

## Colour-breaking/restoration in the Early Universe

### A Minimal Leptoquark Model

Gr@v | University of Aveiro

2024-05-16

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Marco Finetti

#### Project ID

PRT/BD/154730/2023

Bolsas de Investigação para  
Doutoramento FCT-ECIU

#### Supervisors

António Morais  
University of Aveiro | Gr@v

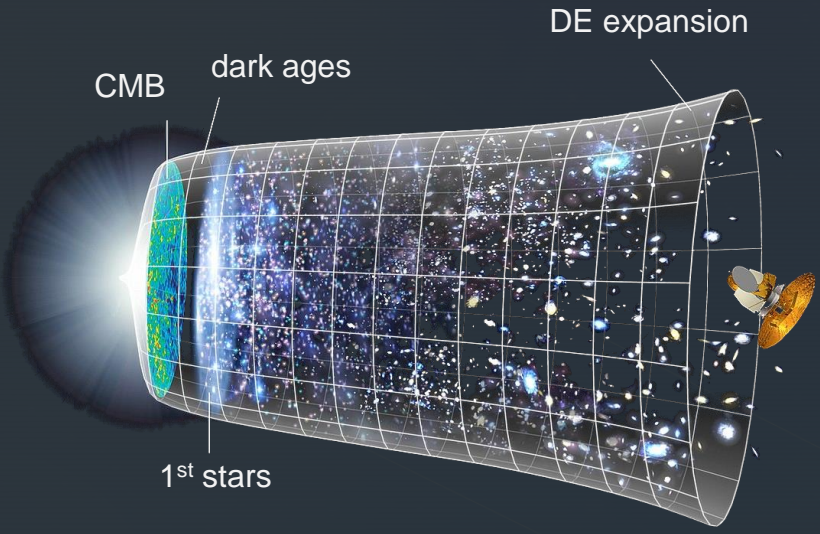
Germano Nardini  
University of Stavanger

#### Contributors

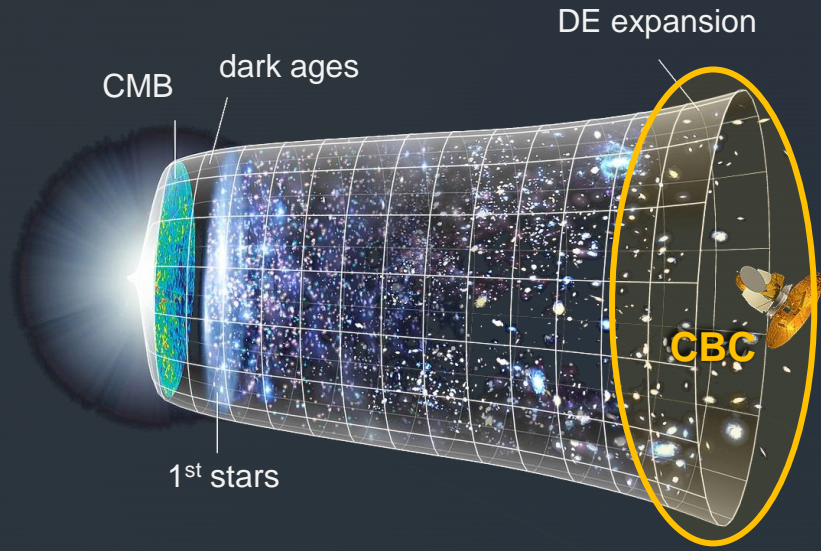
Andreas Ekstedt (U. Uppsala)  
Mårten Bertenstam (U. Lund)  
António Morais (U. Aveiro)  
Roman Pasechnik (U. Lund)  
Johan Rathsman (U. Lund)

# Gravitational Wave Sources

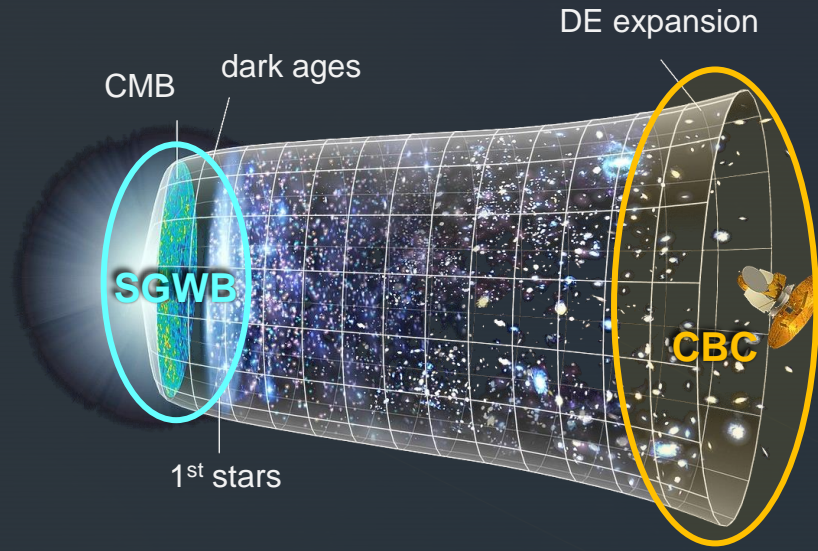
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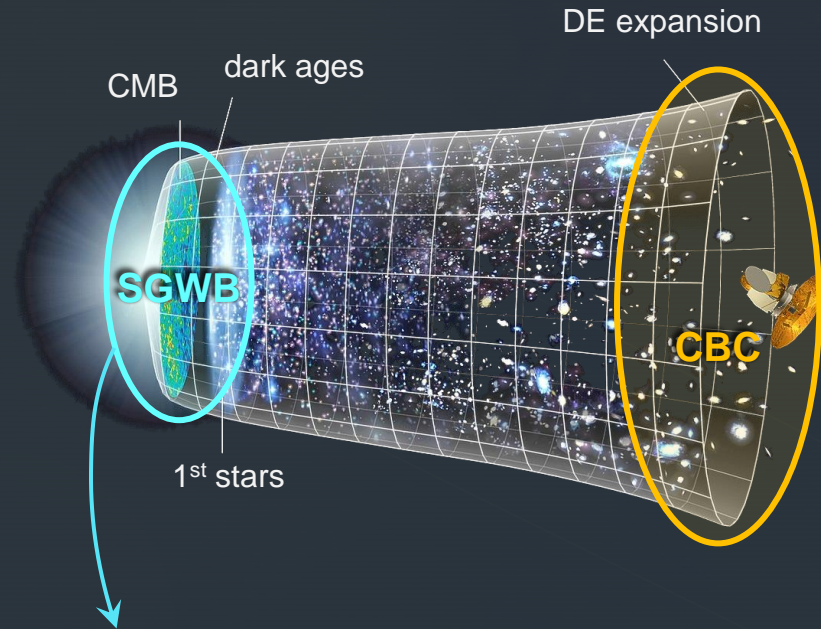
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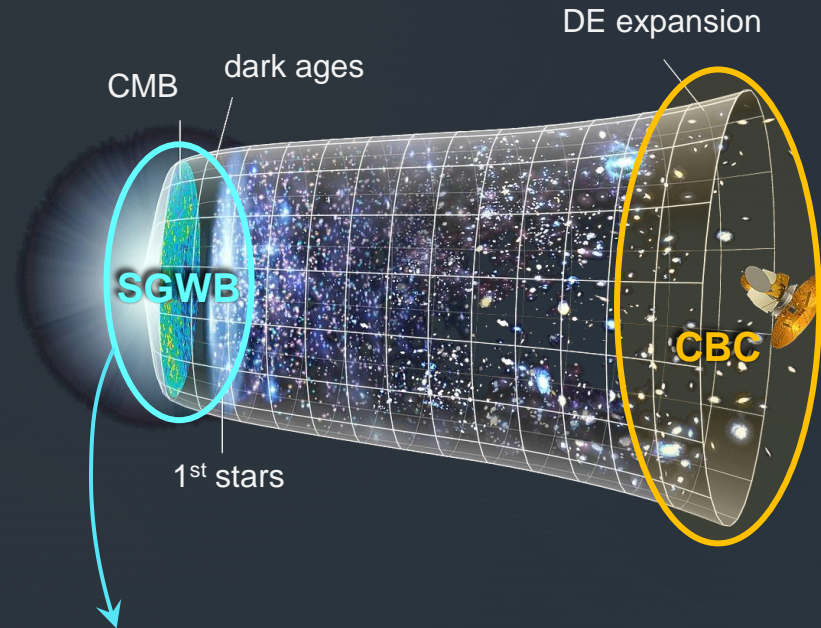


