals for the dark SU(2) sector and their impact on FOPT.

    (i) Dark SU(2) with fermion and Higgs portal can successfully explain DM and provide observable SGWB.

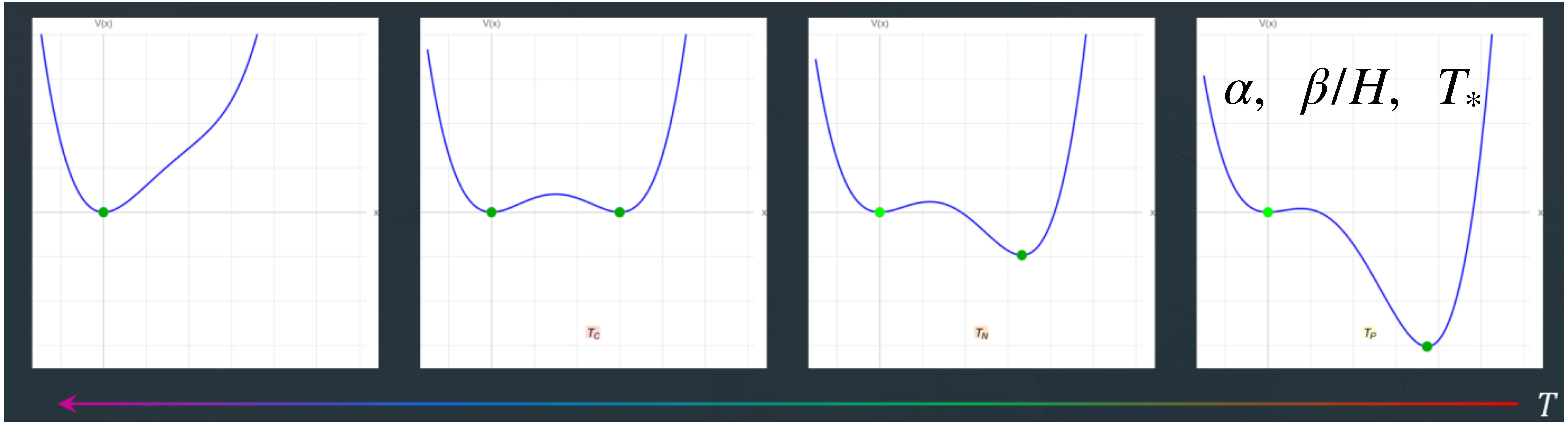
    (ii) There is an interplay between the dark and visible sectors with observable SGWB even in the absence of portals.

3. Combination with collider observables for complementary tests on the scalar sector (trilinear Higgs coupling, new scalars, mixing angles).

THANK YOU

First order phase transition (FOPT)

(Illustration)



Strength and duration of the PT

$$\alpha = \frac{1}{\rho_\gamma}\left(\Delta V - \frac{T}{4}\frac{\partial \Delta V}{\partial T}\right)\Bigg|_{T=T_*} \qquad \frac{\beta}{H} = T_* \frac{\partial}{\partial T}\left(\frac{\hat{S}_3}{T}\right)\Bigg|_{T_*}$$

$$\hat{S}_3(\hat{\phi}, T) = 4\pi \int_0^\infty \mathrm{d}r\, r^2 \left\{ \frac{1}{2}\left(\frac{\mathrm{d}\hat{\phi}}{\mathrm{d}r}\right)^2 + V_{\text{eff}}(\hat{\phi}, T) \right\}$$

$$H(T) = \frac{1}{3\overline{M}_P}\left(\rho_\gamma + \Delta V(T)\right) \quad , \quad \rho_\gamma = g^*(T)\frac{\pi^2}{30}T^4$$

Dimensional reduction

Improved calculation with dimensional reduction

Theoretical predictions are not robust as they strongly depend on the transition temperature

