# Colour-breaking/restoration in the Early Universe

## A Minimal Leptoquark Model

Gr@v | University of Aveiro

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Marco Finetti

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Bolsas de Investigação para Doutoramento FCT-ECIU

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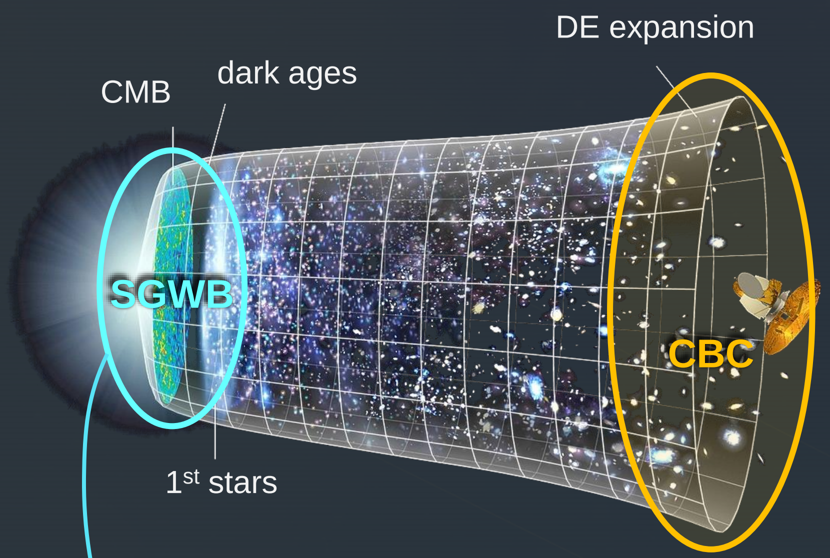
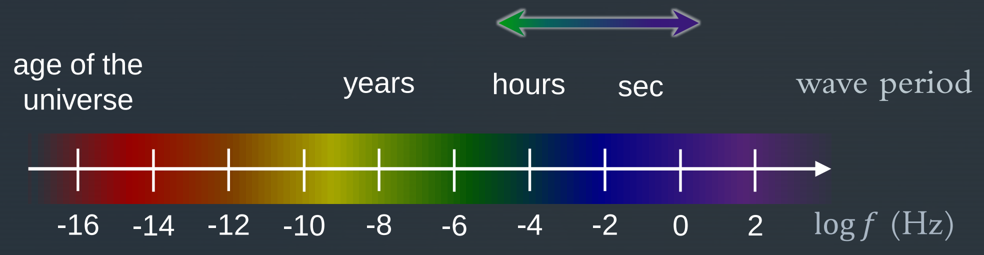
CIDMA

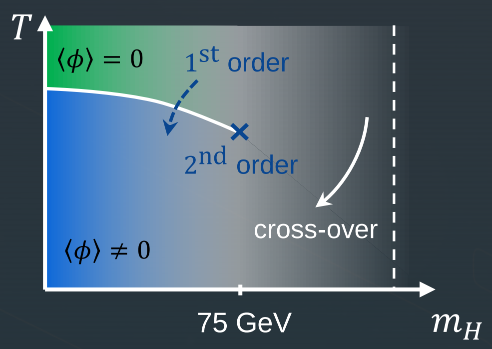
# Gravitational Wave
## Sources







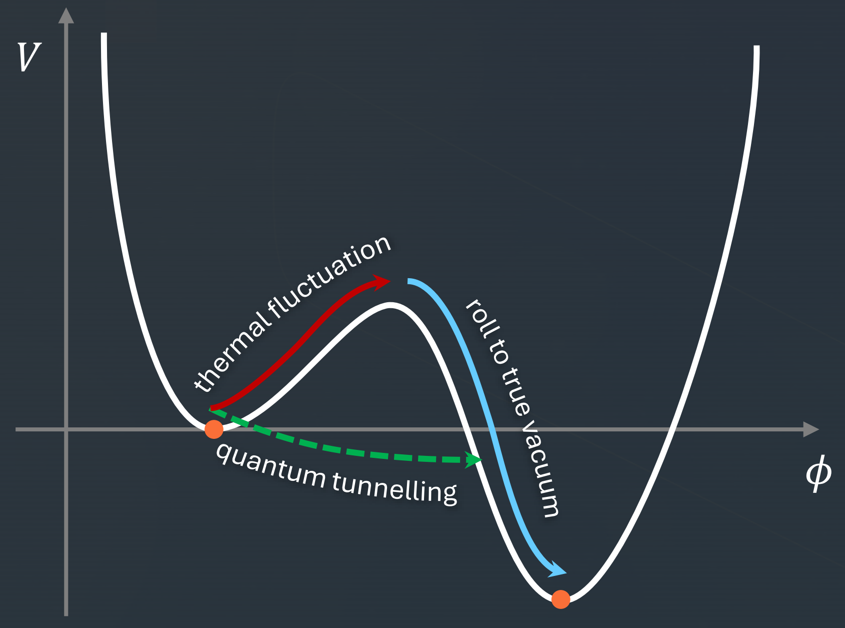

| Main Sources | Frequency (Hz) |
|---|---|
| Inflation & preheating | ?? |
| Cosmic defects | $10^{-12} - 10^{-10}$ (strings) |
| Supermassive BH binaries | $10^{-10} - 10^{-7}$ |
| Phase transitions | $\sim 10^{-5} - 10^{-2}$ (EW) |
| Primordial BHs | $\sim 10^{1} - 10^{2}$ |

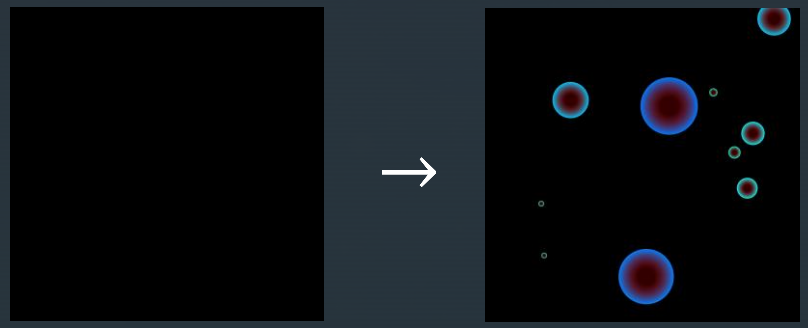



Is colour-restoration observable ?