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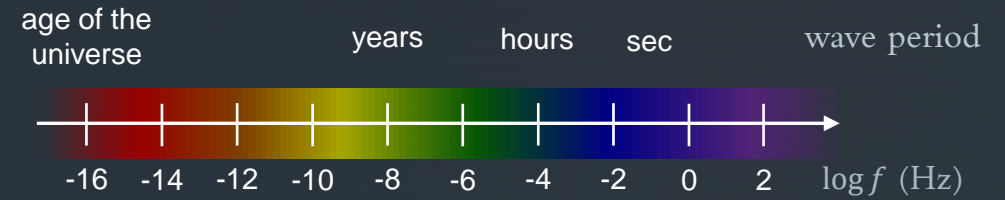
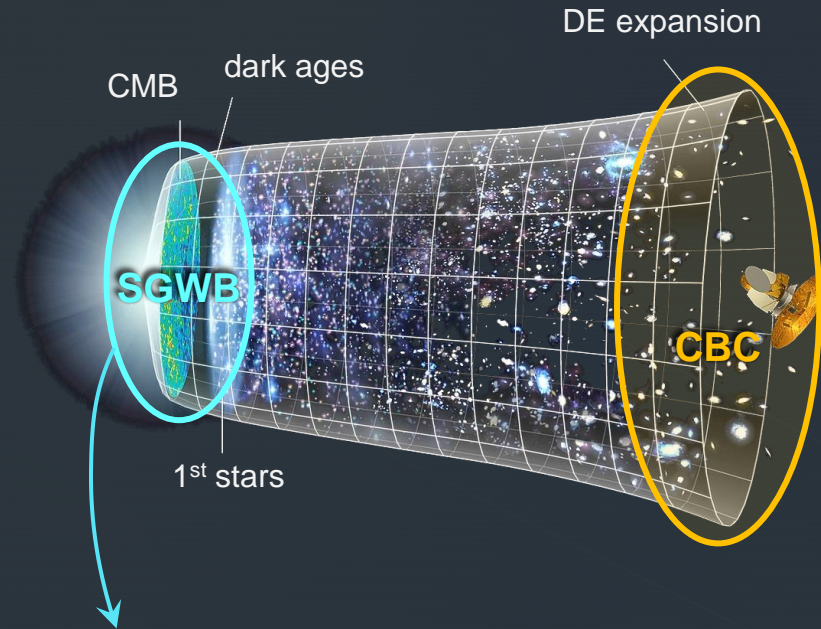
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Inflation & preheating	??
Cosmic defects	$10^{-12} - 10^{-10}$ (strings)
Supermassive BH binaries	$10^{-10} - 10^{-7}$
Phase transitions	$\sim 10^{-5} - 10^{-3}$ (EW)
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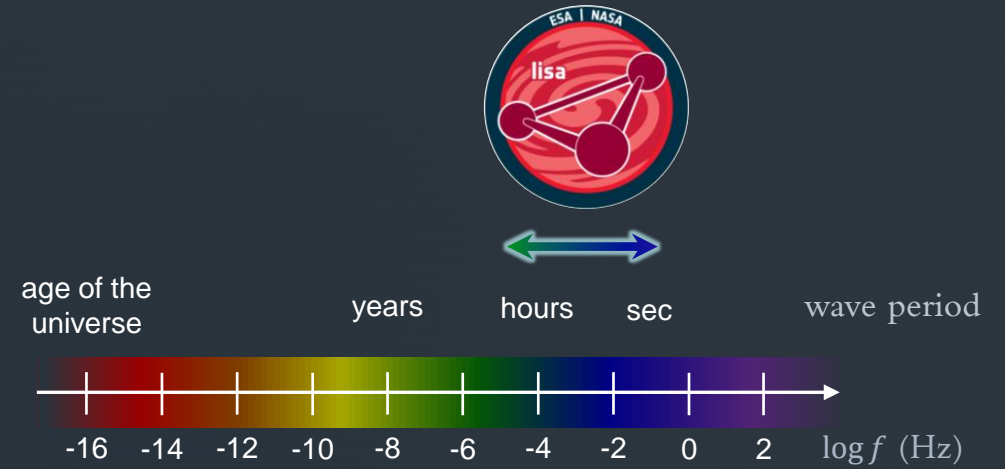
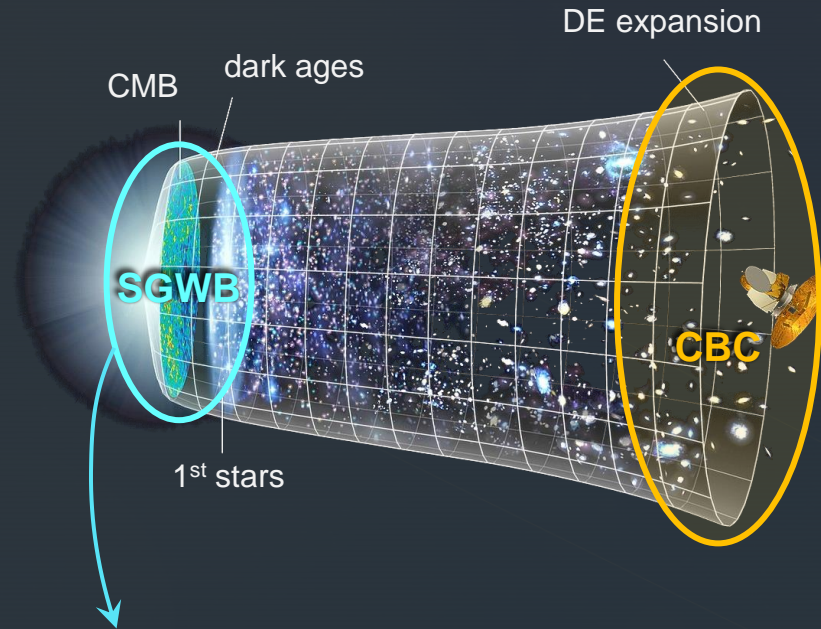
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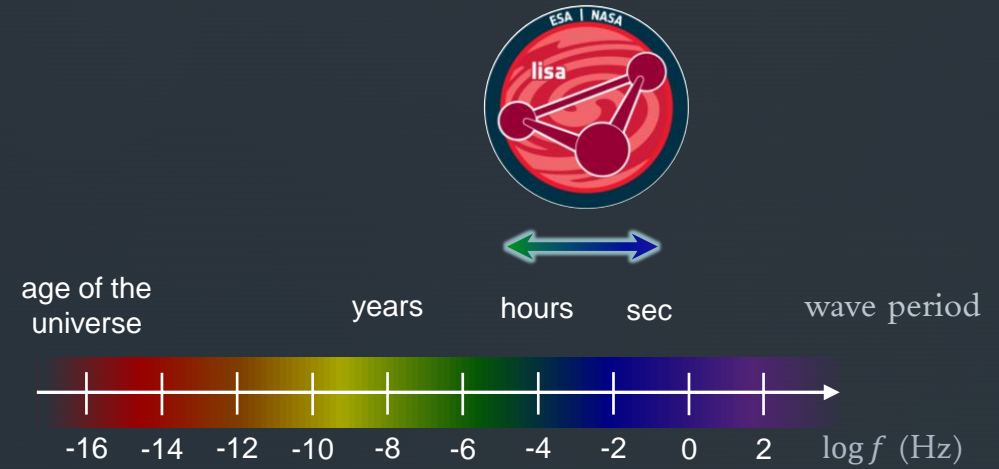
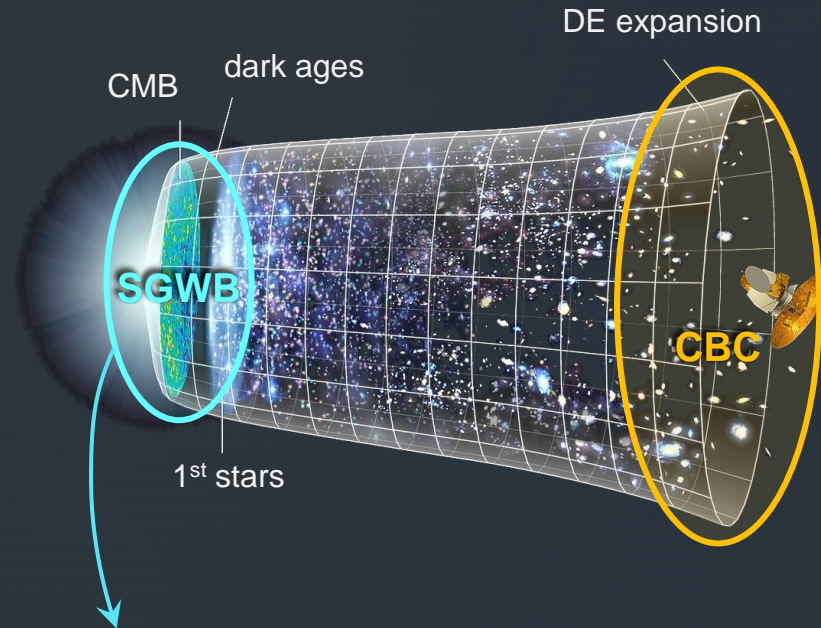