$$h^2\Omega_{\rm GW} \propto \frac{(\Delta V)^2}{T_*^8}$$

- **Why large uncertainties?**

$$m_{\rm eff}^2 = (m^2 + a_{\rm 1-loop} T^2) \ll m^2$$

$$b_{\rm 2-loop} T^2 \approx m_{\rm eff}^2$$

Large theoretical errors at the phase transition

$$\mu \frac{d}{d\log\mu} m_{\rm eff}^2 \approx m_{\rm eff}^2$$

Large scale dependency

$$\log\left(T^2/m_{\rm eff}^2\right) \gg 1$$

Large logs

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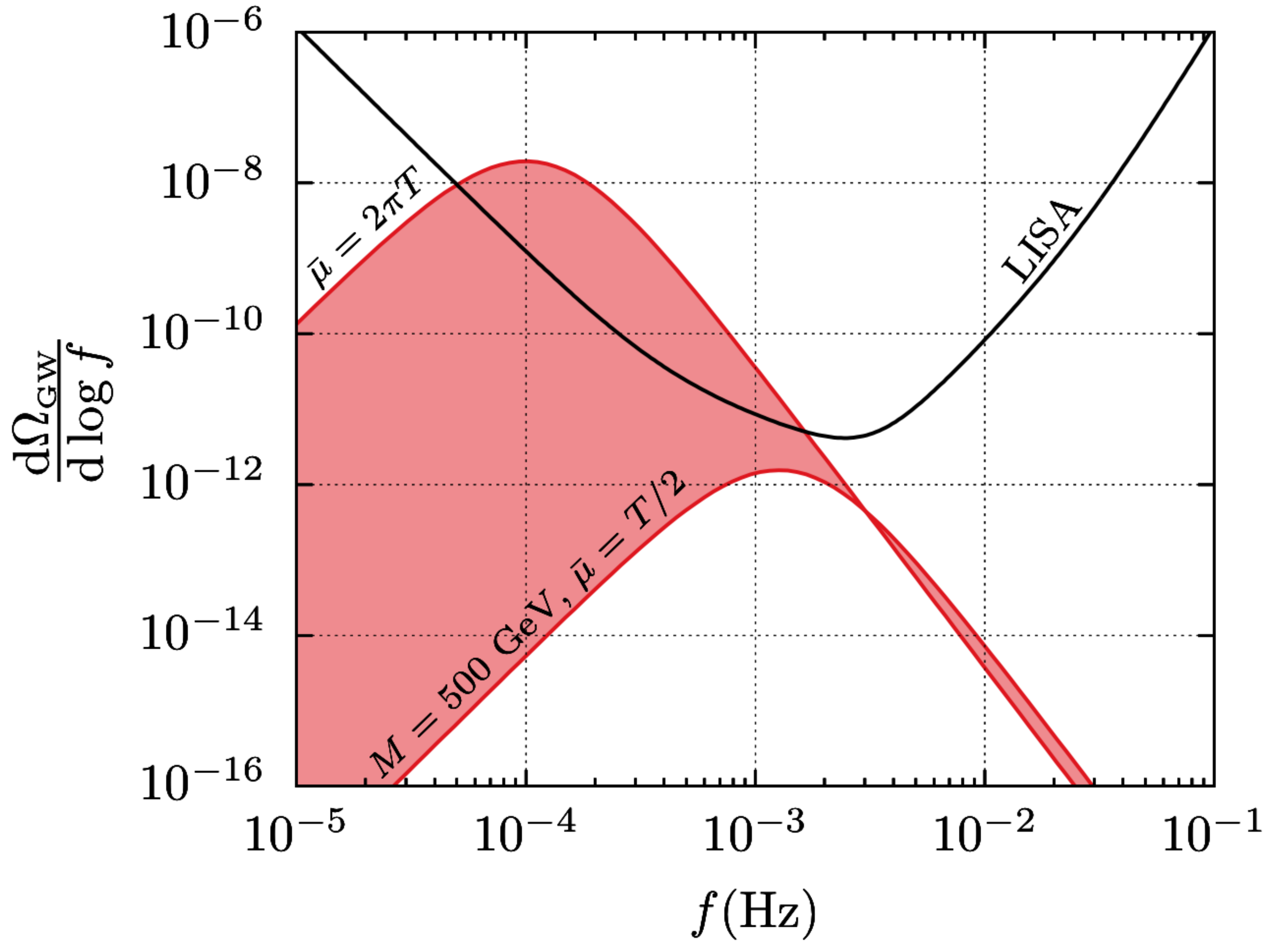


[Image credit: P. Schicho]

Improved calculation with dimensional reduction

Huge higher order corrections → **Use an effective field theory**

[Kajantie et al 9508379, Gould et al 2104.04399]

$$\log\left(T^2/m_{\rm eff}^2\right) \rightarrow \log\left(T^2/\mu^2\right) + \log\left(\mu^2/m_{eff}^2\right)$$

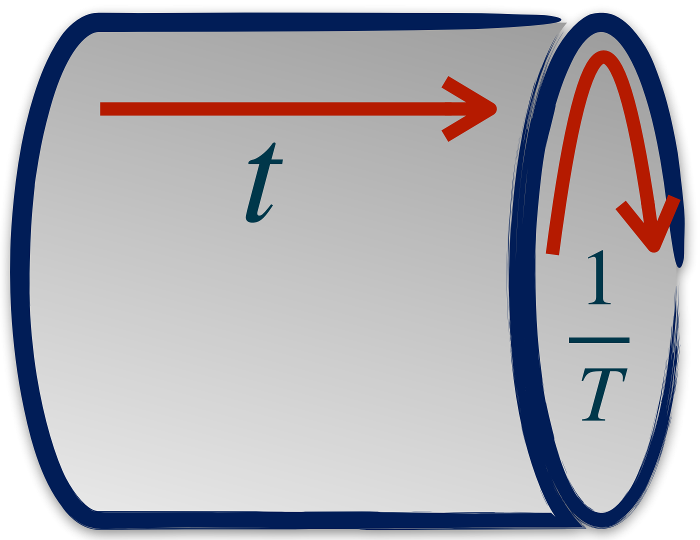
Match at $\mu \sim T$

RG-evolution in the EFT

- In thermal equilibrium heavy "particles" show up as an infinite tower of Matsubara (static) modes:

$$\partial_\mu \phi(x) \partial^\mu \phi(x) \rightarrow \vec{\nabla}\phi(\vec{x}) \cdot \vec{\nabla}\phi(\vec{x}) + \sum_{n=-\infty}^{+\infty} (2\pi n T)^2 \phi(\vec{x})^2$$

Integrate out heavy particles



- No time dependence

Improved calculation with dimensional reduction

In practice: write down the most general 3d-spacial Lagrangian and match the couplings

$$\frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4 \to \frac{1}{2}m_{3\mathrm{d}}^2(T, m, \lambda)\phi^2 + \frac{1}{4}\lambda_{3\mathrm{d}}(T, m, \lambda)\phi^4$$