# Cosmological Phase Transitions
## & Single-Field Models

I order phase transitions (FOPTs)



BSM physics

- EW baryogenesis
- Allowing multiple vacuum directions (multi-field models)

➢ Focus on 3-field model

# vacuum configurations:

$$2^{2\ \#\mathrm{vevs}} = 64$$

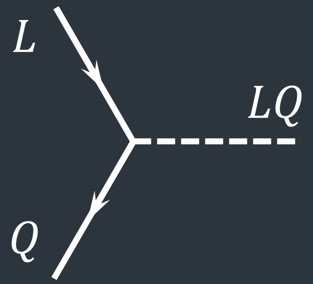
We identify $\mathcal{O}(10)$ of interest

# Leptoquarks

## A minimal 2-LQ model

- LQ model
  - Higgs-like doublet $H$
  - coloured-doublet $R$
  - coloured-singlet $S$

| | $SU(3)$ | $SU(2)$ | $U(1)_Y$ |
|---|---|---|---|
| $H$ | 1 | 2 | 1/2 |
| $R$ | 3 | 2 | 1/6 |
| $S$ | $\bar{3}$ | 1 | 1/3 |




- Scalar content

$$V_{LQ}^{(0)} = \mu_H^2\, H^\dagger H + \mu_S^2\, S^\dagger S + \mu_R^2\, R^\dagger R + \lambda_H\, (H^\dagger H)^2 + \lambda_S\, (S^\dagger S)^2 + \lambda_R\, (R^\dagger R)^2 + g_{HS}(H^\dagger H)(S^\dagger S) + g_{HR}(H^\dagger H)(R^\dagger R) + g'_{HR}(H^\dagger R)(R^\dagger H) + g_{RS}(R^\dagger R)(S^\dagger S) + a_1\, RSH^\dagger + h.c.$$

- Features
  - flavour-consistent: $O(100)$ observables
  - radiative generation of $\nu$ masses and mixing
  - generate strong FOPTs

Model based on F. Freitas, J. Gonçalves, A. P. Morais, R. Pasechnik, W. Porod (2023, PRD 108.115002)

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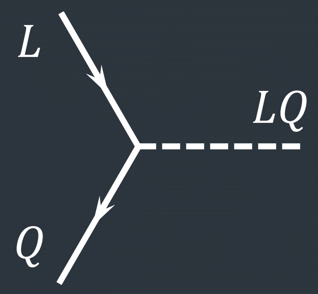


- Scalar content

$$V_{LQ}^{(0)} = \mu_H^2\, H^\dagger H + \mu_S^2\, S^\dagger S + \mu_R^2\, R^\dagger R$$
$$+ \lambda_H\, (H^\dagger H)^2 + \lambda_S\, (S^\dagger S)^2 + \lambda_R\, (R^\dagger R)^2$$
$$+ g_{HS}(H^\dagger H)(S^\dagger S) + g_{HR}(H^\dagger H)(R^\dagger R) + g'_{HR}(H^\dagger R)(R^\dagger H) + g_{RS}(R^\dagger R)(S^\dagger S)$$
$$+ a_1\, RSH^\dagger + h.c.$$

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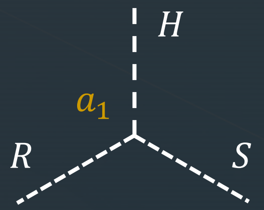
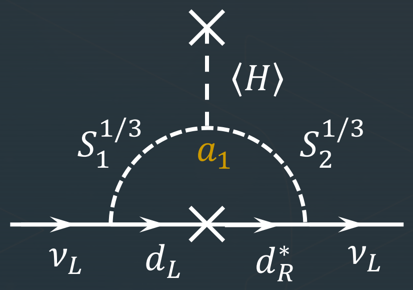



Model based on F. Freitas, J. Gonçalves, A. P. Morais, R. Pasechnik, W. Porod (2023, PRD 108.115002)

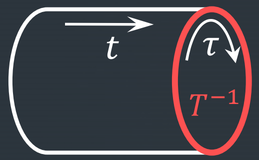
# Dimensional Reduction

## An improved recipe for thermal EFTs

- Leading-order perturbation theory (à la Coleman-Weinberg)
  *Linde problem*: non-perturbative massless vector bosons

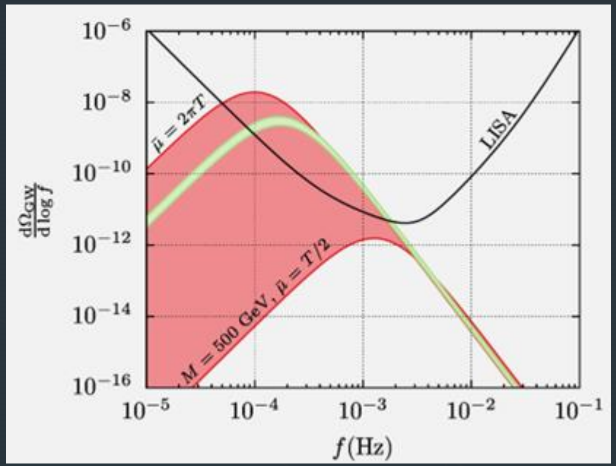
$$V^{(1)} = \underbrace{V_0 + V_{CW}^{(1)}}_{T=0} + \underbrace{V_T + V_{\text{daisy}}}_{T\neq 0}$$

- Dimensional reduction (DR)
  - time → temperature ⇒ high-T approach
  - include systematically higher-order resummations




- Narrower theoretical uncertainties

  ⇒ narrower GWB uncertainties




Credit: P. Schicho

- Weakly-coupled EFTs → thermal scale hierarchy

Boltzmann suppression ($> \pi T$) → hard ($\sim \pi T$) → semisoft ($\sim \left(\frac{g}{4\pi}\right)^{\frac{1}{2}} \pi T$) → soft ($\sim \frac{g}{4\pi} \pi T$) → supersoft ($\sim \left(\frac{g}{4\pi}\right)^{\frac{3}{2}} \pi T$) → ultrasoft ($\sim \left(\frac{g}{4\pi}\right)^{2} \pi T$)

Figure inspired by eq. (2.1) of O. Gould and T.V.I. Tenkanen (JHEP01(2024)048)

# Outcome

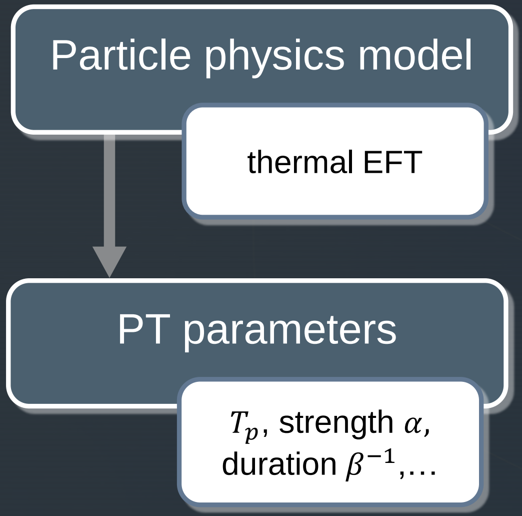
From Particle Physics to Cosmology

Particle physics model

thermal EFT

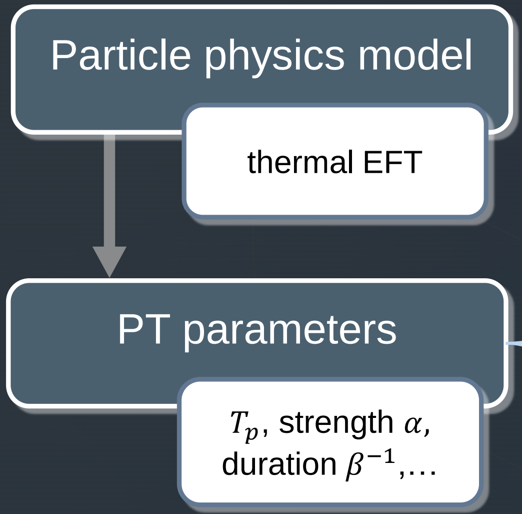
# Outcome

From Particle Physics to Cosmology



# Outcome

## From Particle Physics to Cosmology




Nucleation criterion: $\int_{T_n}^{T_c} dT \frac{\Gamma(T)}{T\, H^4(T)} \approx 1$