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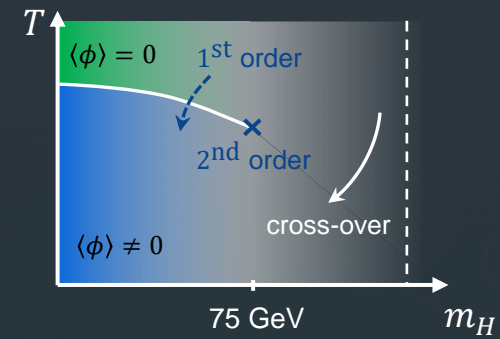


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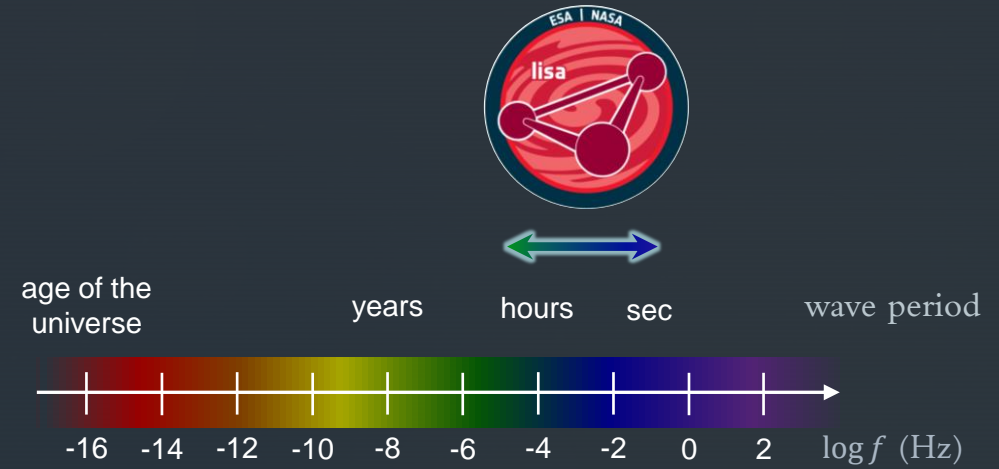
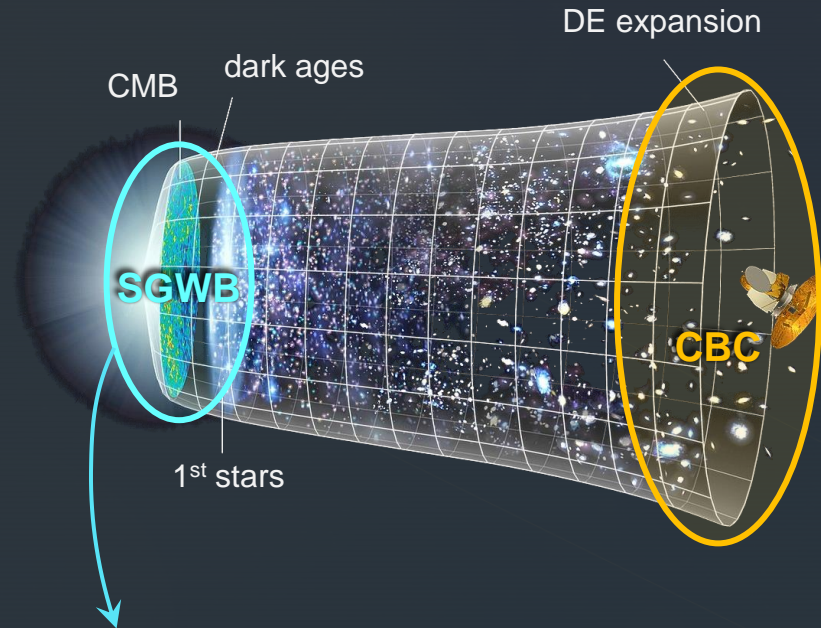
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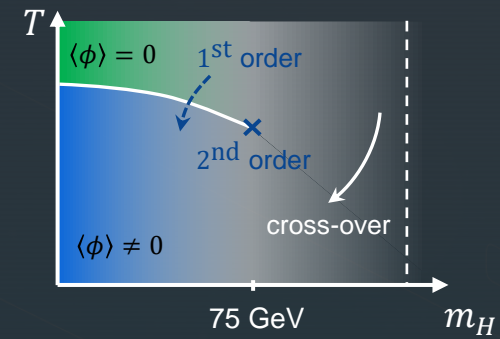
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Is colour-restoration observable ?

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A minimal 2-LQ model

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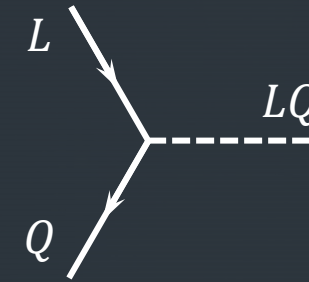
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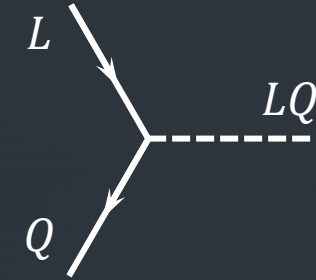