→ Only valid at high-T

$$\phi \to \frac{\phi}{\sqrt{T}}$$

$$V_{4\mathrm{d}} = T V_{3\mathrm{d}}$$

Improved calculation with dimensional reduction

In practice: write down the most general 3d-spacial Lagrangian and match the couplings

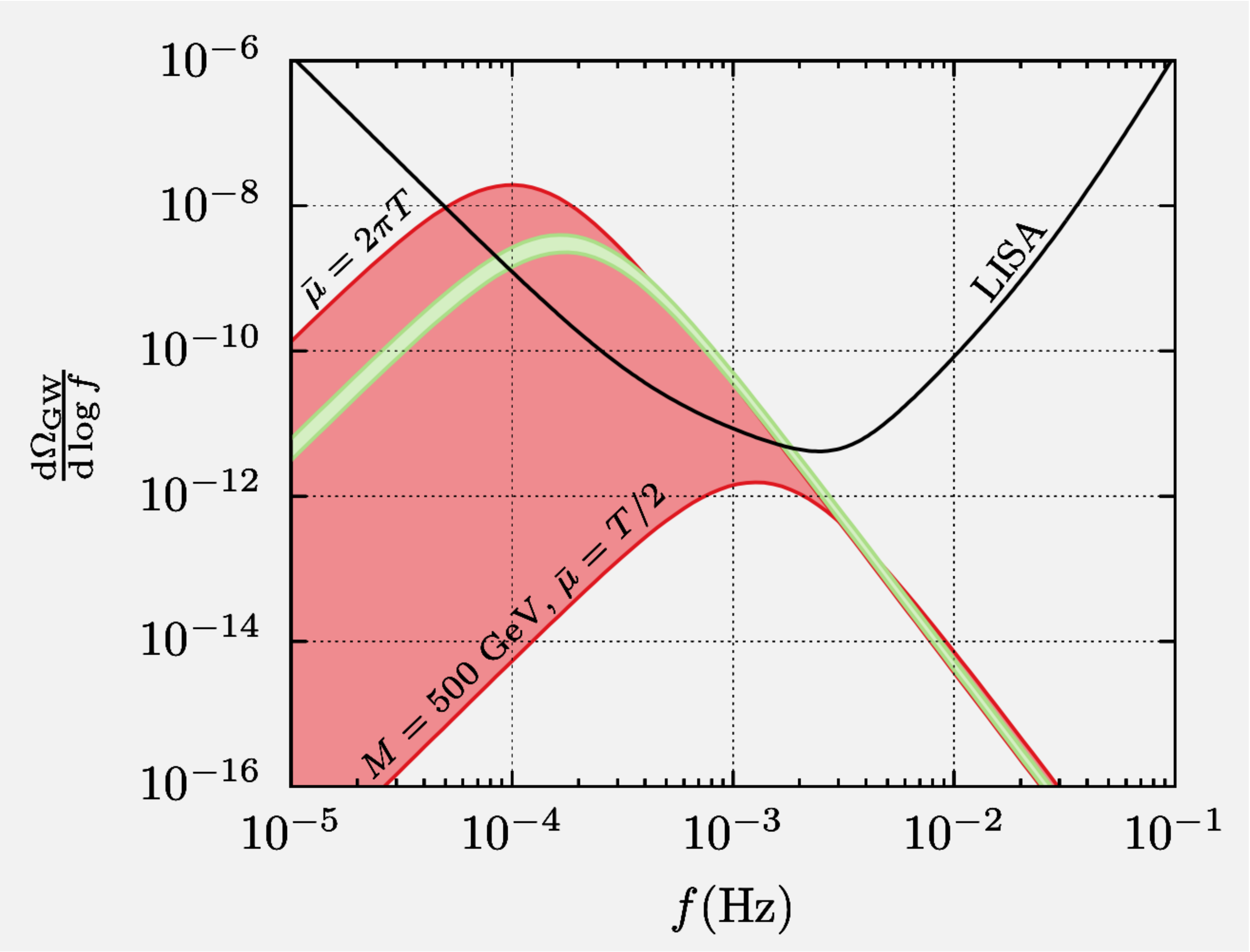
$$\frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4 \to \frac{1}{2}m_{3d}^2(T, m, \lambda)\phi^2 + \frac{1}{4}\lambda_{3d}(T, m, \lambda)\phi^4$$