$$\Gamma(T) = T^4 \left(\frac{S_3}{2\pi T}\right)^{3/2} e^{-S_3/T}$$

energy density: $\rho(T) = \underbrace{\frac{\pi^2}{30} g_* T^4}_{\text{radiation}} + \underbrace{\Delta V}_{\text{vacuum}}$

$$\rightarrow H^2 = \frac{\rho}{3M_P^2}$$

percolation criterion: $I(T_p) \approx 0.34$

$$I(T) = \frac{4\pi}{3} v_w^3 \int_T^{T_p} \frac{dT'}{T'^4} \frac{\Gamma(T')}{H^4(T')} \left(\int_T^{T'} \frac{d\tilde{T}}{H(\tilde{T})}\right)^3$$

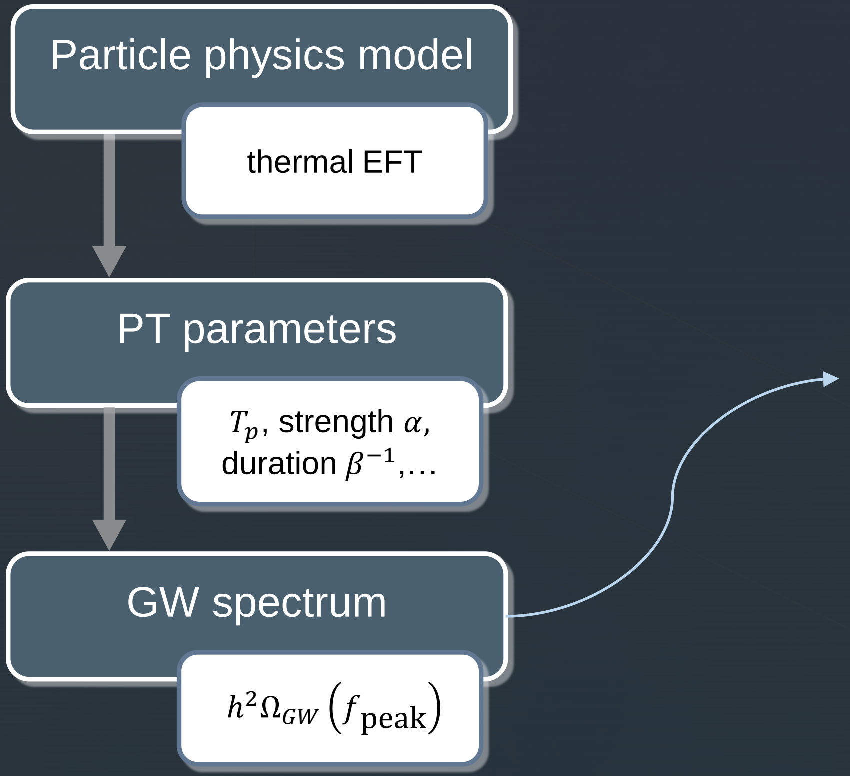
percolation condition: $\mathcal{V}'_{FV}(t_p) < 0$

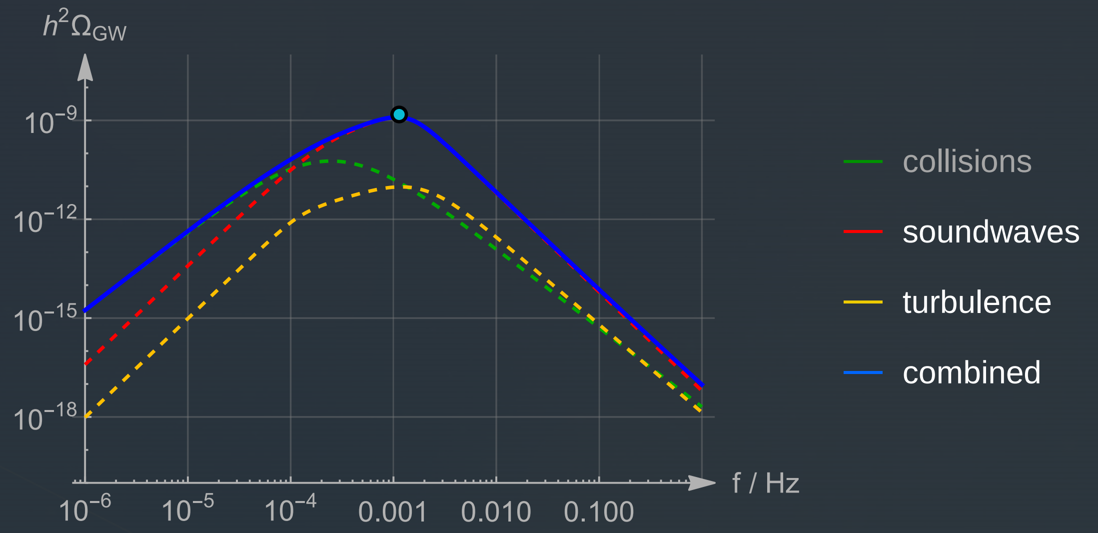
$$H(T)(T I'(T) + 3)\Big|_{T_p} < 0$$

- strength $\alpha = \frac{1}{\rho} \Delta \left(V - \frac{T}{4} \partial_T V\right)$
- duration$^{-1}$ $\frac{\beta}{H} = T \frac{d}{dT} \left(\frac{S_3}{T}\right)$

