

Colour-breaking/restoration in the Early Universe

A Minimal Leptoquark Model

Gr@v | University of Aveiro

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Bolsas de Investigação para
Doutoramento FCT-ECIU

Supervisors

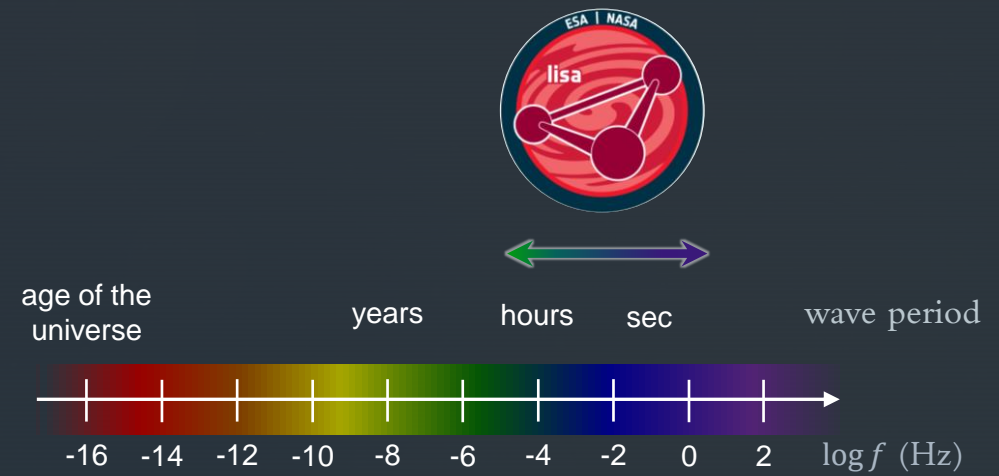
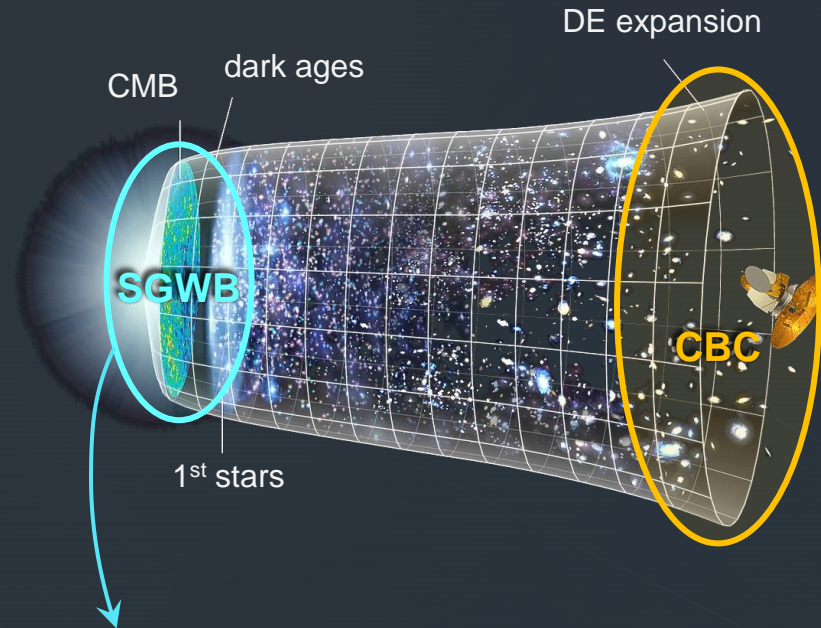
António Morais
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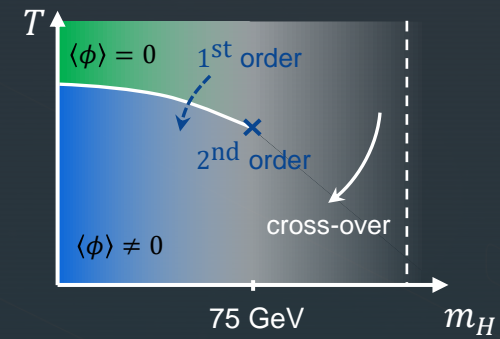
Contributors

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Gravitational Wave Sources



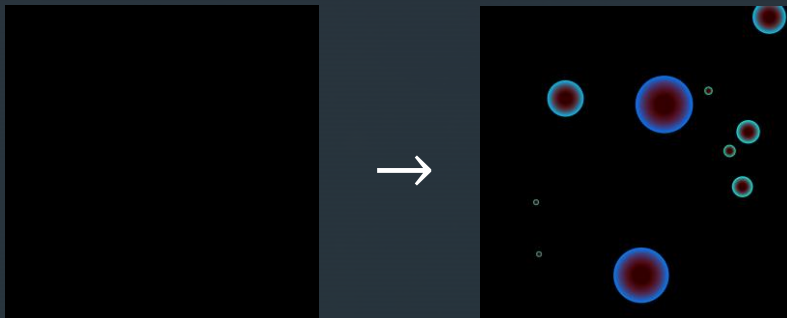
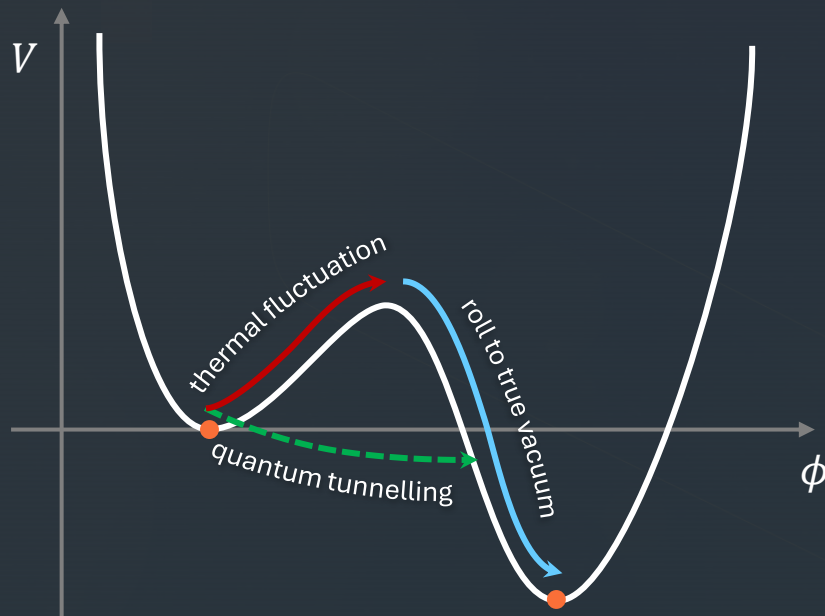
Main Sources	Frequency (Hz)
Inflation & preheating	??
Cosmic defects	$10^{-12} - 10^{-10}$ (strings)
Supermassive BH binaries	$10^{-10} - 10^{-7}$
Phase transitions	$\sim 10^{-5} - 10^{-2}$ (EW)
Primordial BHs	$\sim 10^1 - 10^2$



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:

$$2^2 \#vevs = 64$$

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

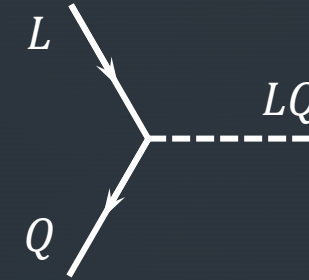
Leptoquarks

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

$$\begin{aligned}
 V_{LQ}^{(0)} = & \mu_H^2 H^\dagger H + \mu_S^2 S^\dagger S + \mu_R^2 R^\dagger R \\
 & + \lambda_H (H^\dagger H)^2 + \lambda_S (S^\dagger S)^2 + \lambda_R (R^\dagger R)^2 \\
 & + g_{HS} (H^\dagger H)(S^\dagger S) + g_{HR} (H^\dagger H)(R^\dagger R) + g'_{HR} (H^\dagger R)(R^\dagger H) + g_{RS} (R^\dagger R)(S^\dagger S) \\
 & + \alpha_1 RSH^\dagger + h.c.
 \end{aligned}$$