$$\phi \to \frac{\phi}{\sqrt{T}}$$

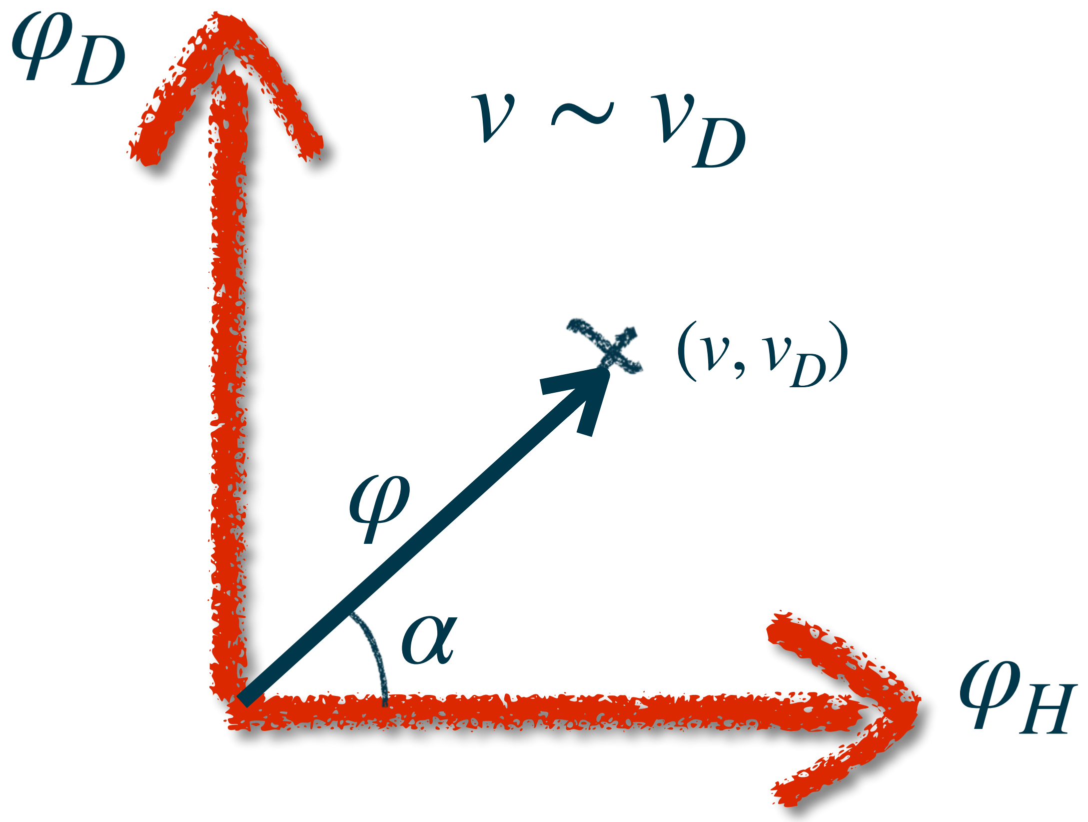
$$V_{4d} = TV_{3d}$$

- **Procedure automatised in DRAlgo**

[A. Ekstedt et al, Comput. Phys. Commun 288 (2023) 108725, 2205.08815]



[Image credit: P. Schicho]



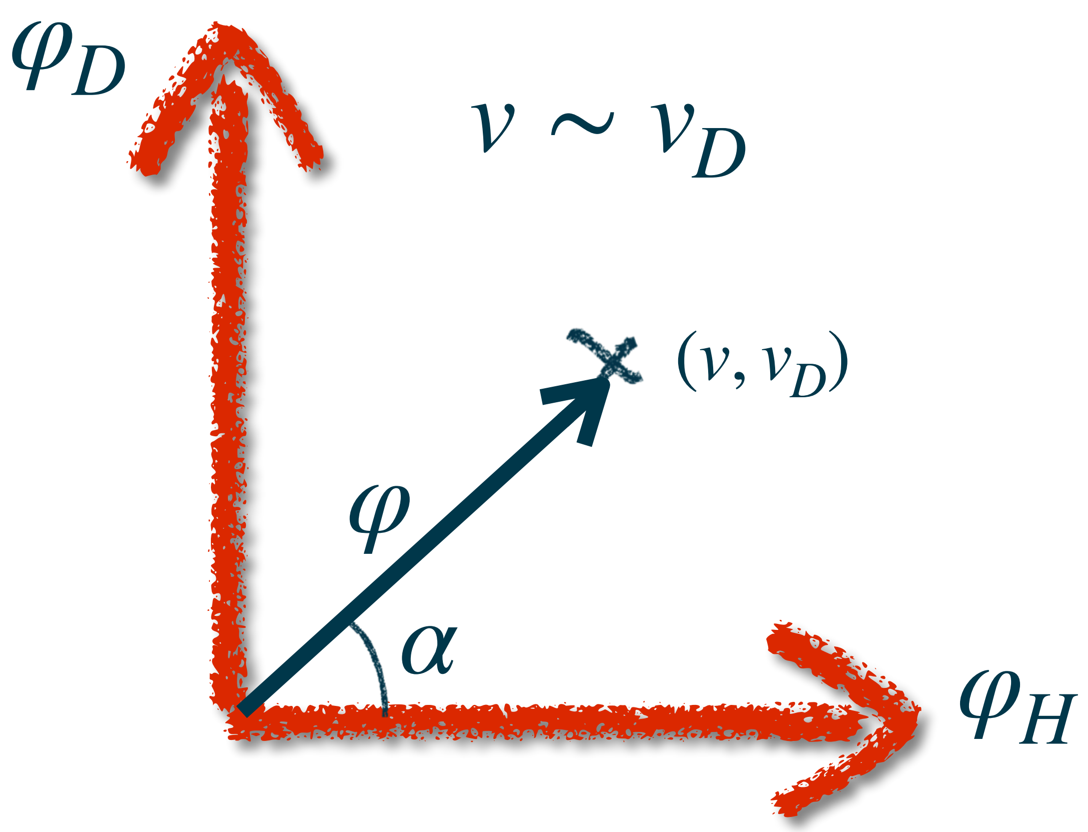
$$\varphi_H(T) = \phi(T)\cos\alpha(T)$$

$$\varphi_D(T) = \phi(T)\sin\alpha(T)$$

$$V^{3D}_{\rm LO}(T) = \frac{1}{2}[\mu_D^{\mathcal{US}}]^2\varphi_D^2 + \frac{1}{2}[\mu_H^{\mathcal{US}}]^2\varphi_H^2 + \frac{1}{4}\lambda_D^{\mathcal{US}}\varphi_D^4 + \frac{1}{4}\lambda_H^{\mathcal{US}}\varphi_H^4\,,$$