# Outcome

From Particle Physics to Cosmology




M. Hindmarsh, S. Huber, K, Rummukainen, D.J. Weir (2015, PRD 92.123009)

# Outcome

From Particle Physics to Cosmology

**Particle physics model**
- thermal EFT

↓

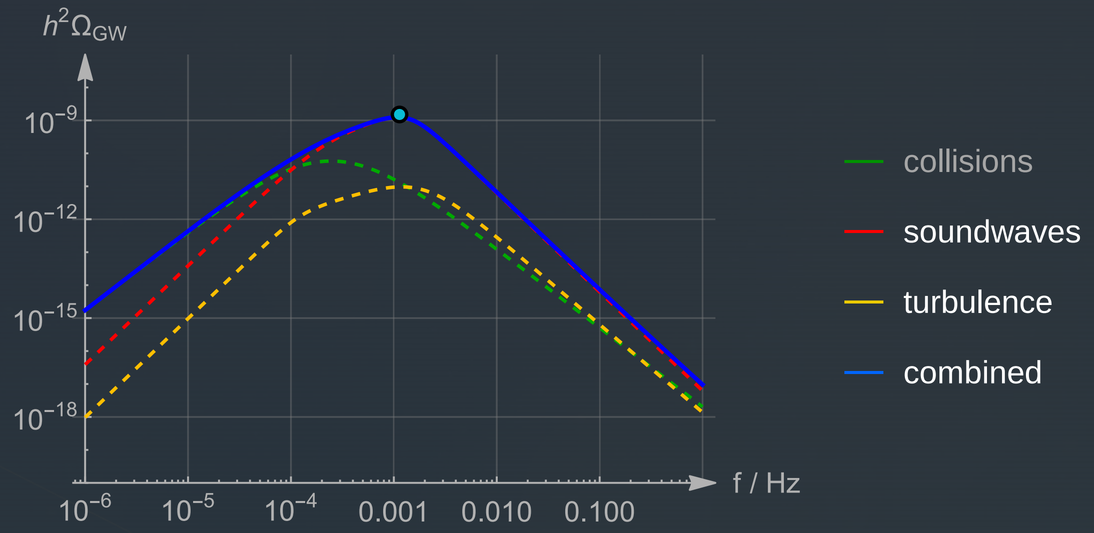
**PT parameters**
- $T_p$, strength $\alpha$, duration $\beta^{-1}$,…

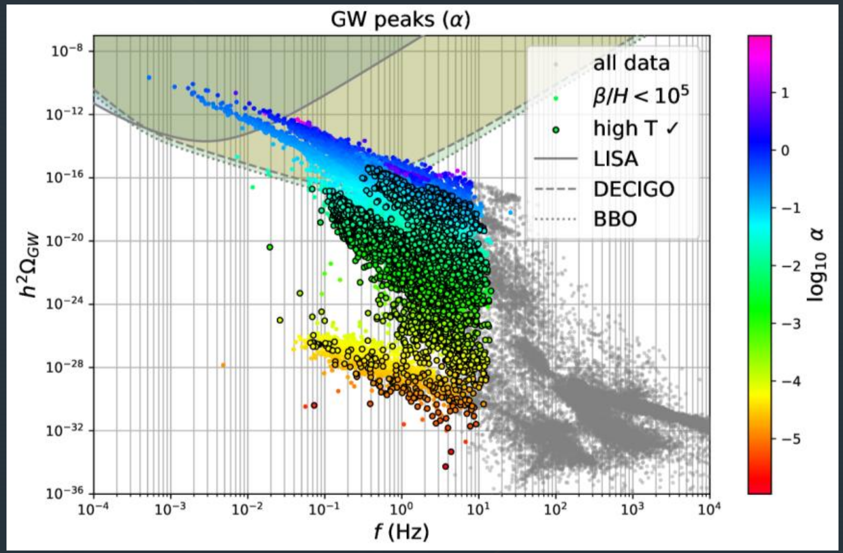
↓

**GW spectrum**
- $h^2\Omega_{GW}\left(f_{\text{peak}}\right)$

↓

**Model parameters scan**
- masses
- couplings




- $\frac{m_{US}}{\pi T} \lesssim 1$

# Outcome

From Particle Physics to Cosmology

**Particle physics model**

thermal EFT

**PT parameters**

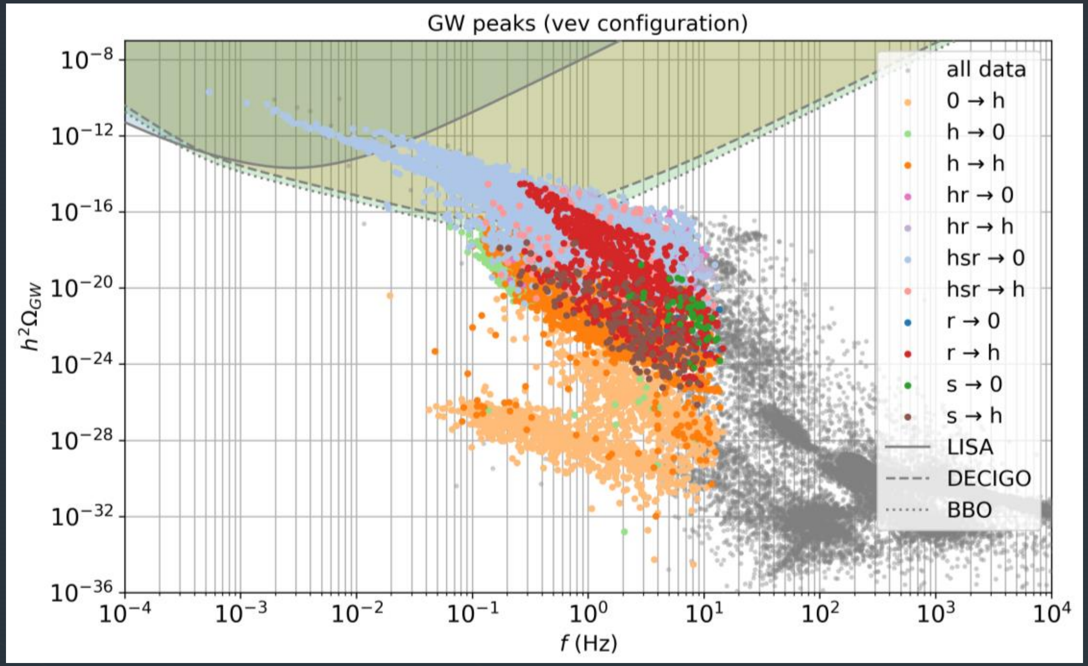
$T_p$, strength $\alpha$, duration $\beta^{-1}$,…

**GW spectrum**

$h^2\Omega_{GW}\left(f_{\text{peak}}\right)$

**Model parameters scan**

masses couplings,…




Colour breaking and restoration!