- Features

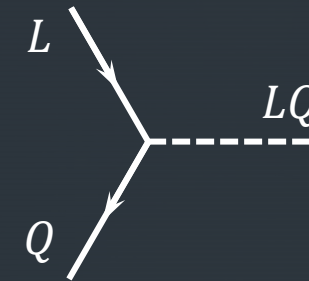
- flavour-consistent: $O(100)$ observables
- radiative generation of ν masses and mixing
- generate strong FOPTs

Leptoquarks

A minimal 2-LQ model

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

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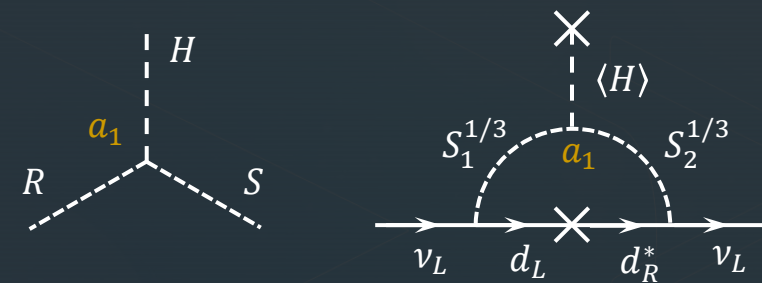


- Scalar content

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 & + \lambda_H (H^\dagger H)^2 + \lambda_S (S^\dagger S)^2 + \lambda_R (R^\dagger R)^2 \\
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 & + a_1 RSH^\dagger + h.c.
 \end{aligned}$$

- Features

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

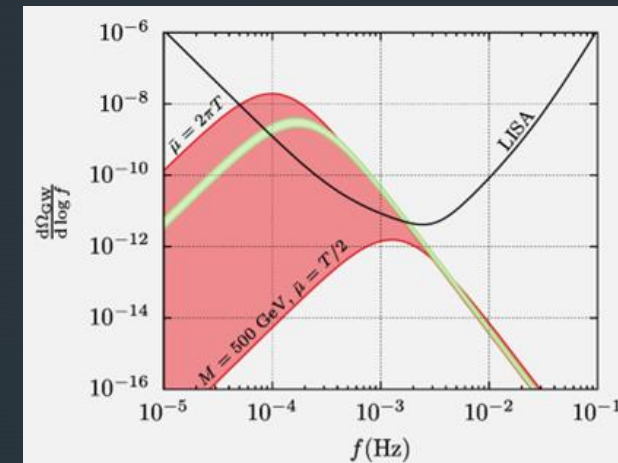
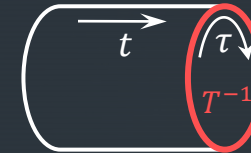


Dimensional Reduction

An improved recipe for thermal EFTs

- Leading-order perturbation theory (à la Coleman-Weinberg)
Linde problem: non-perturbative massless vector bosons
- Dimensional reduction (DR)
 - time \rightarrow temperature \Rightarrow high-T approach
 - include systematically higher-order resummations
- Narrower theoretical uncertainties
 \Rightarrow narrower GWB uncertainties
- Weakly-coupled EFTs \rightarrow thermal scale hierarchy

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



Credit: P. Schicho

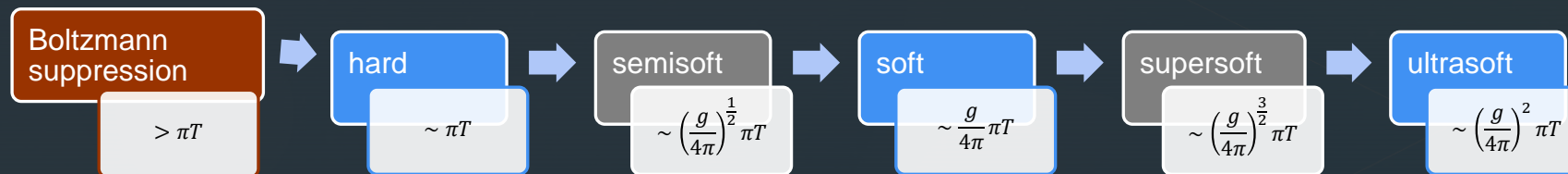
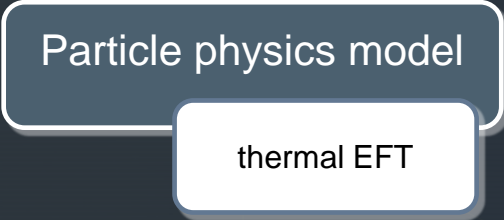


Figure inspired by eq. (2.1) of O. Gould and T.V.I. Tenkanen (JHEP01(2024)048)