$$V^{3D}_{\rm NLO}(T) = -\frac{1}{12}\sum_{i\subset{\rm scl.}} M_i^3(\varphi_H,\varphi_D,T) - \frac{2}{12}\sum_{i\subset{\rm vec.}} M_i^3(\varphi_H,\varphi_D,T)$$

$$V^{4D}_{\rm eff.} = T\left[(V^{3D}_{\rm LO}(T) + V^{3D}_{\rm NLO}(T)\right]$$



$$V^{3D}_{\mathrm{LO}}(T) = \frac{1}{2}[\mu_D^{\mathcal{US}}]^2\varphi_D^2 + \frac{1}{2}[\mu_H^{\mathcal{US}}]^2\varphi_H^2 + \frac{1}{4}\lambda_D^{\mathcal{US}}\varphi_D^4 + \frac{1}{4}\lambda_H^{\mathcal{US}}\varphi_H^4\,,$$

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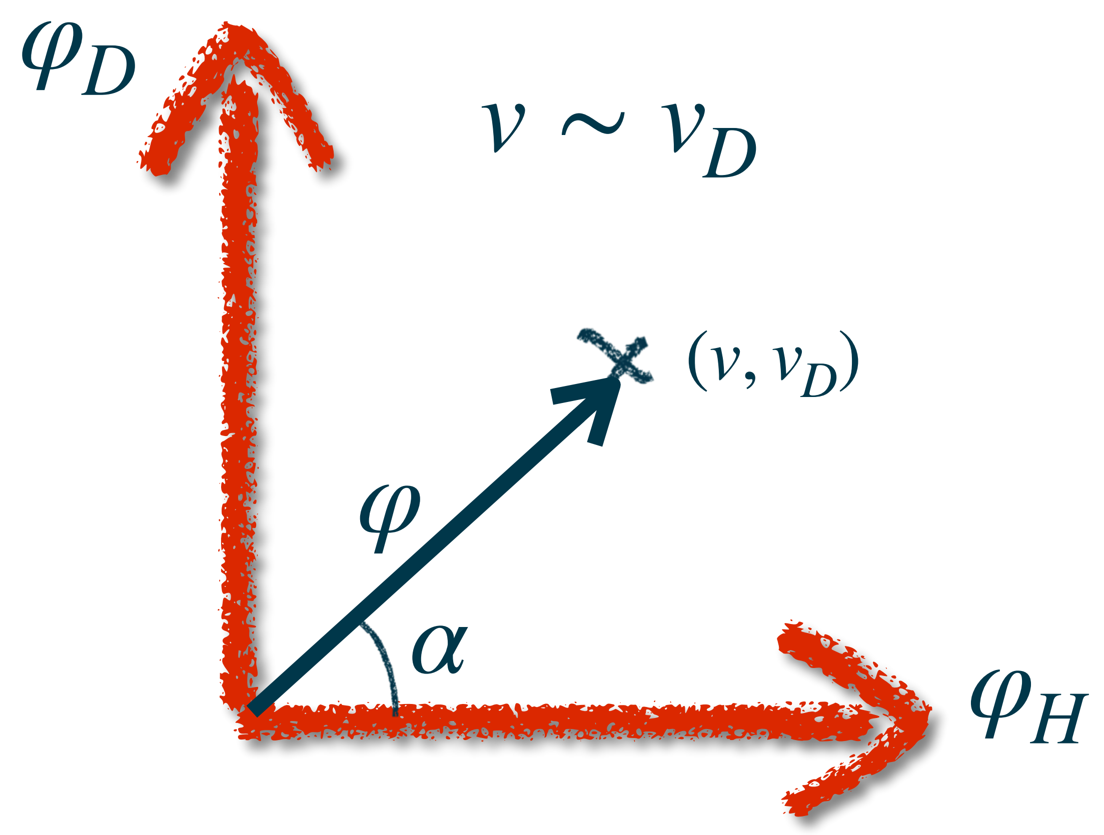
$$\varphi_H(T) = \phi(T)\cos\alpha(T)$$

$$\varphi_D(T) = \phi(T)\sin\alpha(T)$$

$\phi \to \varphi\sqrt{T}$

$$V_\varphi(\alpha,T) = d(\alpha,T)\varphi^2 + e(\alpha,T)\varphi^3 + \lambda(\alpha,T)\varphi^4$$

FOPT if $e(\alpha,T) < 0$



$$V^{3D}_{\rm LO}(T) = \frac{1}{2}[\mu_D^{\mathcal{US}}]^2\varphi_D^2 + \frac{1}{2}[\mu_H^{\mathcal{US}}]^2\varphi_H^2 + \frac{1}{4}\lambda_D^{\mathcal{US}}\varphi_D^4 + \frac{1}{4}\lambda_H^{\mathcal{US}}\varphi_H^4\,,$$

$$V^{3D}_{\rm NLO}(T) = -\frac{1}{12}\sum_{i\subset{\rm scl.}} M_i^3(\varphi_H,\varphi_D,T) - \frac{2}{12}\sum_{i\subset{\rm vec.}} M_i^3(\varphi_H,\varphi_D,T)$$

$$V^{4D}_{\rm eff.} = T\left[(V^{3D}_{\rm LO}(T) + V^{3D}_{\rm NLO}(T)\right]$$

$$\mathcal{M}^2_{\mathcal{V}_{1,2,3}} = \frac{1}{4}[g_D^{\mathcal{US}}]^2\varphi_D^2$$