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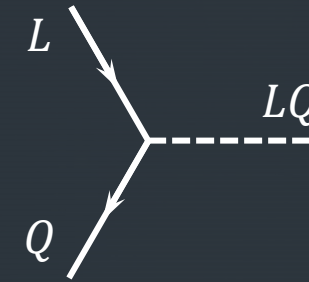
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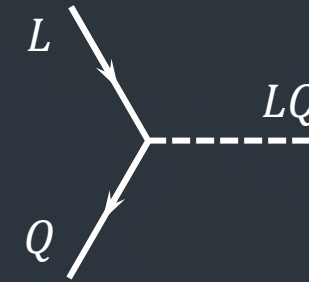
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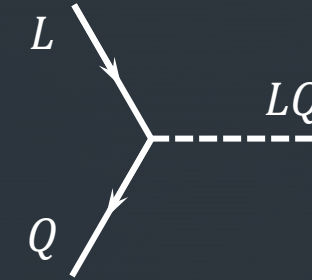
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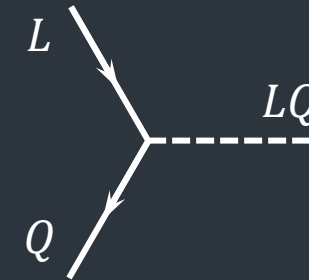
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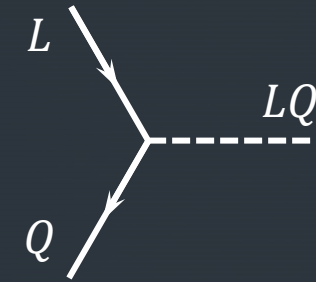
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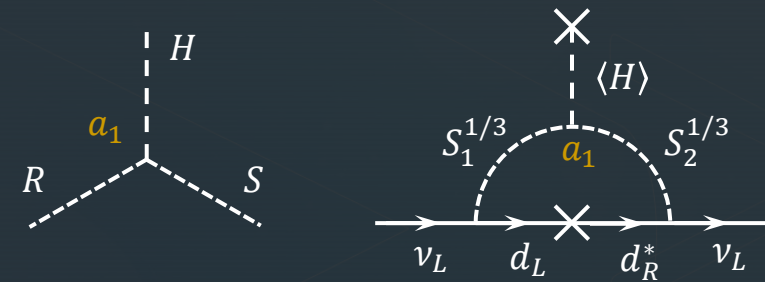


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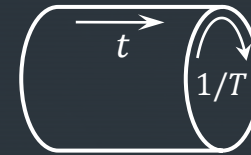
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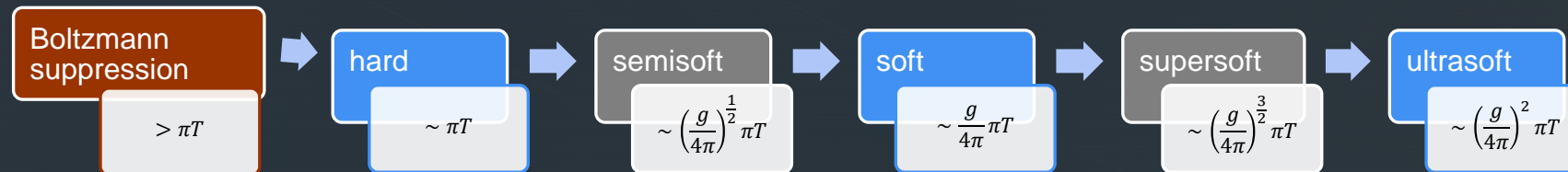
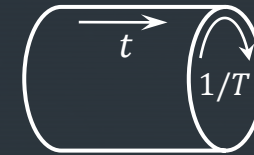


Figure inspired by eq. (2.1) of O. Gould and T.V.I. Tenkanen (JHEP01(2024)048)

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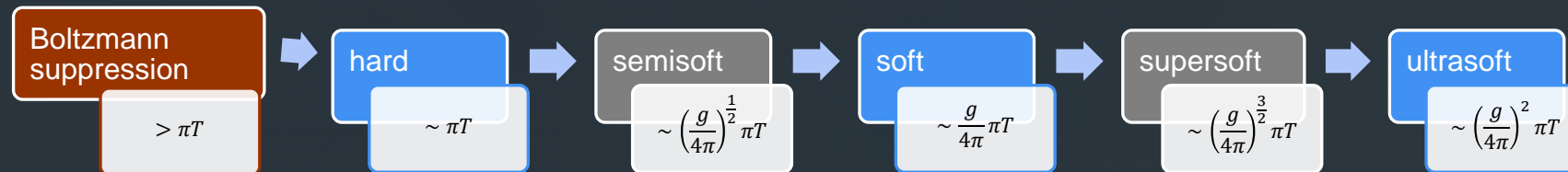
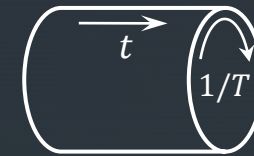


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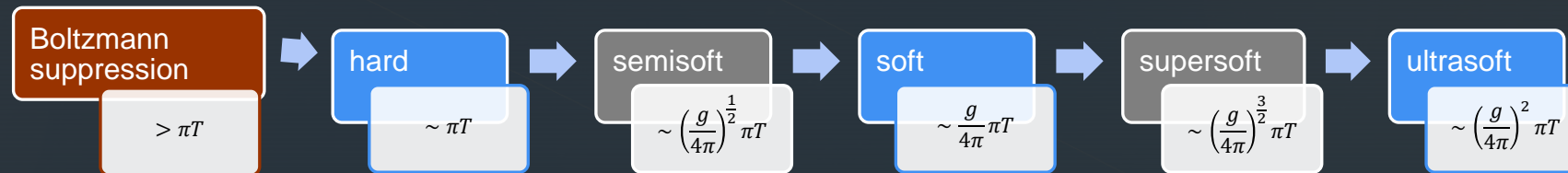
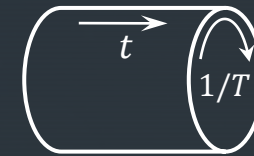


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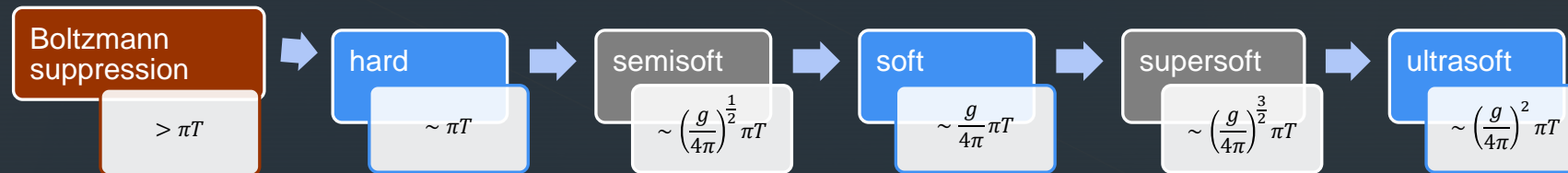
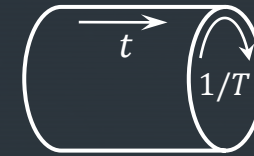


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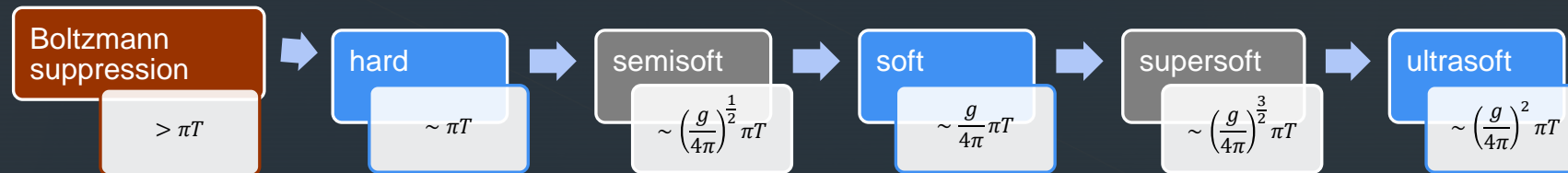
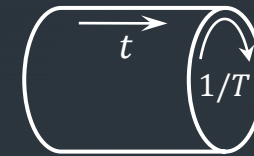