# Outcome

## From Particle Physics to Cosmology

**Particle physics model**
thermal EFT

↓

**PT parameters**
$T_p$, strength $\alpha$, duration $\beta^{-1}$,…

↓

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↓

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masses
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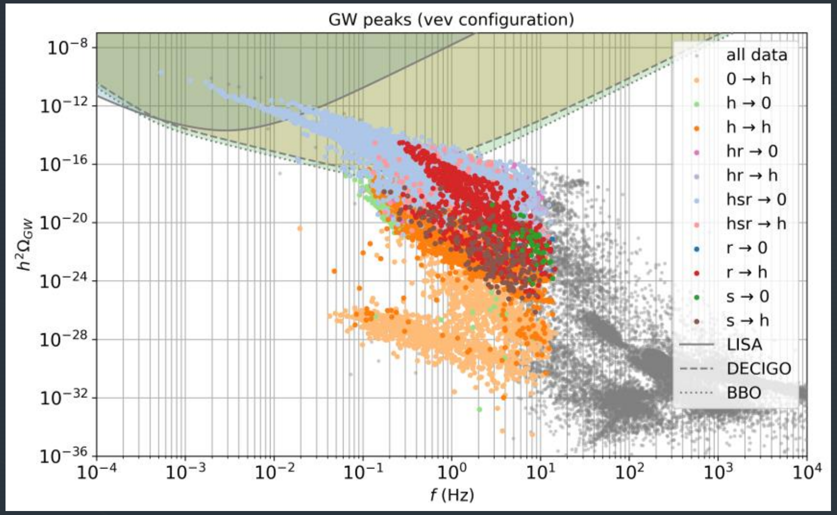


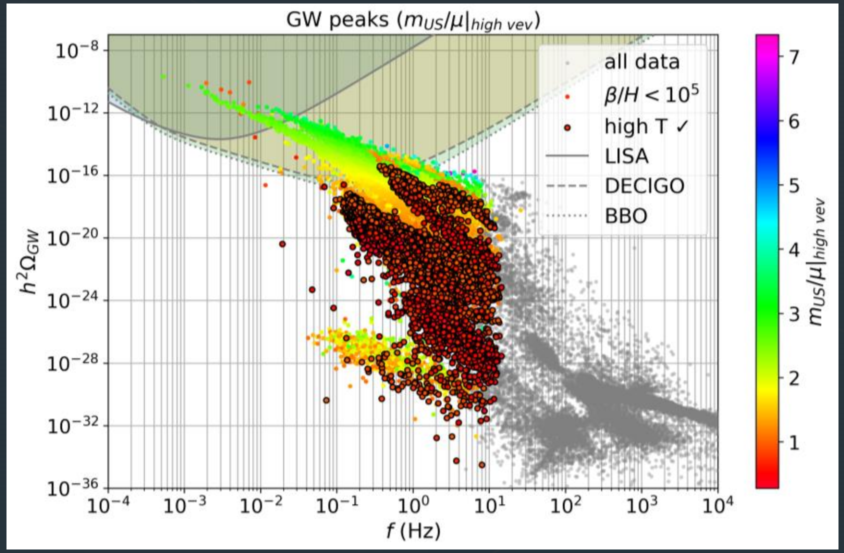

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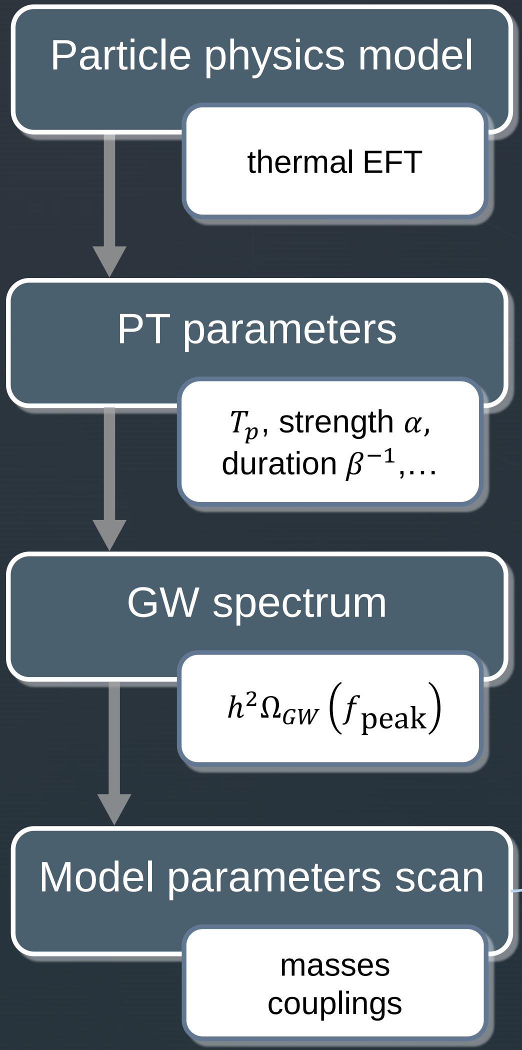
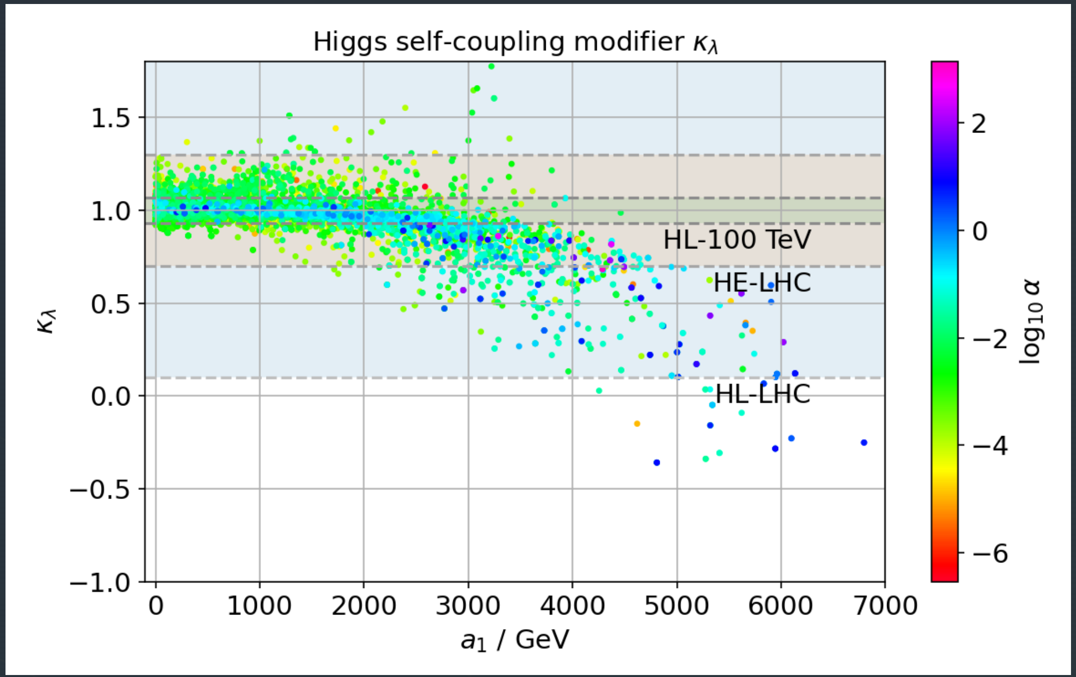
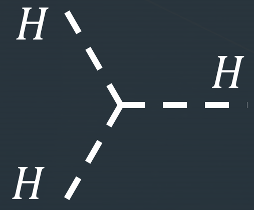