$$\varphi_H(T) = \phi(T)\cos\alpha(T)$$

$$\varphi_D(T) = \phi(T)\sin\alpha(T)$$

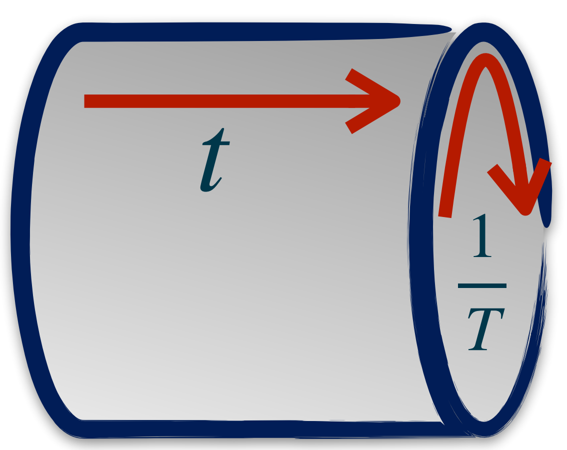
$$\phi \to \varphi\sqrt{T}$$

$$V_\varphi(\alpha,T) = d(\alpha,T)\varphi^2 + e(\alpha,T)\varphi^3 + \lambda(\alpha,T)\varphi^4$$

$$e(\alpha,T) = -\frac{T^{5/2}}{48}\Big\{3[g_D^{\mathcal{US}}]^3\sin^3(\alpha) + \left[2[g_W^{\mathcal{US}}]^3 + \left([g_W^{\mathcal{US}}]^2 + [g_Y^{\mathcal{US}}]^2\right)^{3/2}\right]\cos^3(\alpha)\Big\}$$

FOPT if $e(\alpha,T) < 0$

Potential barrier between true and false vacua induced by the secluded sector



Used dimensional reduction

$$\alpha, \quad \beta/H, \quad T_* \longrightarrow$$

calculated from a certain BSM theory, used as inputs to obtain the GW power spectrum

$$h^2\Omega_{\rm GW} = h^2\Omega_{\rm GW}^{\rm peak} \left(\frac{4}{7}\right)^{-\frac{7}{2}} \left(\frac{f}{f_{\rm peak}}\right)^3 \left[1 + \frac{3}{4}\left(\frac{f}{f_{\rm peak}}\right)\right]^{-\frac{7}{2}}$$

Peak amplitude

Spectral function

$$h^2\Omega_{\rm GW}^{\rm peak} = 3 \times 10^{-12} \left(\frac{100}{g_*}\right)^{\frac{5}{6}} \left(\frac{T_*}{100 c_s}\right) f_{\rm peak}^{-1} K^2$$

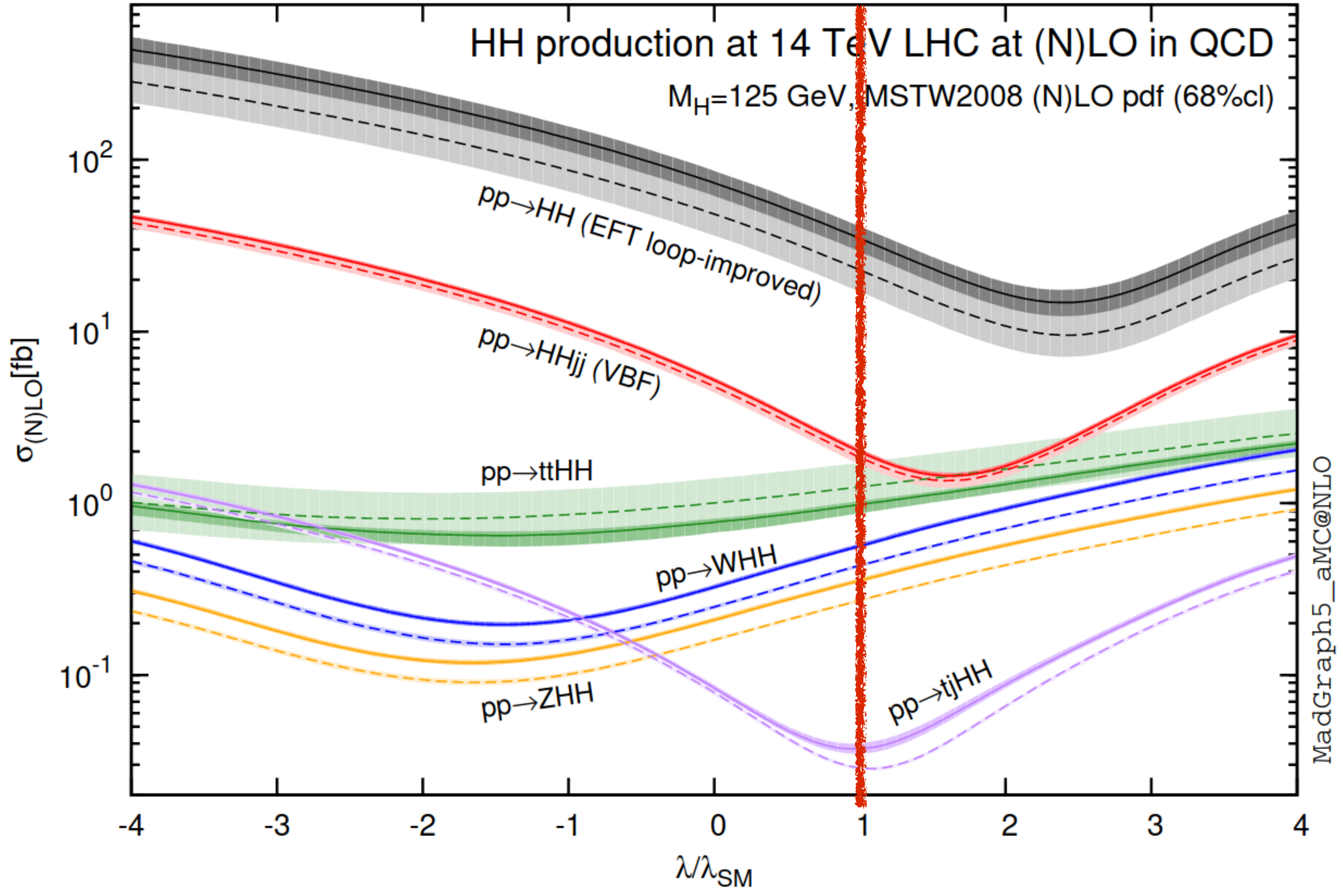
$$f_{\rm peak} = 26 \times 10^{-6} \left(\frac{1}{HR}\right) \left(\frac{T_*}{100}\right) \left(\frac{g_*}{100\ {\rm GeV}}\right)^{\frac{1}{6}} {\rm Hz}$$