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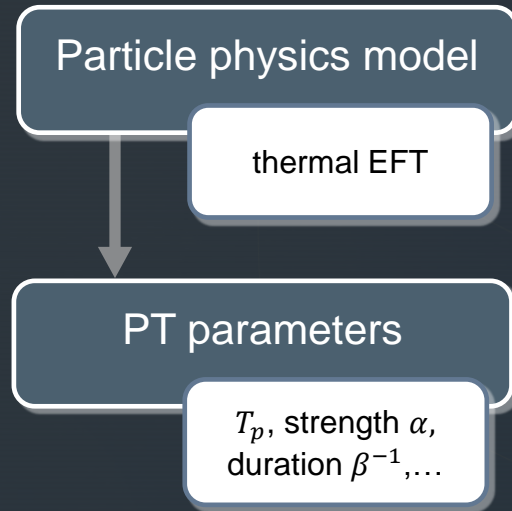
Particle physics model

thermal EFT

Outcome  
From Particle Physics to Cosmology

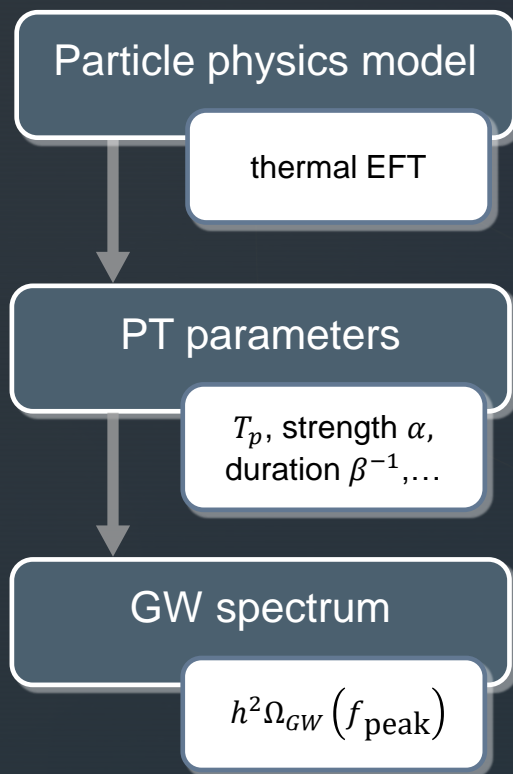
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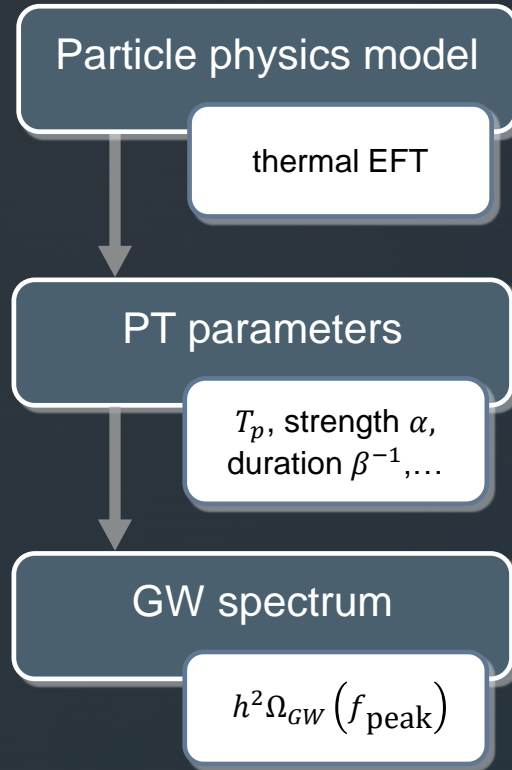
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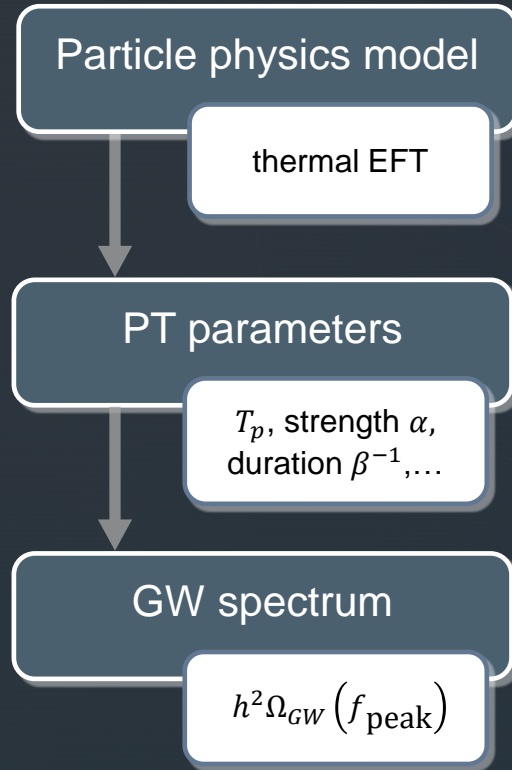
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collisions