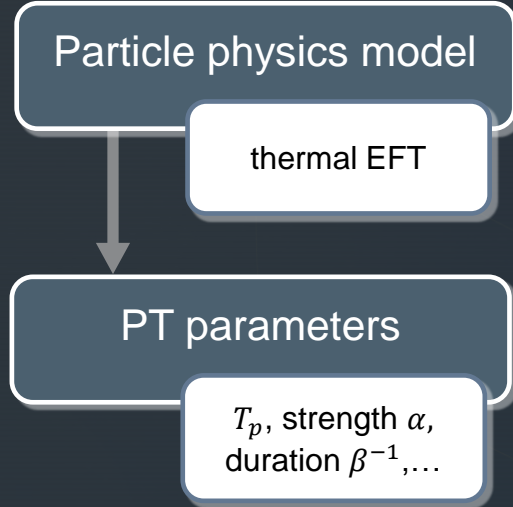
Outcome

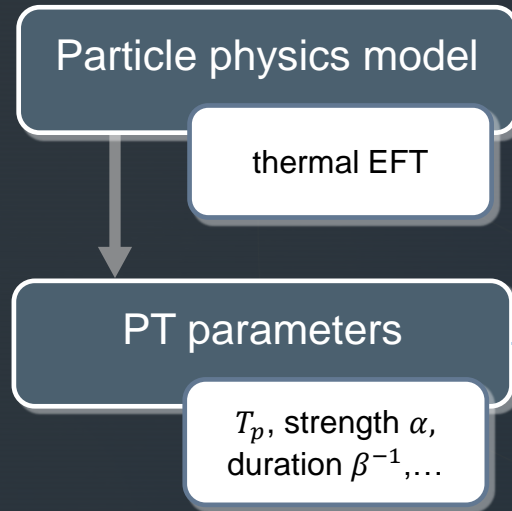
From Particle Physics to Cosmology



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: $I(T_p) \approx 0.34$

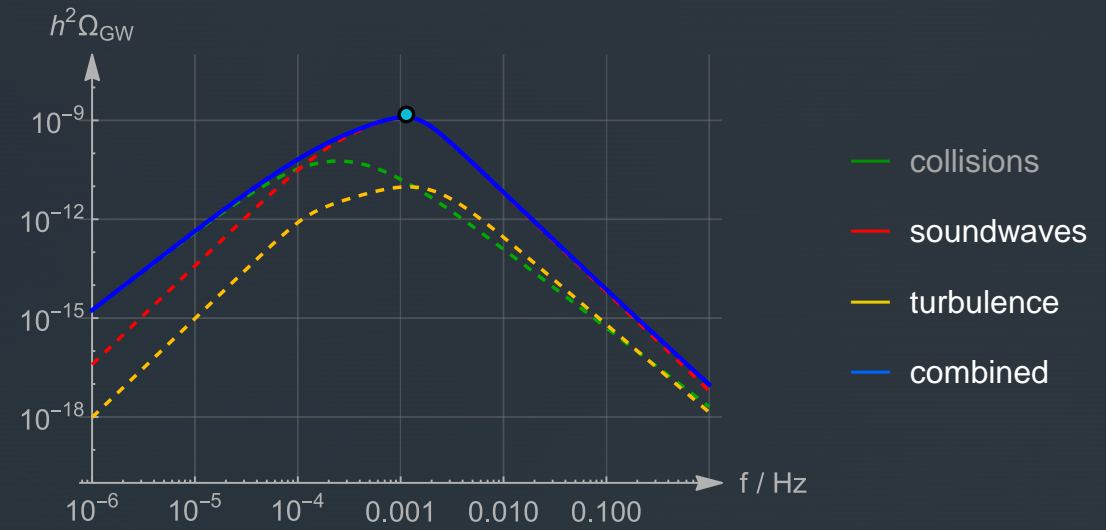
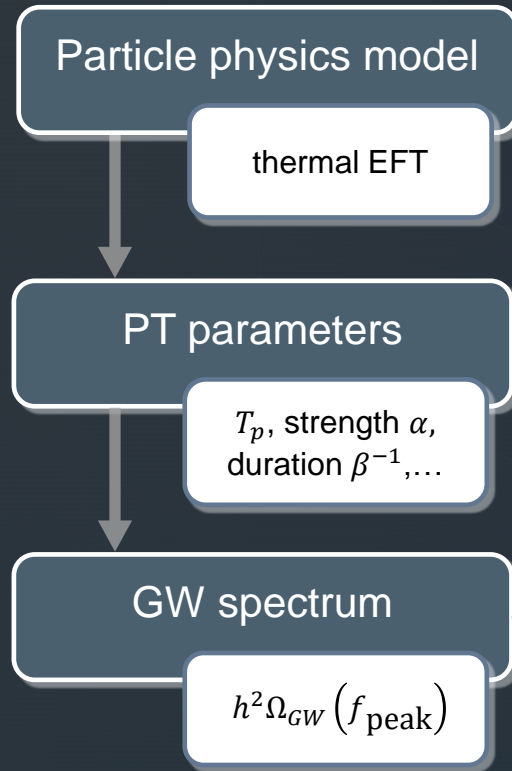
$$I(T) = \frac{4\pi}{3} v_w^3 \int_T^{T_p} \frac{dT'}{T'^4} \frac{\Gamma(T')}{H^4(T')} \left(\int_T^{T'} \frac{d\tilde{T}}{H(\tilde{T})} \right)^3$$

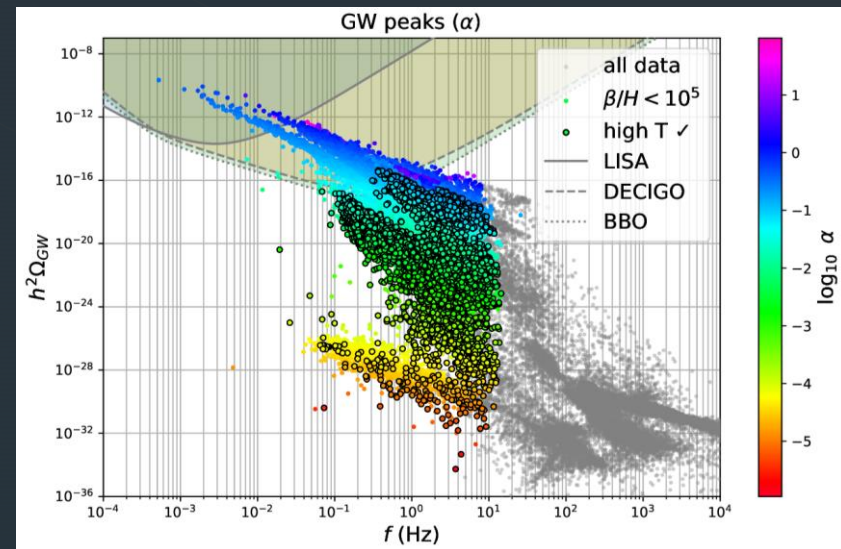
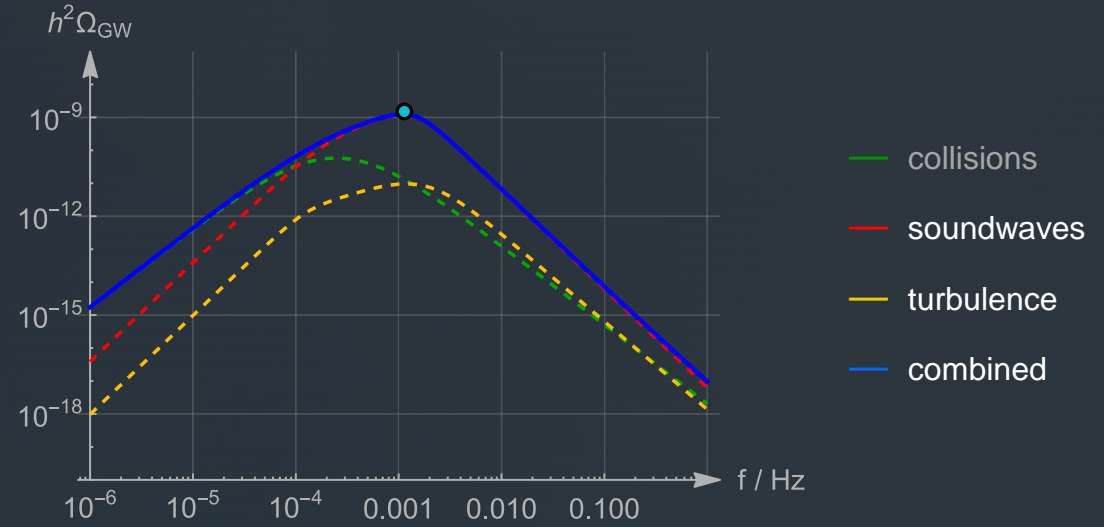
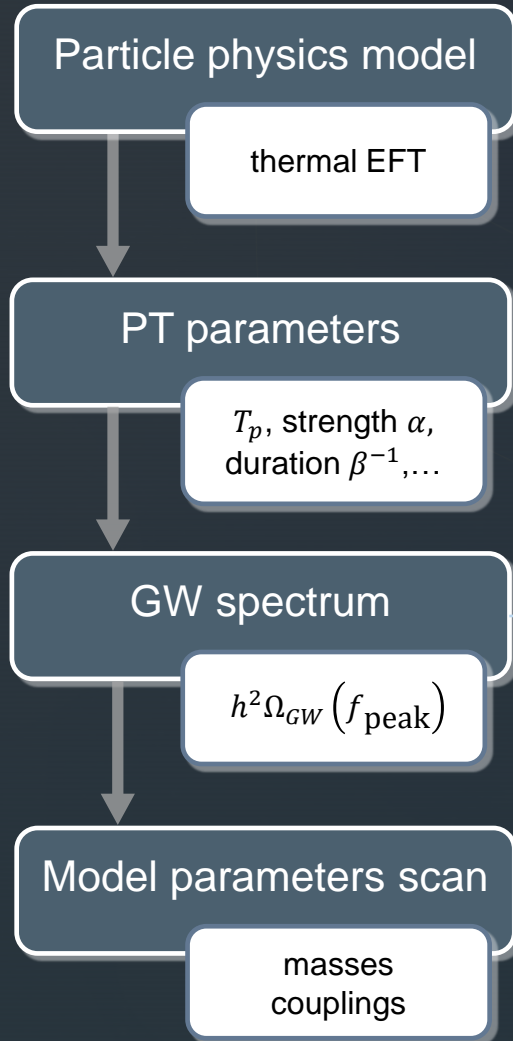
percolation condition: $\mathcal{V}'_{FV}(t_p) < 0$