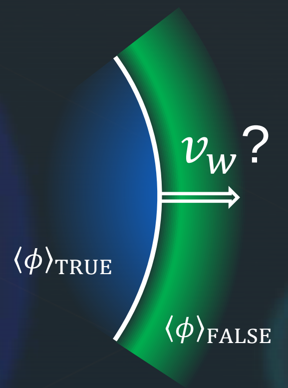

$$\kappa_\lambda \equiv \frac{\lambda_{hhh}^{BSM}}{\lambda_{hhh}^{SM}} = 1 + \frac{\lambda_{hhh}^{LQ}}{\lambda_{hhh}^{(0)} + \lambda_{hhh}^{t}}$$

# Outcome
## & Future Endeavours

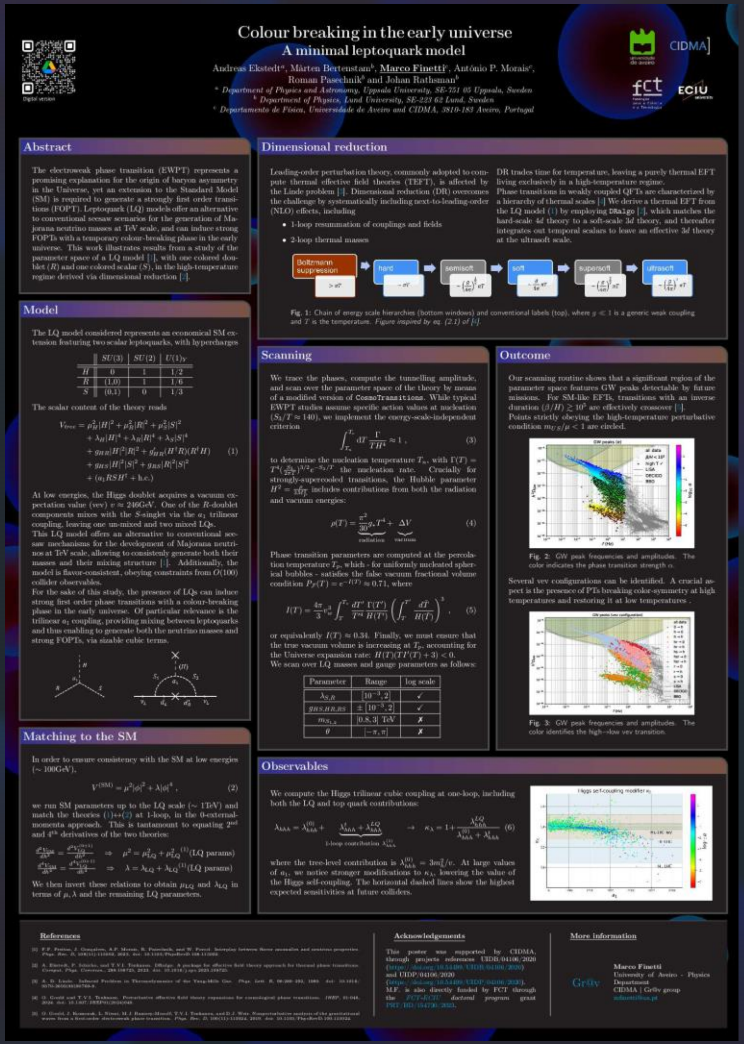
- Model
  - ✓ flavour-consistent LQ model generating $\nu$ masses
  - ✓ featuring colour-breaking at high-$T$
  - ✓ and colour-restoration at lower $T$

- Detectability
  - ✓ at future detectors (DECIGO, BBO, ..)
  - ✓ correlation GW↔collider observables

- Further developments
  - → `DRalgo`: EFT at **NNLO**
  - → bubble wall velocity $v_w$ in LTE
  - → Decay rate prefactor $\Gamma = A\, e^{-S_3/T}$



Thanks for listening!

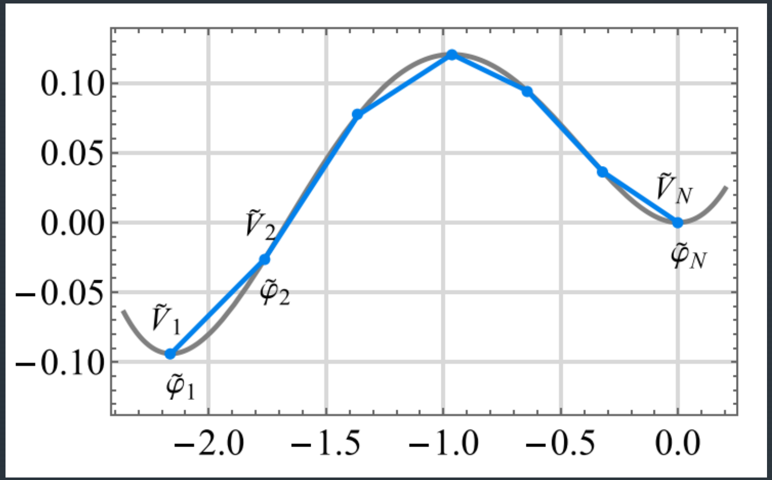


# Additional slides

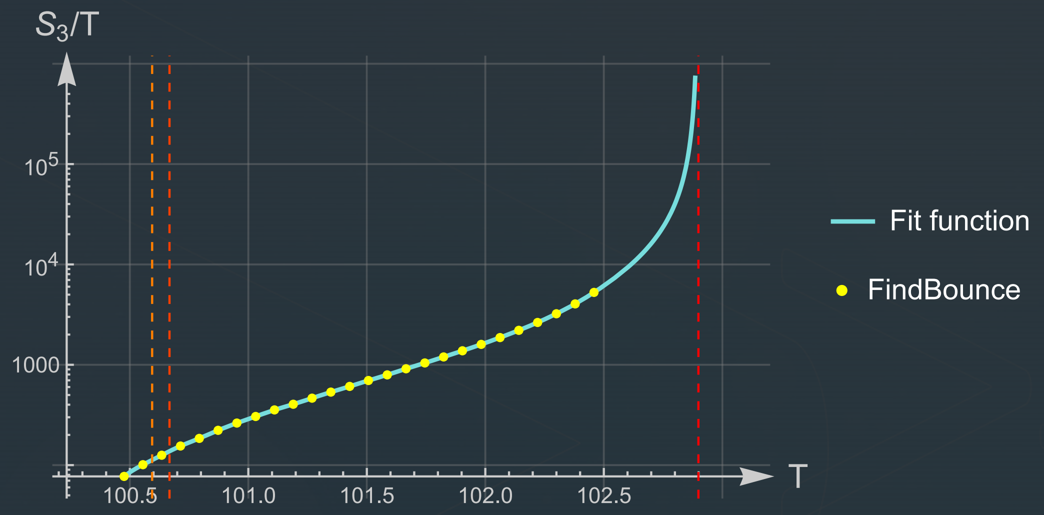
# Paclet
FindBounce + action fit

- Pipeline requires to determine temperatures of
  - nucleation $\int_{T_n}^{T_c} dT \, \frac{\Gamma(T)}{T\,H^4(T)} \sim 1$
  - percolation $I\left(\Gamma, T_p\right) \approx 0.34$