# Outcome

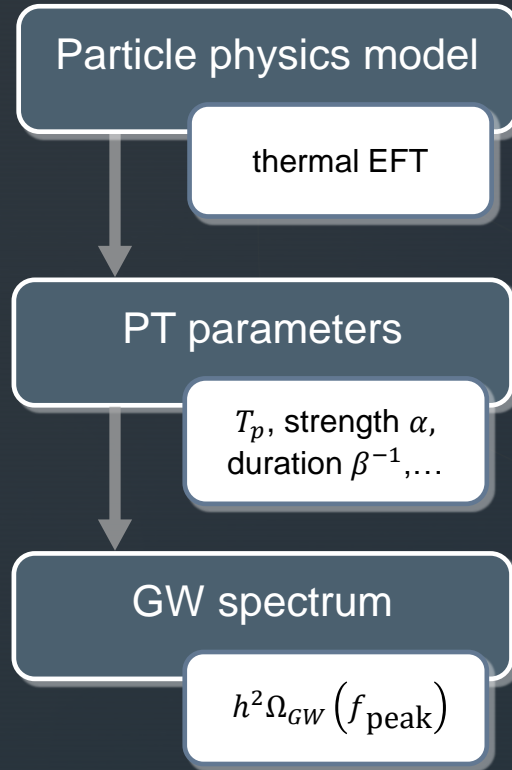
From Particle Physics to Cosmology



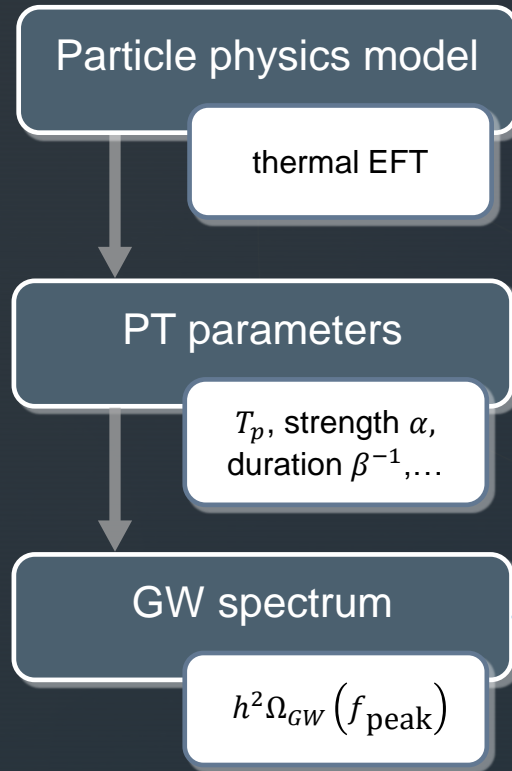
- collisions
- soundwaves

# Outcome

From Particle Physics to Cosmology

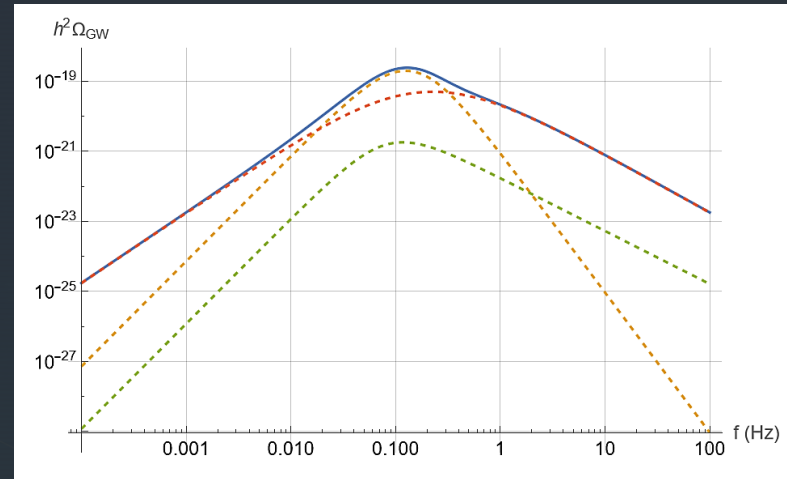


- collisions
- soundwaves
- turbulence

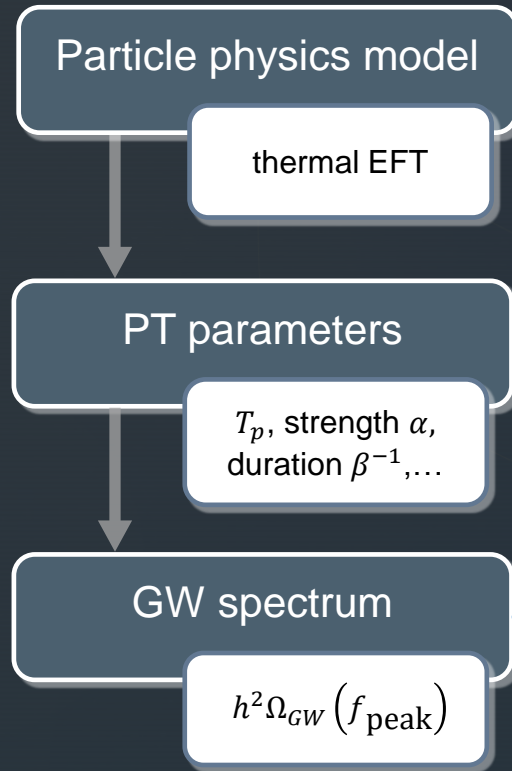


## Outcome

From Particle Physics to Cosmology

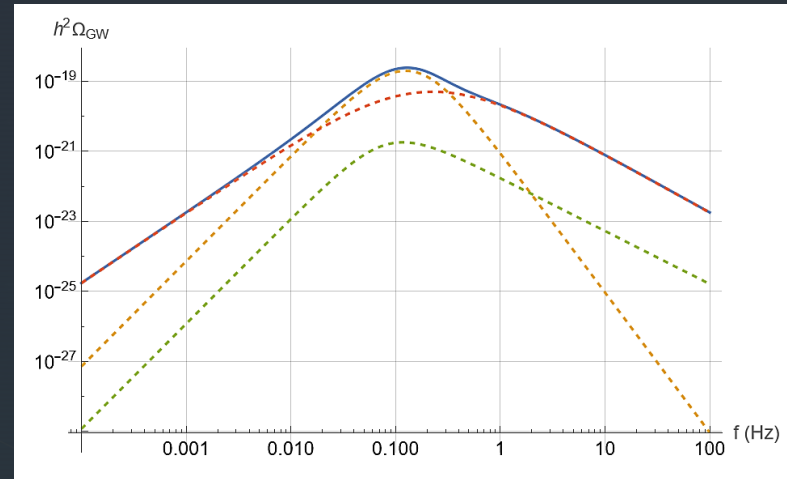


- collisions
- soundwaves
- turbulence
- combined



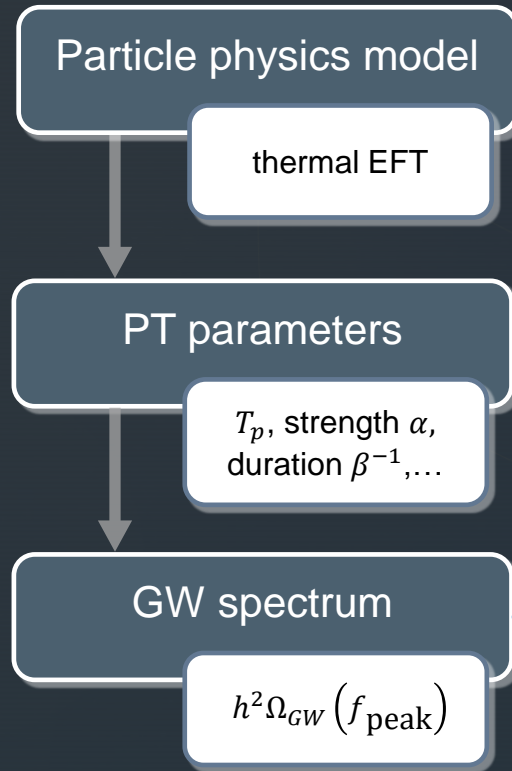
## Outcome

From Particle Physics to Cosmology



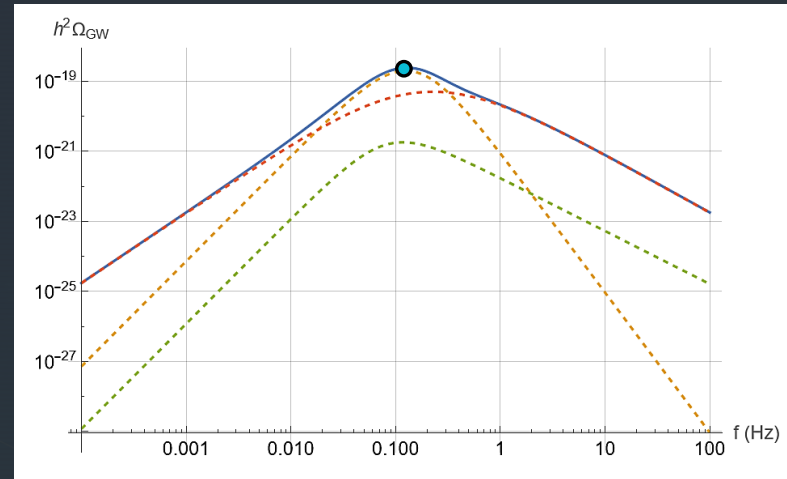
- collisions
- soundwaves
- turbulence
- combined