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

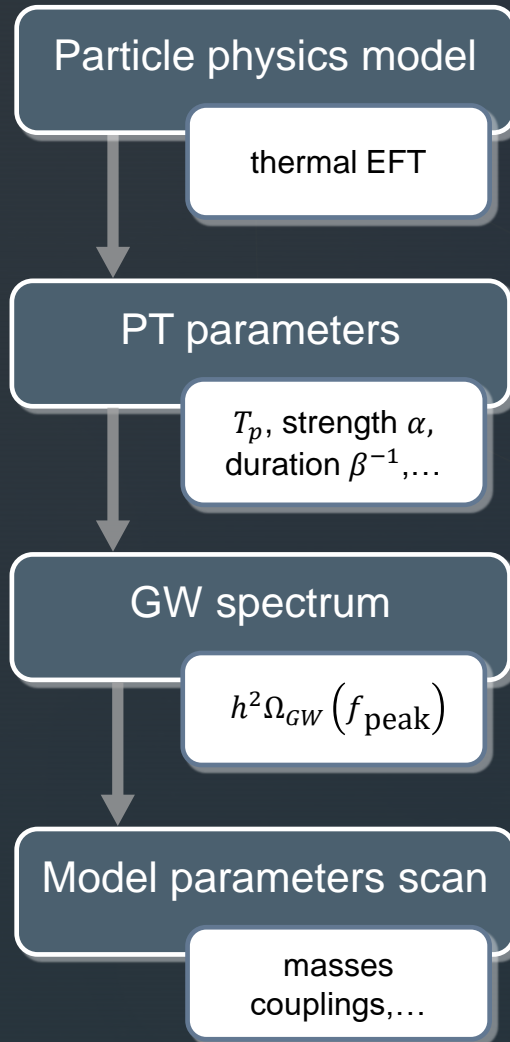
- strength $\alpha = \frac{1}{\rho} \Delta \left(V - \frac{T}{4} \partial_T V \right)$

- duration⁻¹ $\frac{\beta}{H} = T \frac{d}{dT} \left(\frac{S_3}{T} \right)$



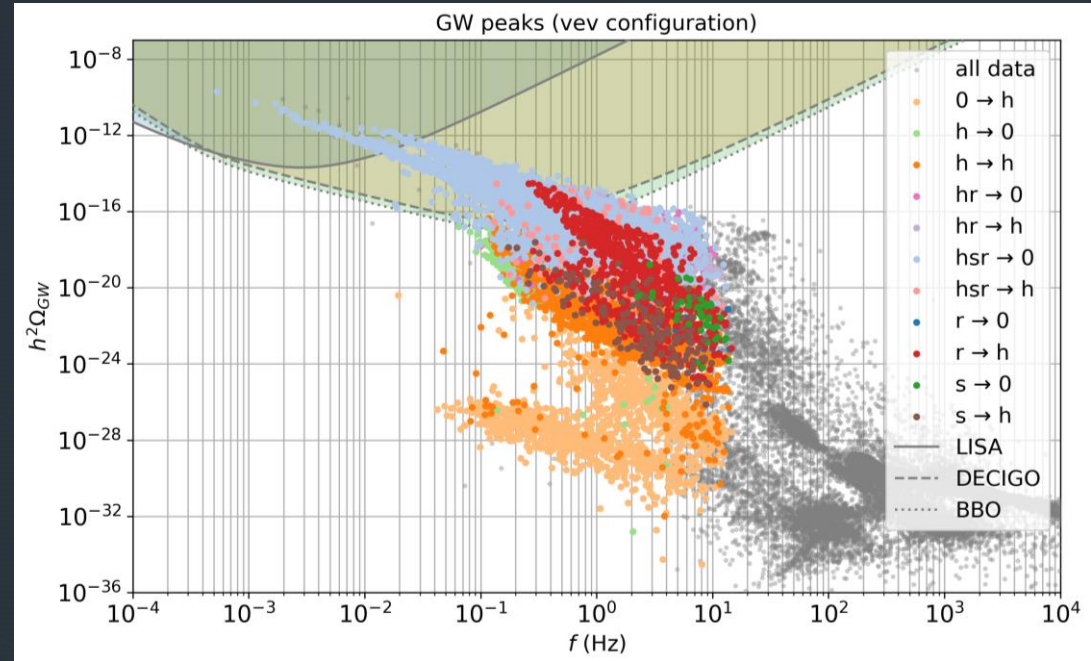


$$\circ \frac{m_{US}}{\pi T} \lesssim 1$$

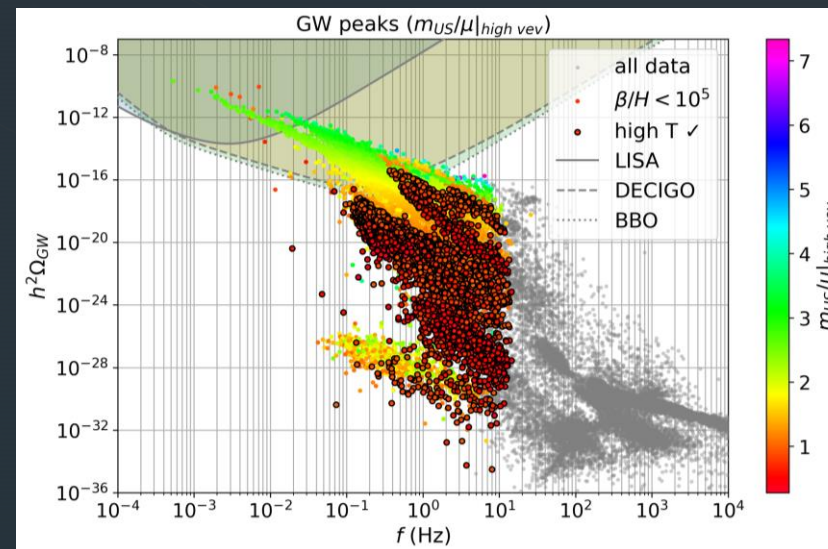
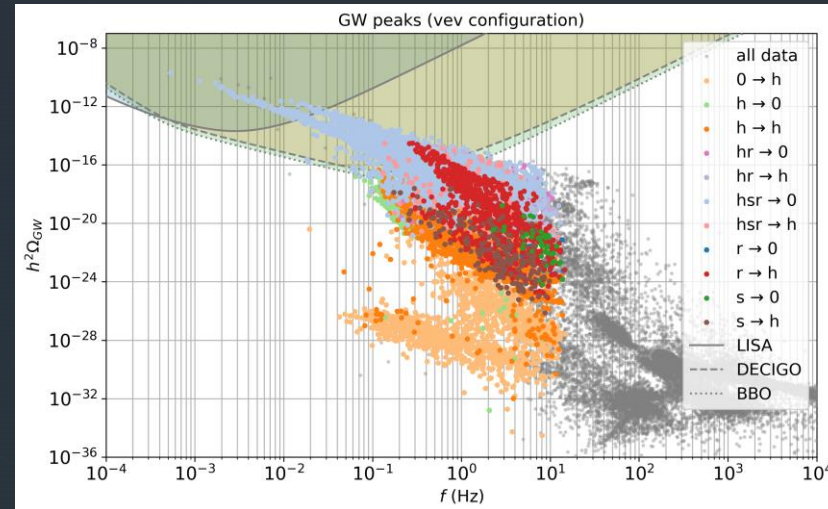
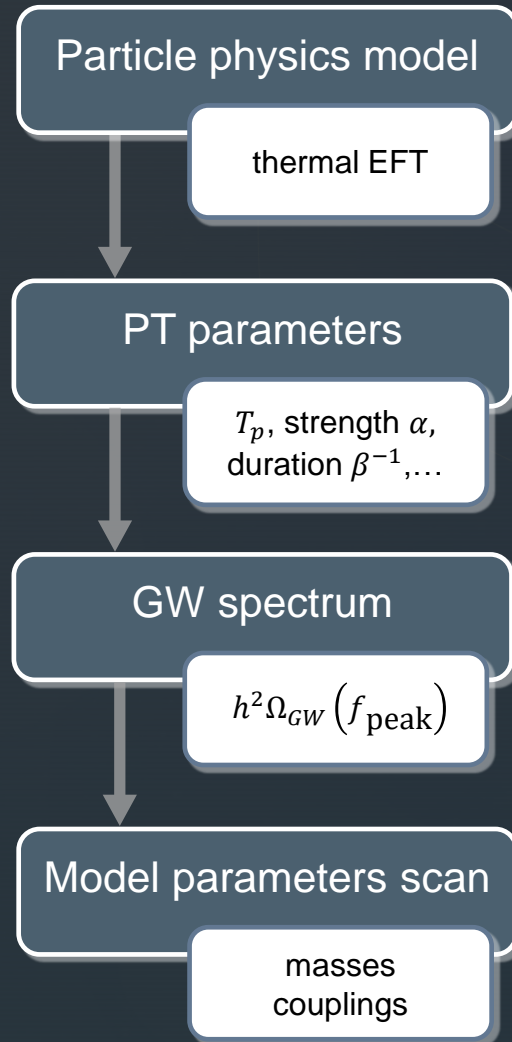