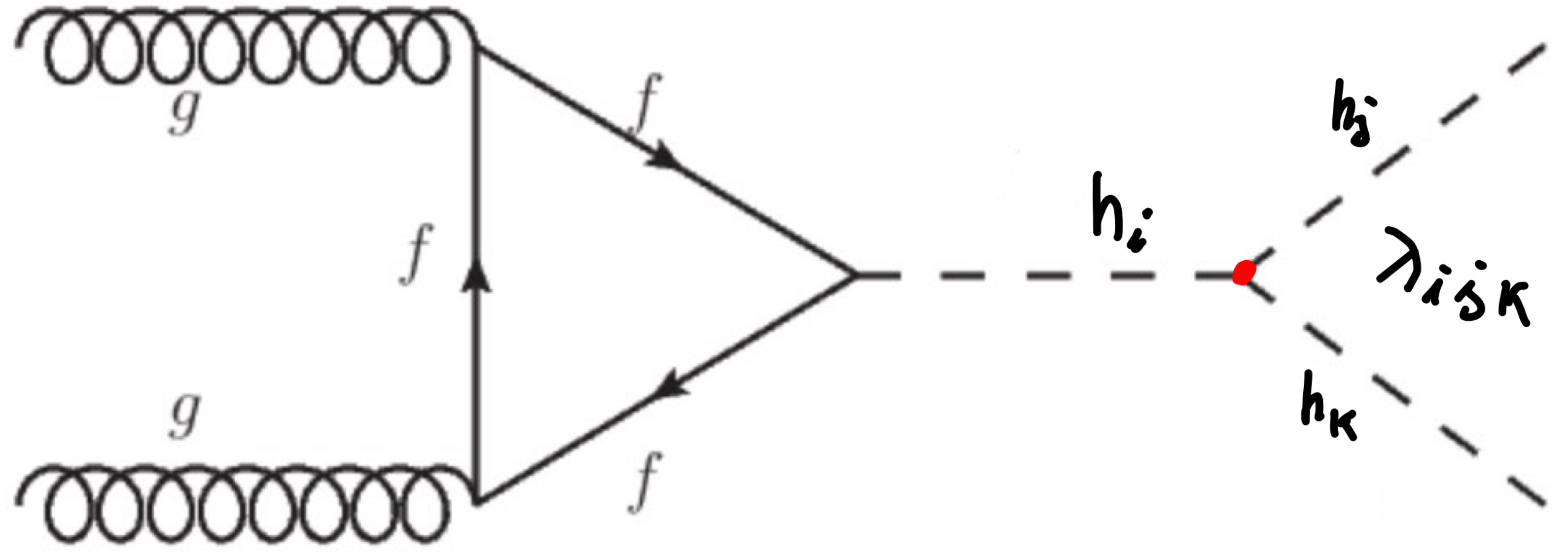
$$HR = \frac{H}{\beta} (8\pi)^{\frac{1}{3}} \max(v_b, c_s)$$

$$K = \frac{\kappa\alpha}{1+\alpha}$$

We use the templates for SW peak in [Caprini et al. JCAP 03 (2020) 024]

Di-Higgs production





Phys.Lett.B 732 (2014) 142-149

Thermal effective potential

$$V_{\text{eff}}(T) = V_0 + V_{\text{CW}}^{(1)} + \Delta V(T) + V_{\text{ct}}$$

$$V_{\text{CW}}^{(1)} = \sum_i (-1)^{F_i} n_i \frac{m_i^4(\phi_\alpha)}{64\pi^2}\left(\log\left[\frac{m_i^2(\phi_\alpha)}{Q^2}\right] - c_i\right)$$

$$n_s = 6, \qquad n_{A_L} = 1$$

$$n_W = 6, \qquad n_Z = 3, \qquad n_\gamma = 2$$

$$n_{u,d,c,s,t,b} = 12, \qquad n_{e,\mu,\tau} = 4\,, \qquad n_{\nu_{1,2,3}} = n_{N^\pm_{1,2,3}} = 2$$

$$\Delta V(T) = \frac{T^4}{2\pi^2}\left\{\sum_b n_b J_B\left[\frac{m_b^2(\phi_\alpha)}{T^2}\right] - \sum_f n_f J_F\left[\frac{m_f^2(\phi_\alpha)}{T^2}\right]\right\}$$

$$J_{B/F}(y^2) = \int_0^\infty dx\, x^2 \log\left(1 \mp \exp[-\sqrt{x^2+y^2}]\right).$$