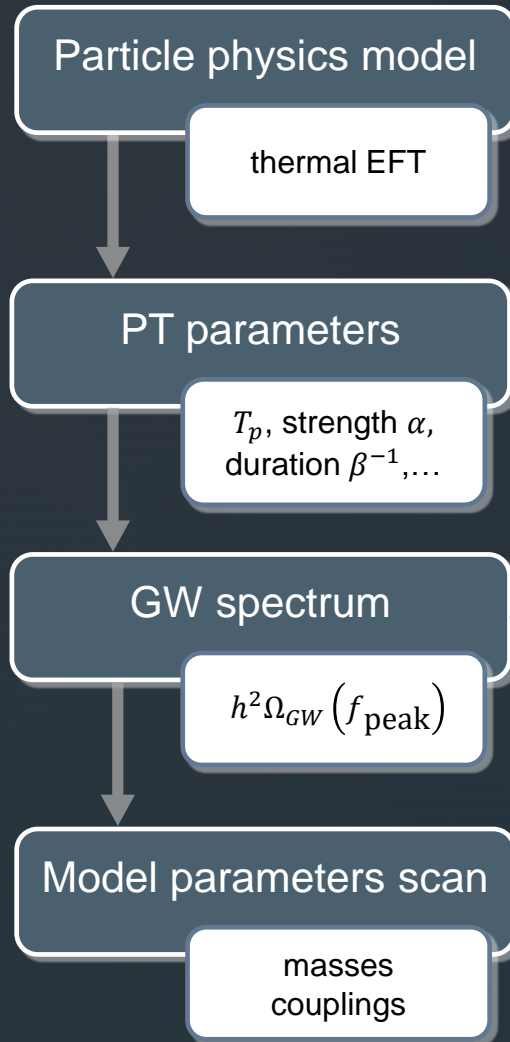


## Outcome

From Particle Physics to Cosmology

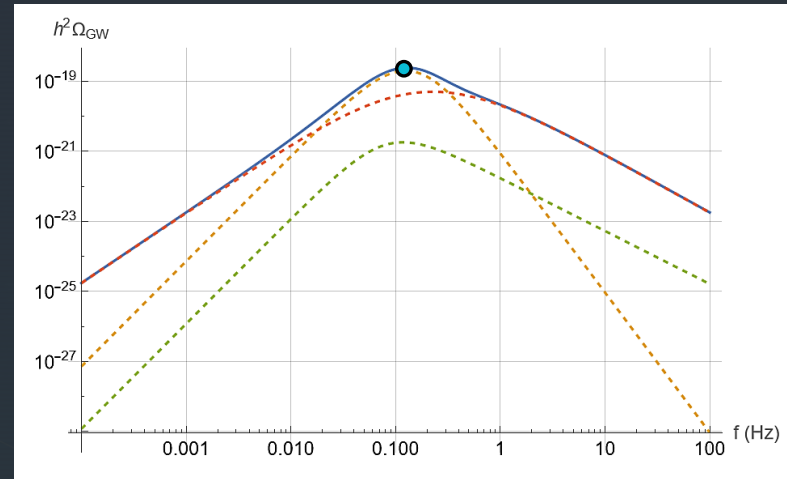


- collisions
- soundwaves
- turbulence
- combined

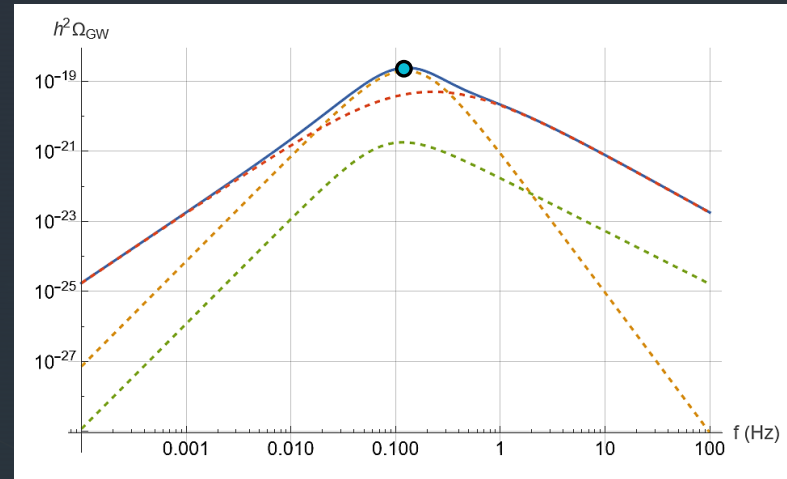
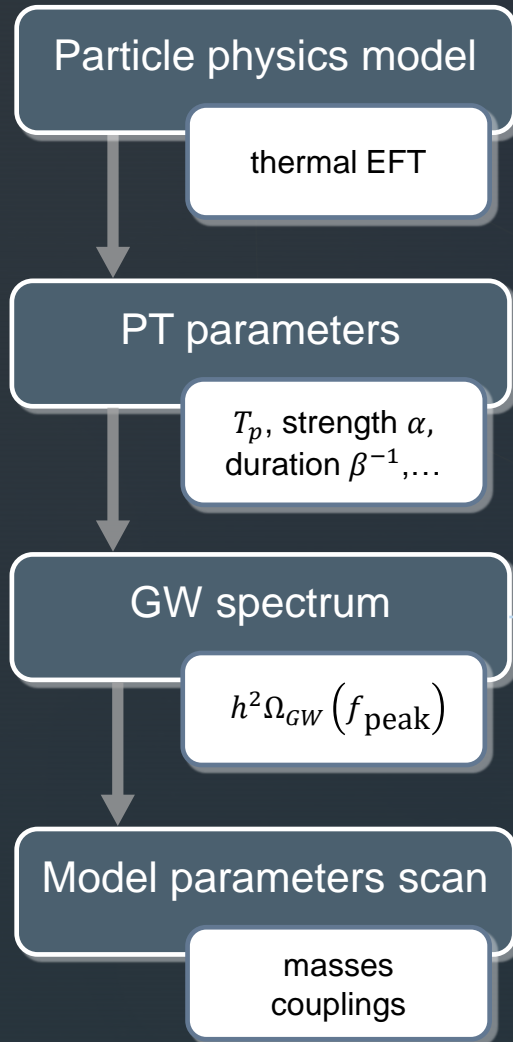