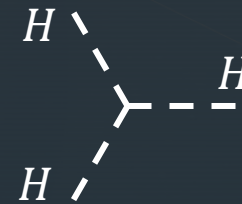
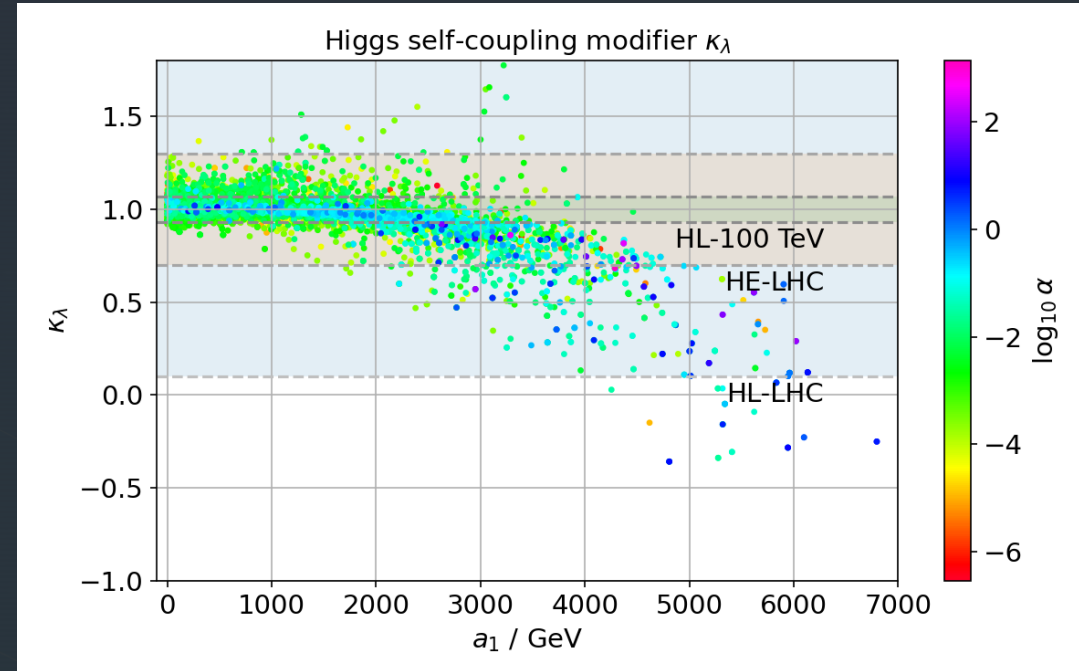
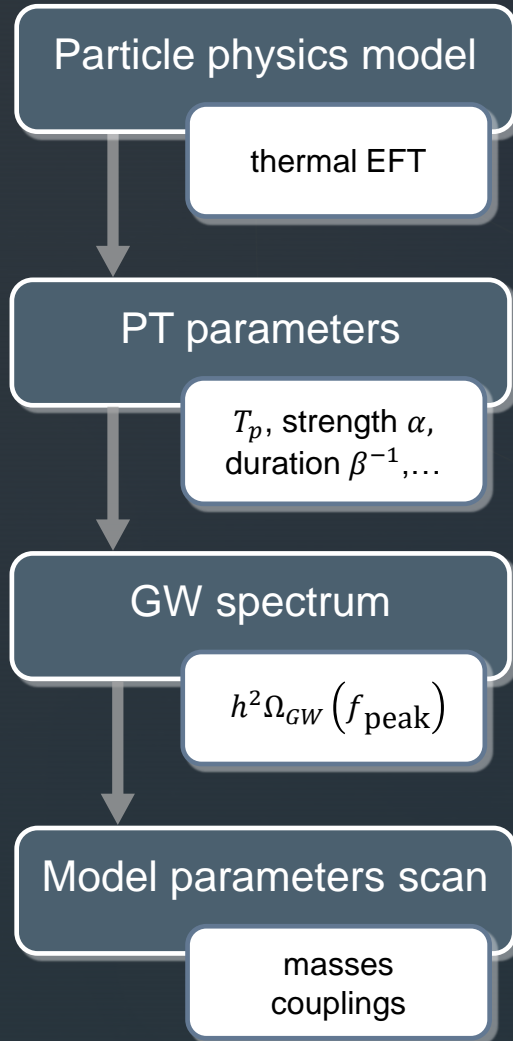
Outcome

From Particle Physics to Cosmology



Colour breaking
and restoration!





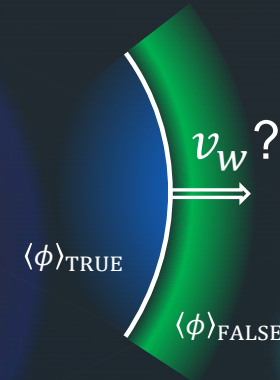
$$\kappa_\lambda \equiv \frac{\lambda_{hhh}^{BSM}}{\lambda_{hhh}^{SM}} = 1 + \frac{\lambda_{hhh}^{LQ}}{\lambda_{hhh}^{(0)} + \lambda_{hhh}^t}$$

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

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

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

Outcome & Future Endeavours



Thanks for listening!

Colour breaking in the early universe A minimal leptokuark model

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Abstract

The electroweak phase transition (EWPT) represents a promising explanation for the origin of baryon asymmetry in the Universe, yet an extension to the Standard Model (SM) is required to generate a strongly first order transition (FOPT). Leptoquark (LQ) models offer an alternative to conventional mass scenarios for the generation of Majorana neutrino masses at UV scale, and can induce strong FOPTs with a temporary colour-breaking phase in the early universe. This work illustrates results from a study of the parameter space of a LQ model [1], with one colored doublet (D) and one colored singlet (S), in the high-temperature regime defined via dimensional reduction [2].

Model

The LQ model considered represents an economical SM extension featuring two scalar leptoquarks, with hypercharges


$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\mathbb{3}$	$\mathbb{1}$	$1/2$
$\mathbb{3}$	$\mathbb{1}$	$1/6$
$\mathbb{1}$	$\mathbb{1}$	$1/3$

The scalar content of the theory reads

$$V_{\text{tree}} = \mu_1^2 H^2 + \mu_2^2 \tilde{H}^2 + \mu_3^2 S^2 + \lambda_1 |H|^4 + \lambda_2 |\tilde{H}|^4 + \lambda_3 |S|^4 + g_1 H^2 \tilde{H}^2 + g_2 H^2 S^2 + g_3 \tilde{H}^2 S^2 + (c_1 H S H + \text{h.c.}) \quad (1)$$

At low energies, the Higgs doublet acquires a vacuum expectation value $\langle v \rangle \approx 246$ GeV. One of the \tilde{H} doublets mixes with the S -singlet via the g_3 trilinear coupling, leaving one unmixed and two mixed LQs. The LQ model offers an alternative to conventional mass mechanisms for the development of Majorana neutrinos at UV scale, allowing to consistently generate both their masses and their mixing structure [1]. Additionally, the model is flavor-consistent, obeying constraints from $O(100)$ collider observables.

For the sake of this study, the presence of LQs can induce strong first order phase transitions with a colour-breaking phase in the early universe. Of particular relevance is the trilinear g_3 coupling, providing mixing between leptoquarks and thus enabling to generate both the neutrino masses and strong FOPTs, via stable cubic terms.