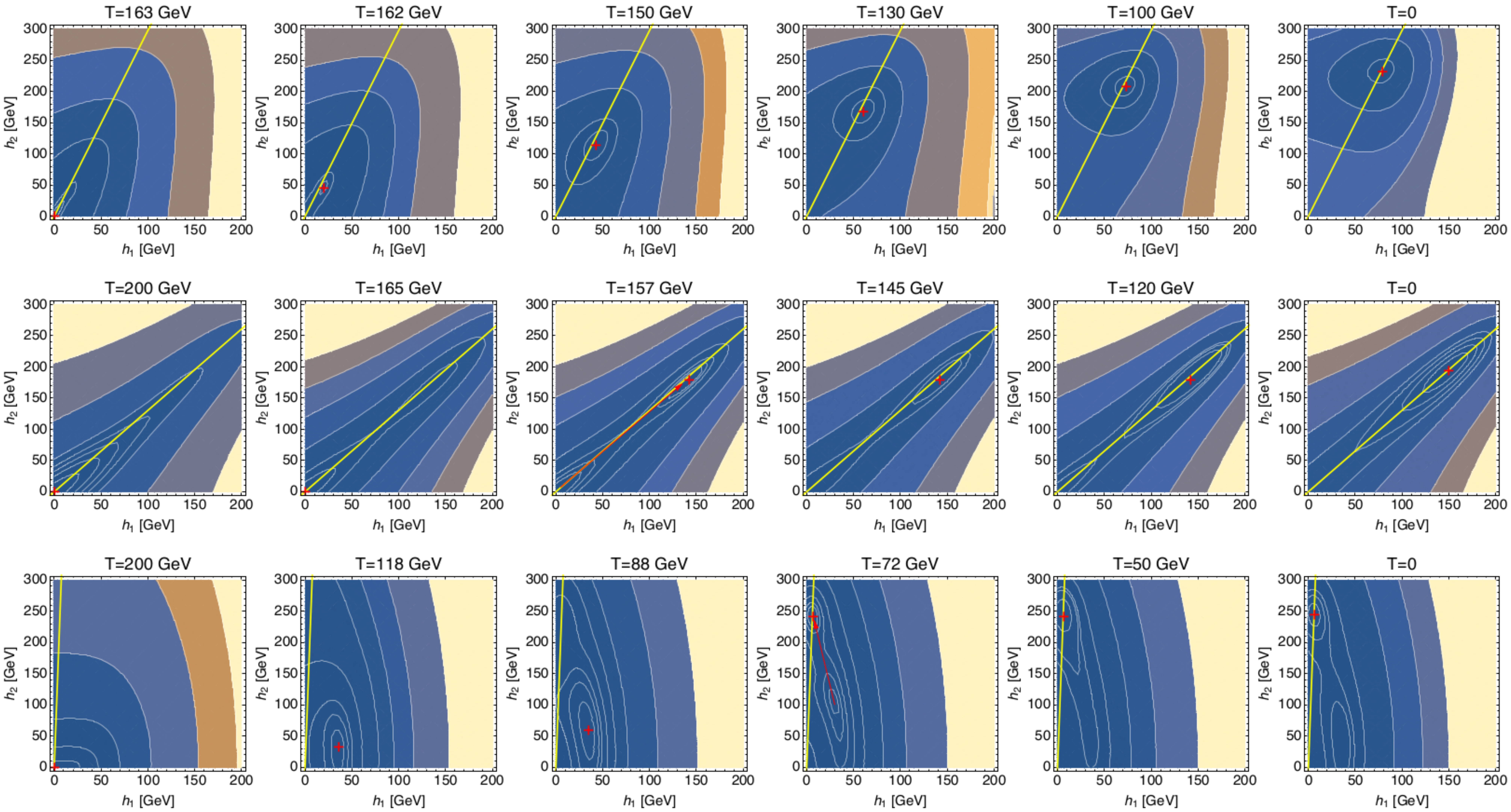
$$m_i^2 \to m_i^2 + c_i T^2$$

$$\left\langle \frac{\partial V_{\text{ct}}}{\partial \phi_\alpha} \right\rangle = \left\langle -\frac{\partial V_{\text{CW}}^{(1)}}{\partial \phi_\alpha} \right\rangle \qquad \left\langle \frac{\partial^2 V_{\text{ct}}}{\partial \phi_\alpha \partial \phi_\beta} \right\rangle = \left\langle -\frac{\partial^2 V_{\text{CW}}^{(1)}}{\partial \phi_\alpha \partial \phi_\beta} \right\rangle$$

⟶ **Counterterms are fixed such that the T=0 minimum conditions and physical masses are preserved at 1-loop**

If a multi-Higgs theory contains multiple vacua, phase transitions can take place:

$$V_{\mathrm{BSM}}(h_1, h_2, T)$$



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Scenario II: Include fermion and Higgs portals

Explanation of DM and observability of SGWB (LISA and/or future facilities)