  $\Big\}\ \Gamma(T) = A\left(\frac{S_3}{T}, T\right) e^{-\frac{S_3}{T}}$
- $\frac{S_3}{T}(T)$ numerical estimation: `FindBounce`
  - implements *polygonal bounces*
  - $4d\ (S_4)$ or $3d\ (S_3)$
  - ✓ thin-wall regime
  - efficient: $t \sim O(\#\ \text{fields}), O(\#\ \text{segments})$
- Method
  1. $\hat{T}_n$ estimate via $\Gamma/H^4 \sim 1$
  2. $S_3/T$ fit/interpolation about $\left(\sim \hat{T}_n, T_c\right)$
  3. $T_n, T_p$ via above integrals




Guada, Nemevšek, Pintar (CPC 256 (2020) 10748)



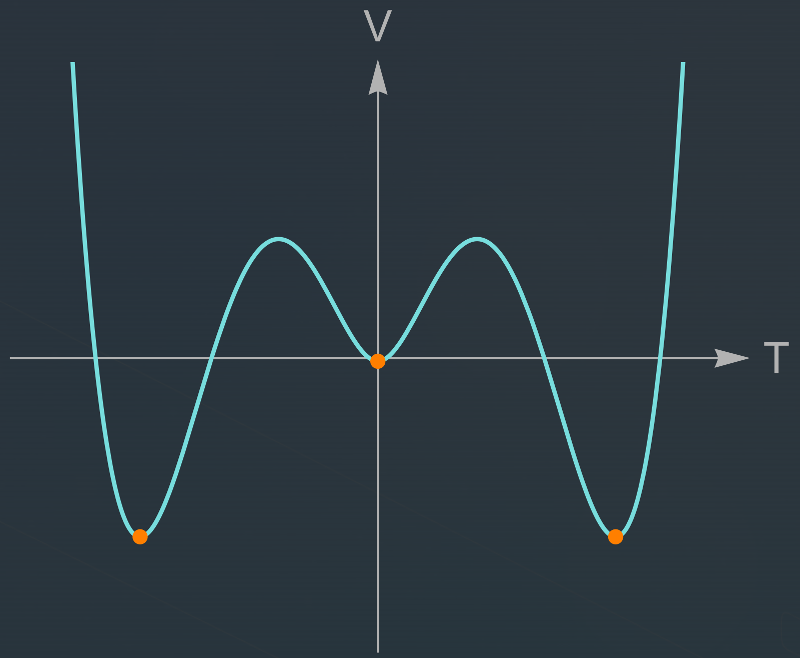
# Exampl
Dark photon model

- Dark $U(1)$ gauge sector
- Scalar content:

  $V(\phi, T) = \mu^2\phi^2 + \lambda\phi^4$

  \+ fermions
- $V_{\text{eff}}$ @ NLO

→ Paclet



# Example II
## Dark photon model

- Dark $U(1)$ gauge sector
- Scalar content:

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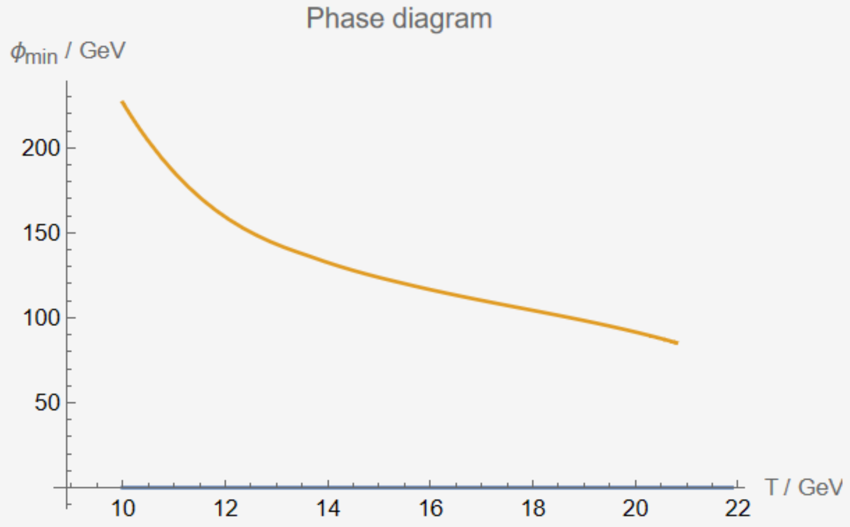
  + fermions
- $V_{\text{eff}}$ @ NLO

$\rightarrow$ Paclet

In[351]:=
```
trs=TBounce[V,vw,
    "TRange"→{10,4μ0},"SymmetricPhaseThreshold"→v/100,
    "PlotAction"→True,"PlotGWSpectrum"→True
    ];//EchoTiming
```




Looping over pairs of phases

Found transition at critical temperature

» $T_c \rightarrow$ 19.9172

Computing nucleation temperature via $\Gamma/H^4 \approx 1$ criterion and bisection method...

» $T_n^{\text{estimate}} \rightarrow$ 11.542 $S_3/T$ = 158.914 $\Gamma/H^4$ = 1.02425

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» $T_n^{\text{estimate}} \to$ 11.542 $S_3/T = 158.914$ $\Gamma/H^4 = 1.02425$

Fitting action...

» Action function → ActionFunction[ Type: PWLaurent Domain: {11.1, 19.9} ]

Computing nucleation temperature via $\int dT/T\, \Gamma/H^4 \approx 1$ criterion and action fit method...

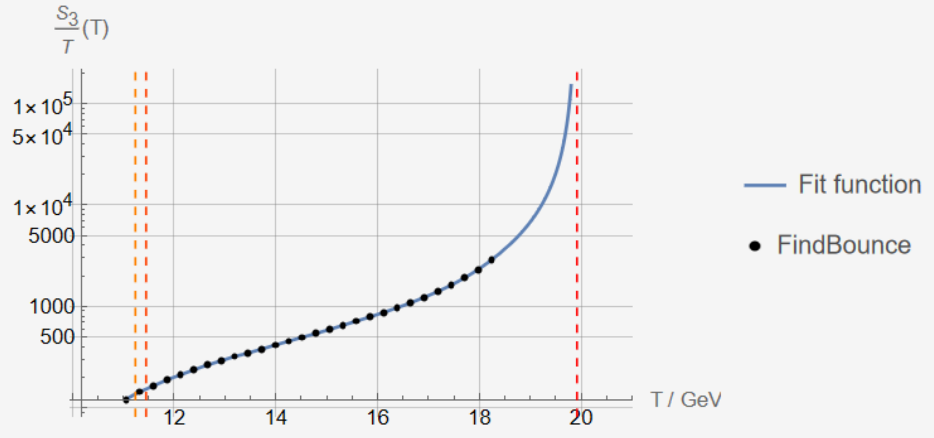
» $T_n \to$ 11.4517 $S_3/T = 150.997$ $\Gamma/H^4 = 2595.43$ $\int_{T_n}^{T_c} \frac{dT}{T} \frac{\Gamma}{H^4} = 0.878556$

Computing phase transition parameters...