Matching to the SM

In order to ensure consistency with the SM at low energies (~ 100 GeV),

$$v^2 \text{tr}(S^\dagger S) = \mu_3^2 v^2 + \lambda_3 v^4, \quad (2)$$

we run SM parameters up to the LQ scale (~ 1 TeV) and match the theories (1)+(2) at 1-loop, in the $\overline{\text{MS}}$ -renormalization approach. This is tantamount to equating 2^{nd} and 3^{rd} derivatives of the two theories:

$$\frac{d^2 \mu_3}{d\ln \mu^2} = \frac{d^2 \mu_3^{\text{SM}}}{d\ln \mu^2} \Rightarrow \mu_3^2 = \mu_3^{\text{SM}^2} + \mu_3^{\text{LQ}^2} \quad (\text{LQ param})$$

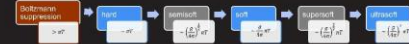
$$\frac{d^3 \mu_3}{d\ln \mu^3} = \frac{d^3 \mu_3^{\text{SM}}}{d\ln \mu^3} \Rightarrow \lambda = \lambda_{\text{SM}} + \lambda_{\text{LQ}} \quad (\text{LQ param})$$

We then insert these relations to obtain μ_3 and λ_{LQ} in terms of μ_3 , λ and the remaining LQ parameters.

Dimensional reduction

Leading-order perturbation theory, commonly adopted to compute thermal effective field theories (EFT), is affected by the Linde problem [3]. Dimensional reduction (DR) overcomes the challenge by systematically including next-to-leading-order (NLO) effects, including

- 1-loop renormalization of couplings and fields
- 2-loop thermal masses



DR trades time for temperature, leaving a purely thermal EFT living exclusively in a high-temperature regime. Phase transitions in weakly coupled QFTs are characterized by a hierarchy of thermal scales [4]. We derive a thermal EFT from the LQ model [1] by employing $\mathcal{O}(2+1)_g$ [5], which matches the hard-scale of theory to a soft-scale M theory, and thereafter integrates out temporal modes to lower an effective $3d$ theory at the ultraviolet scale.

Scanning

We trace the phases, compute the tunnelling amplitude, and scan over the parameter space of the theory by means of a modified version of CosmoTransitions. While typical EWPT studies assume specific action values at nucleation ($S_4/T \approx 140$), we implement the energy-scale-independent criterion

$$\int_{\text{wall}} \frac{T_4}{T} \frac{dV}{d\vec{x}} = 1, \quad (3)$$

to determine the nucleation temperature T_4 , with $T_4^4 = T_4^4 \langle \sigma \rangle^4 |v|^{-4} \sim \sigma^4$ the nucleation rate. Crucially for strongly-supersaturated conditions, the Hubble parameter $H = \sigma/g_{\text{eff}}$ includes contributions from both the radiation and vacuum energies:

$$H(T) = \frac{c^2}{3} \frac{g_{\text{eff}}}{M_{\text{pl}}^2} T^4 + \frac{\Delta V}{3M_{\text{pl}}^2} \quad (4)$$

Phase transition parameters are computed at the preheating temperature T_4 , which, for uniformly nucleated spherical bubbles, satisfies the false vacuum fractional volume condition $P(T) = c \ll \rho^*/\rho \approx 0.1$, where

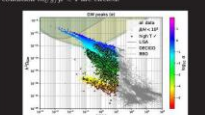
$$H(T) = \frac{4\pi}{3} \frac{dV}{d\ln T} \frac{d\ln T}{dT} \left(\int_{\text{wall}} \frac{dV}{d\vec{x}} \right)^2 \frac{1}{H(T)^2}, \quad (5)$$

or equivalently $|cT| \approx 0.34$. Finally, we must ensure that the true vacuum volume is increasing at T_4 , accounting for the Universe expansion rate: $H(T_4)/H(T) + \dot{T} < 0$. We scan over LQ masses and gauge parameters as follows:

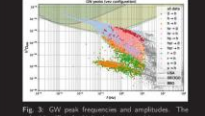
Parameter	Range	Log scale
$\lambda_{1,2}$	$[10^{-1}, 2]$	✓
$g_{1,2,3}$	$\pm [10^{-3}, 2]$	✓
$m_{1,2}$	$[0.8, 3]$ TeV	✗
θ	$[-\pi, \pi]$	✗

Outcome

Our scanning routine shows that a significant region of the parameter space features GW peaks detectable by future missions. For SM-like EFTs, transitions with an inverse duration $(\dot{H}/H) \gtrsim 10^5$ are effectively quenched [1]. Points strictly obeying the high-temperature perturbative condition $m_{1,2}/\mu \ll 1$ are checked.



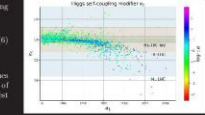
Several vev configurations can be identified. A crucial aspect in the presence of PGB breaking color-symmetry at high temperatures and restoring it at low temperatures:



We compute the Higgs trilinear cubic coupling at one-loop, including both the LQ and top-quark contributions:

$$\lambda_{\text{HSS}} = \lambda_{\text{SM}}^{\text{tree}} + \frac{\lambda_{\text{SM}}^{\text{1-loop}}}{16\pi^2} \rightarrow \kappa_3 = 1 + \frac{\lambda_{\text{LQ}}^{\text{1-loop}}}{\lambda_{\text{SM}}^{\text{tree}} + \lambda_{\text{SM}}^{\text{1-loop}}} \quad (6)$$

where the tree-level contribution is $\lambda_{\text{SM}}^{\text{tree}} = 3m_t^2/v$. At large values of κ_3 , we notice stronger modifications to κ_3 , lowering the value of the Higgs self-coupling. The horizontal dashed lines show the highest expected sensitivities at future colliders.



References

[1] P. P. Giardino, J. Guzman, A. P. Morais, R. Pasechnik, and M. Ratz, *Strongly first order phase transitions, baryon asymmetry and neutrino production*, *Phys. Rev. D* **104**, 035011 (2021).
 [2] A. Ekstedt, M. Berntson, and J. Rathsman, *Origin of baryon asymmetry from thermal phase transitions*, *Phys. Rev. D* **104**, 035011 (2021).
 [3] G. 't Hooft, *Instantaneous Approximation to the Yang-Mills Heat Kernel*, *Nucl. Phys. B* **190**, 455 (1981).
 [4] G. 't Hooft, *Dimensional Reduction in Quantum Chromodynamics*, *Nucl. Phys. B* **190**, 455 (1981).
 [5] G. 't Hooft, *Dimensional Reduction in Quantum Chromodynamics*, *Nucl. Phys. B* **190**, 455 (1981).

Acknowledgments

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More Information

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CIDMA | Collo group





Additional slides

- Pipeline requires to determine temperatures of

$$\left. \begin{array}{l} \bullet \text{ nucleation } \int_{T_n}^{T_c} dT \frac{\Gamma(T)}{T H^4(T)} \sim 1 \\ \bullet \text{ percolation } I(\Gamma, T_p) \approx 0.34 \end{array} \right\} \Gamma(T) = A \left(\frac{S_3}{T}, T \right) e^{-\frac{S_3}{T}}$$

- $\frac{S_3}{T}(T)$ numerical estimation: FindBounce

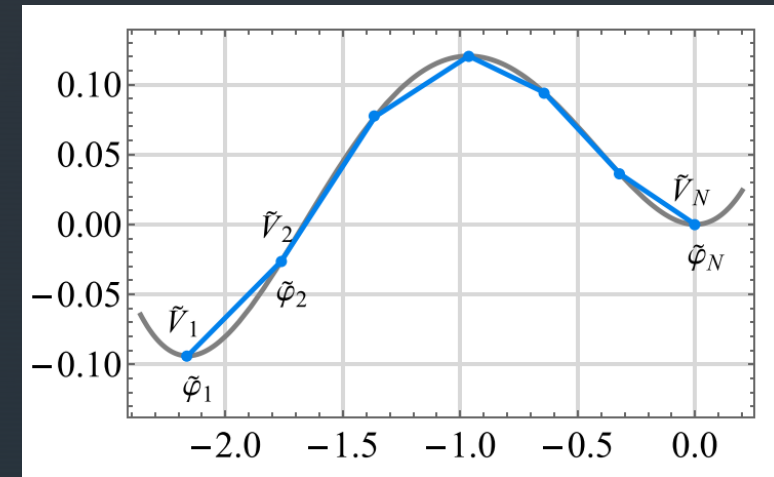
- implements *polygonal bounces*
- $4d (S_4)$ or $3d (S_3)$
- ✓ thin-wall regime
- efficient: $t \sim O(\# \text{ fields}), O(\# \text{ segments})$

- Method

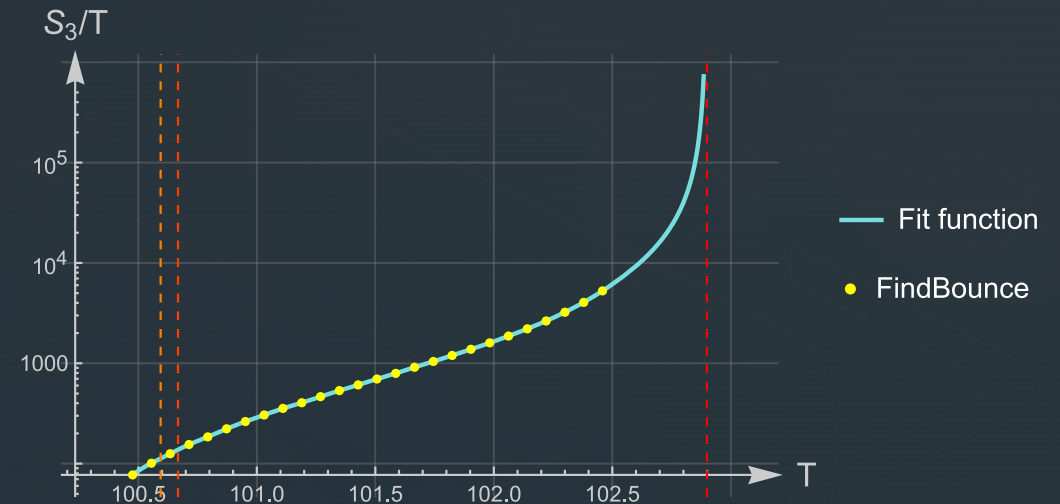
1. \hat{T}_n estimate via $\Gamma/H^4 \sim 1$
2. S_3/T fit/interpolation about ($\sim \hat{T}_n, T_c$)
3. T_n, T_p via above integrals

Paclet

FindBounce + action fit



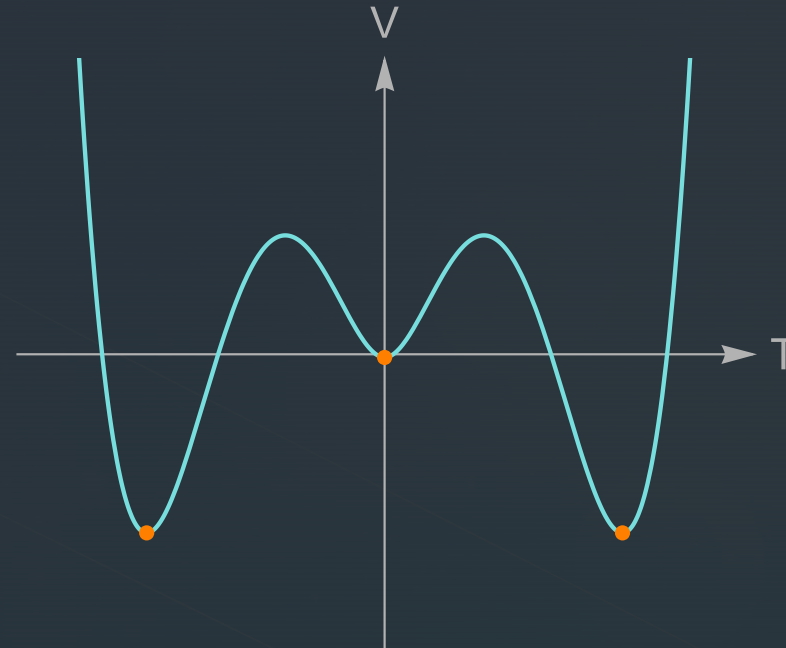
Guada, Nemevšek, Pintar ([CPC 256 \(2020\) 10748](#))



Exempl

Dark photon model

- Dark $U(1)$ gauge sector
 - Scalar content:
 $V(\phi, T) = \mu^2 \phi^2 + \lambda \phi^4$
+ fermions
 - V_{eff} @ NLO
- Paclet



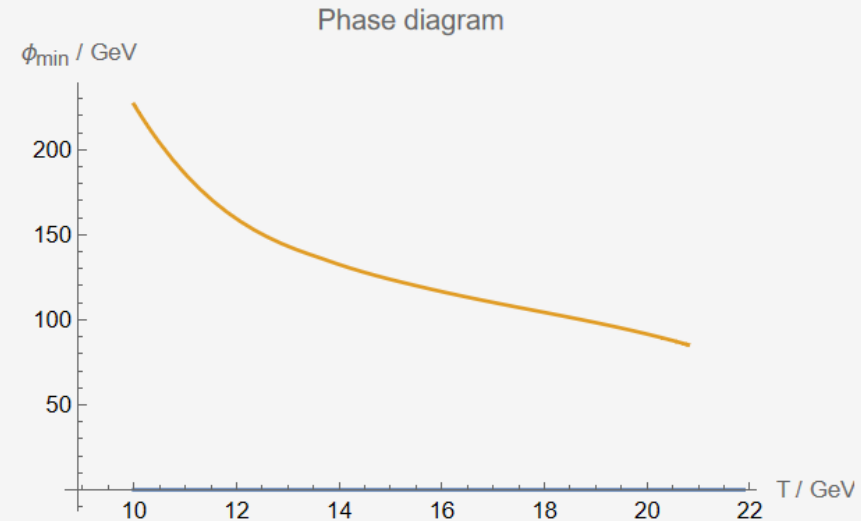
Example II

Dark photon model

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

$$V(\phi, T) = \mu^2 \phi^2 + \lambda \phi^4$$
 - + fermions
 - V_{eff} @ NLO
- 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...

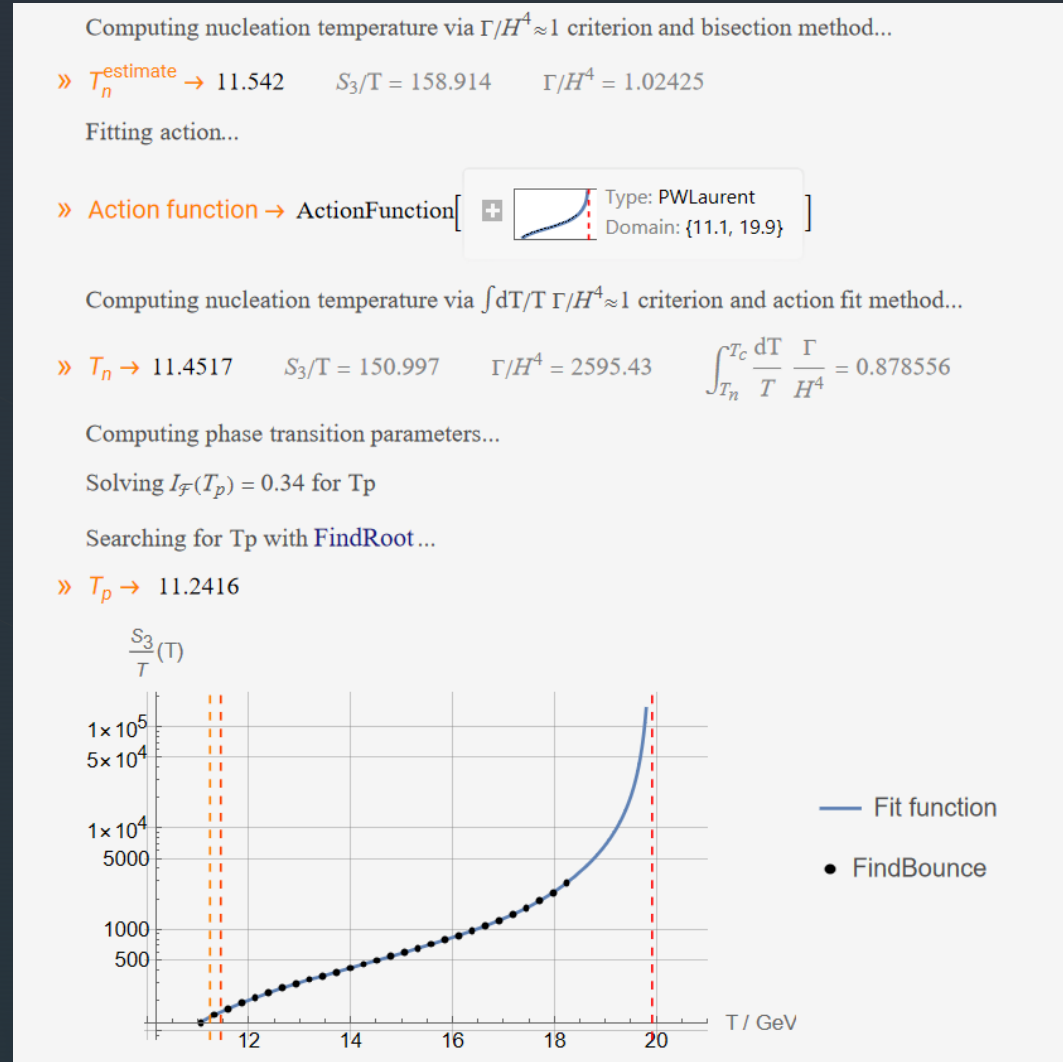
» $T_n^{\text{estimate}} \rightarrow 11.542$ $S_3/T = 158.914$ $\Gamma/H^4 = 1.02425$