Solving $I_{\mathcal{F}}(T_p) = 0.34$ for Tp

Searching for Tp with FindRoot...

» $T_p \to$ 11.2416



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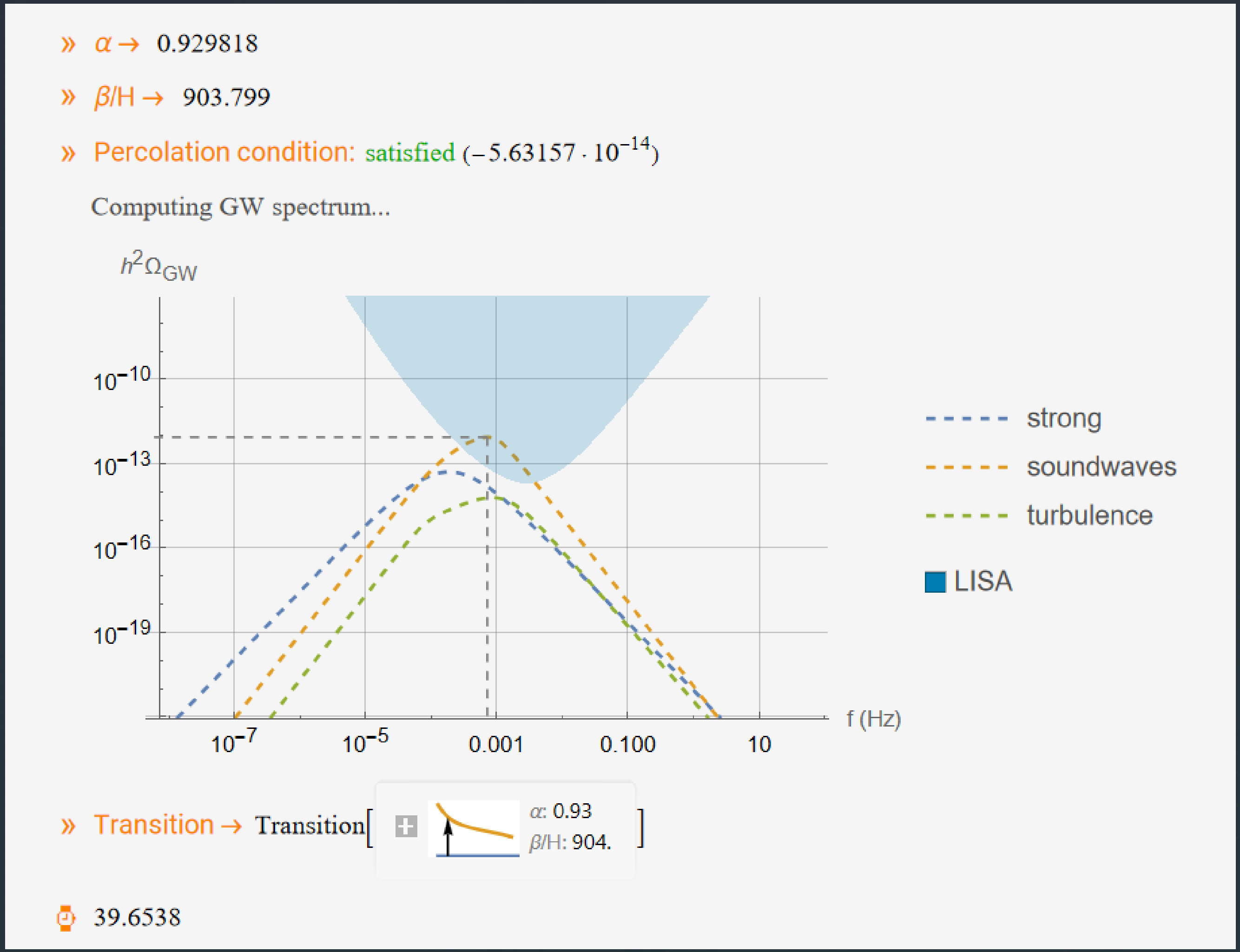
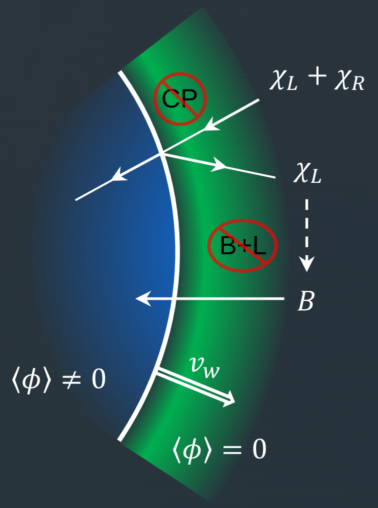
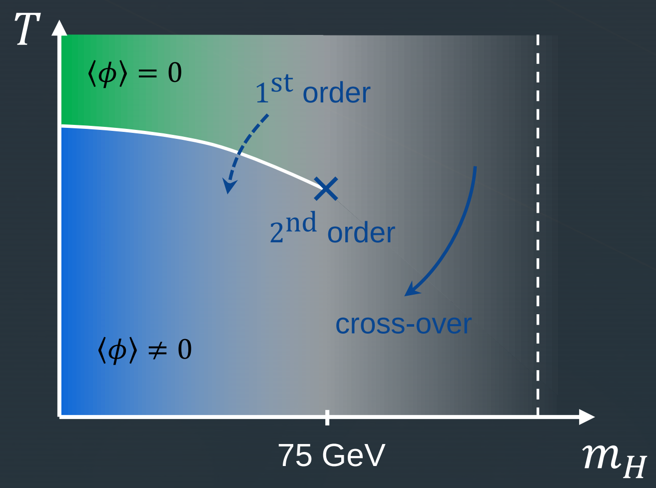


# EW Baryogenesis
The matter-antimatter problem

- Fundamental problem: baryon asymmetry
- Sakharov conditions (1967)

| Sakharov conditions (1967) | SM | LQ Model |
| --- | --- | --- |
| 1. B-number violation | ✓ → non-perturbatively | ✓ → LQs acquire vev |
| 2. C & P violation | ✓ → weakly | ✓ → potential |
| 3. Departure from $T$-equilibrium | ✗ → cross-over | ✓ → strong FOPTs |




BSM physics required!