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

$$V(\phi, T) = \mu^2 \phi^2 + \lambda \phi^4$$
 + fermions
 - V_{eff} @ NLO
- Paclet

Example II

Dark photon model

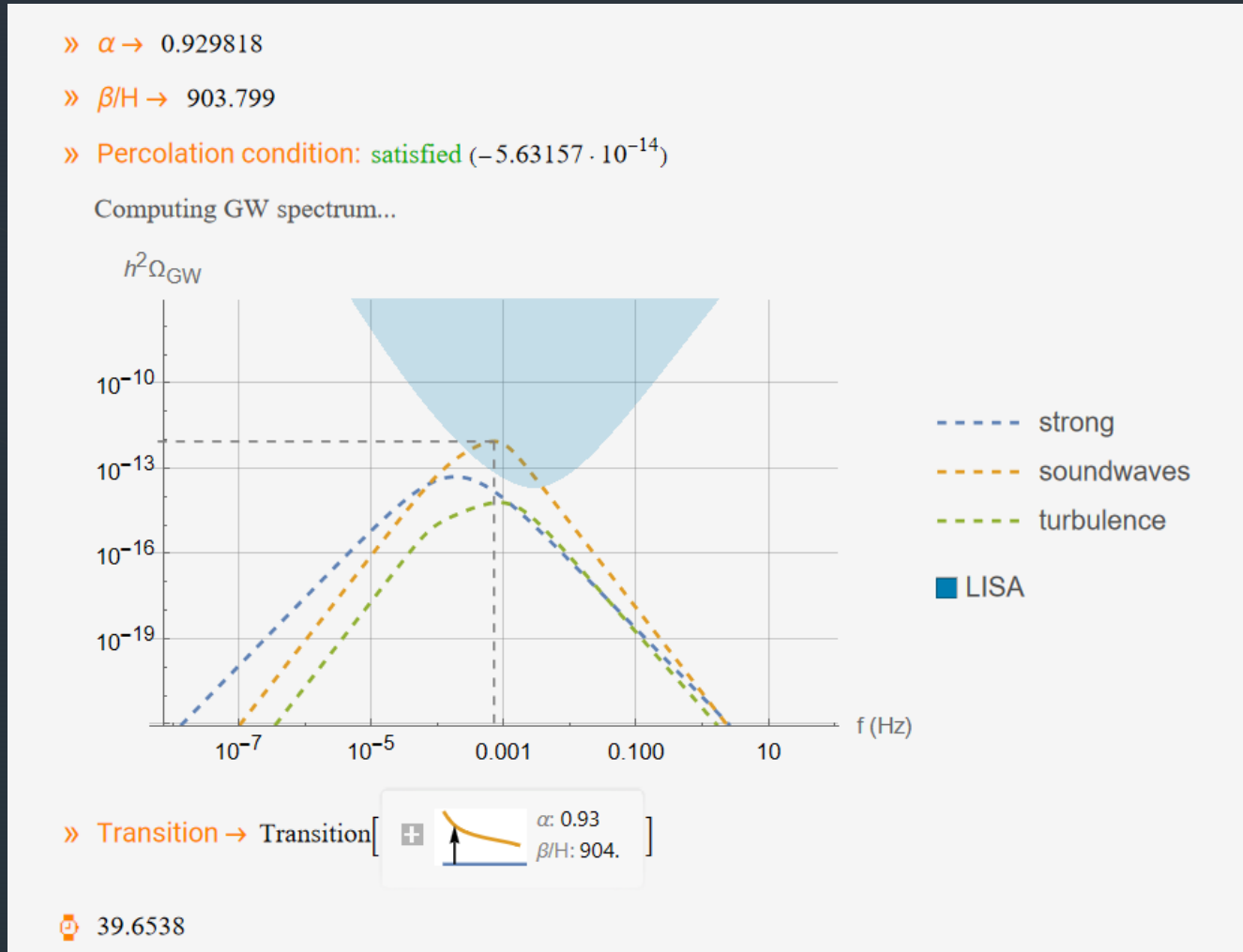


- Dark $U(1)$ gauge sector
 - Scalar content:

$$V(\phi, T) = \mu^2 \phi^2 + \lambda \phi^4$$
 - + fermions
 - V_{eff} @ NLO
- Paclet

Example II

Dark photon model

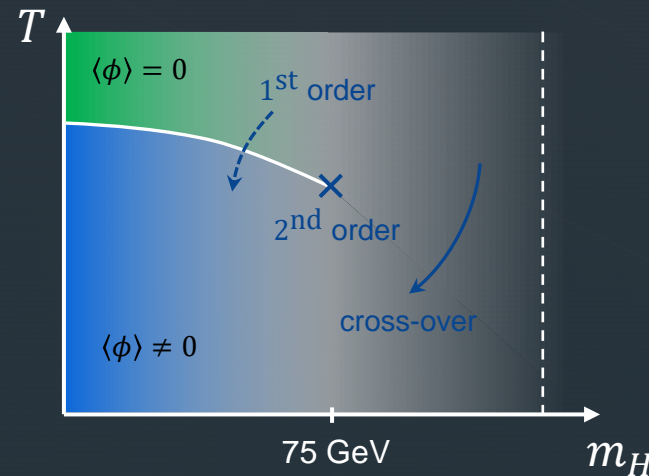
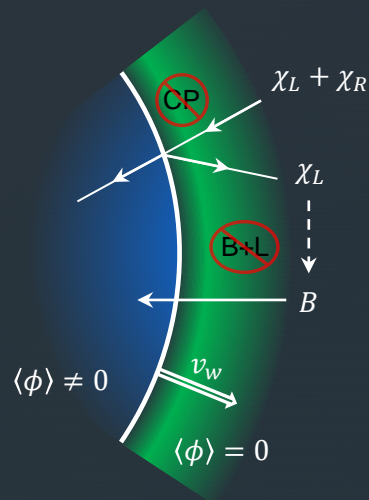


EW Baryogenesis

The matter-antimatter problem

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

	SM	LQ Model
1. B-number violation	$\checkmark \rightarrow$ non-perturbatively	$\checkmark \rightarrow$ LQs acquire vev
2. C & P violation	$\checkmark \rightarrow$ weakly	$\checkmark \rightarrow$ potential
3. Departure from T -equilibrium	$\times \rightarrow$ cross-over	$\checkmark \rightarrow$ strong FOPTs



BSM physics
required!