## Outcome

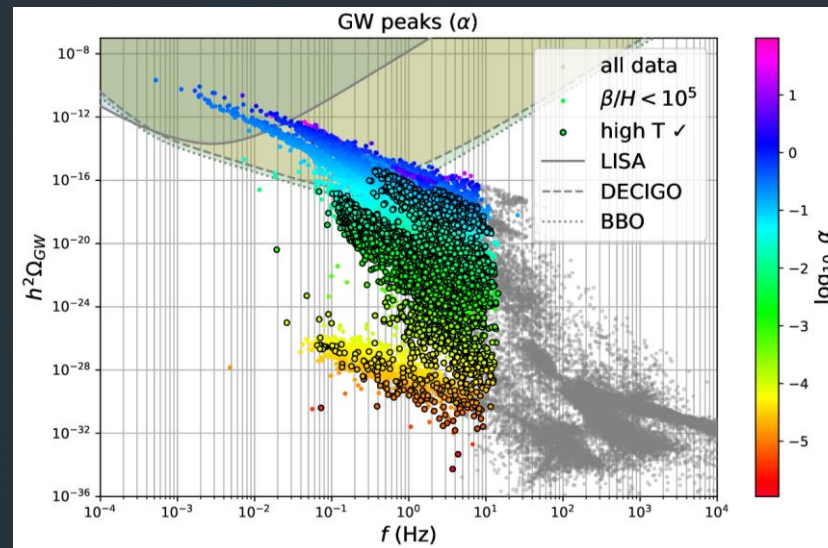
From Particle Physics to Cosmology



- collisions
- soundwaves
- turbulence
- combined

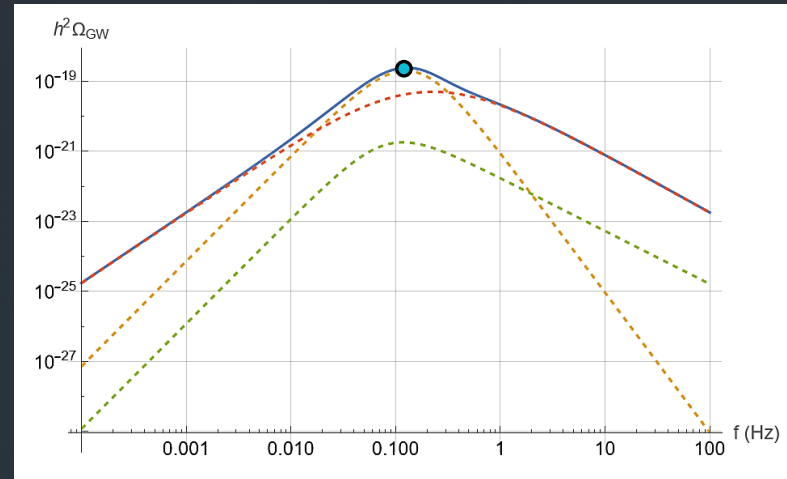
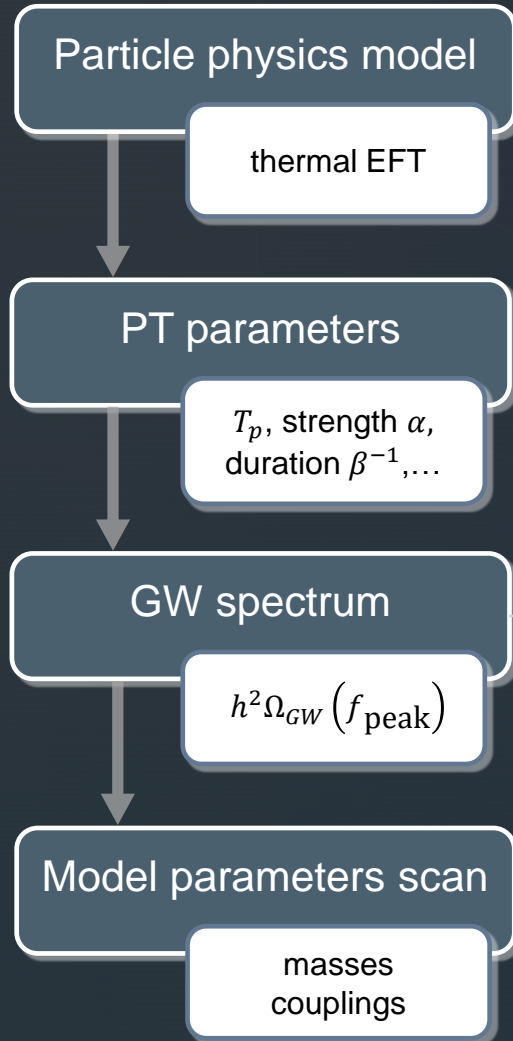


- collisions
- soundwaves
- turbulence
- combined

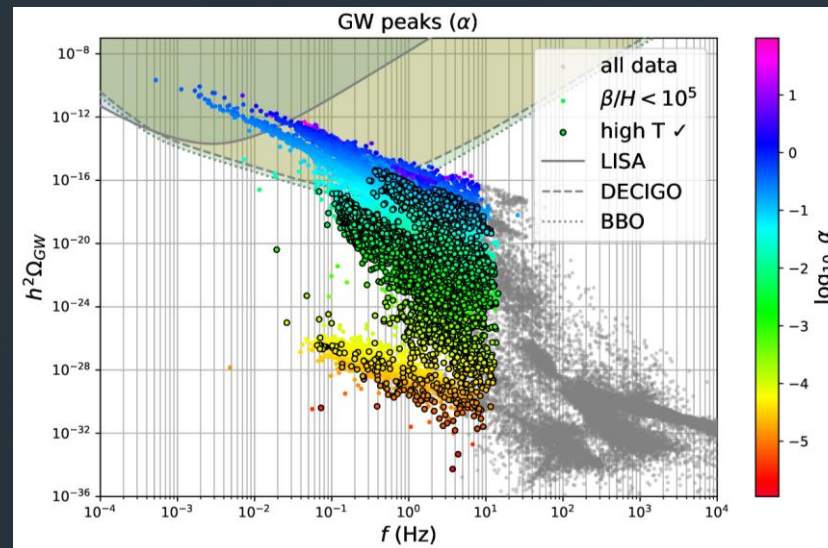


# Outcome

From Particle Physics to Cosmology



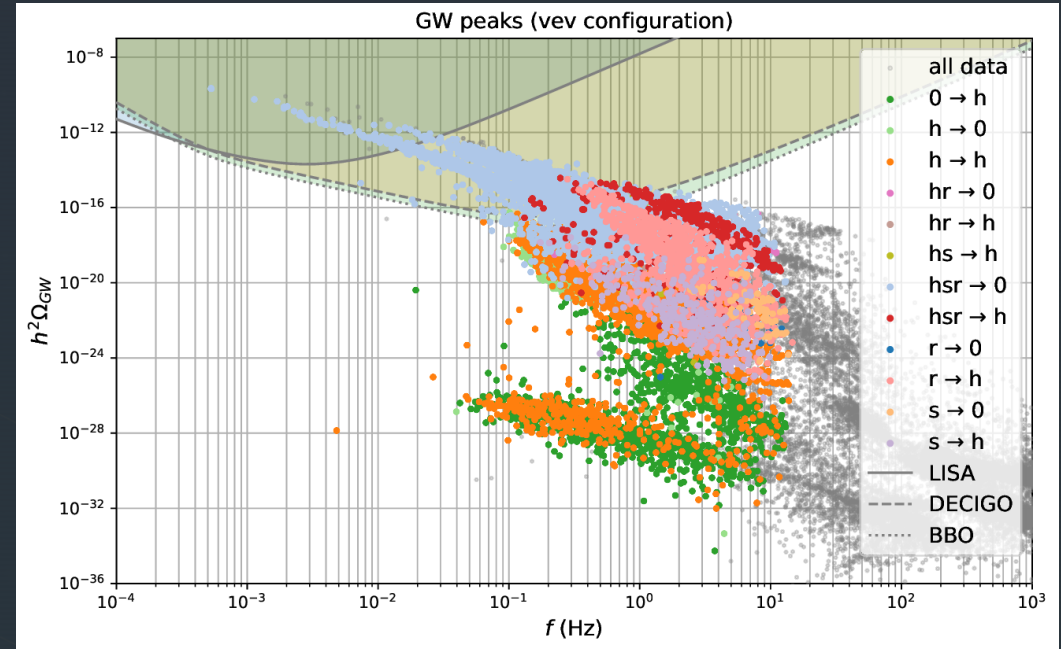
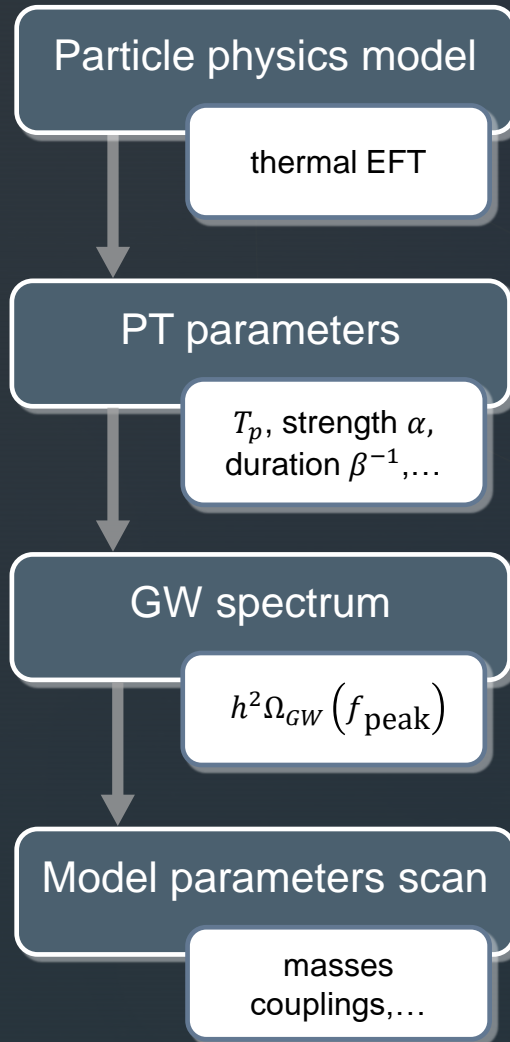
- collisions
- soundwaves
- turbulence
- combined



$$\frac{m_{US}}{\pi T} < 1$$

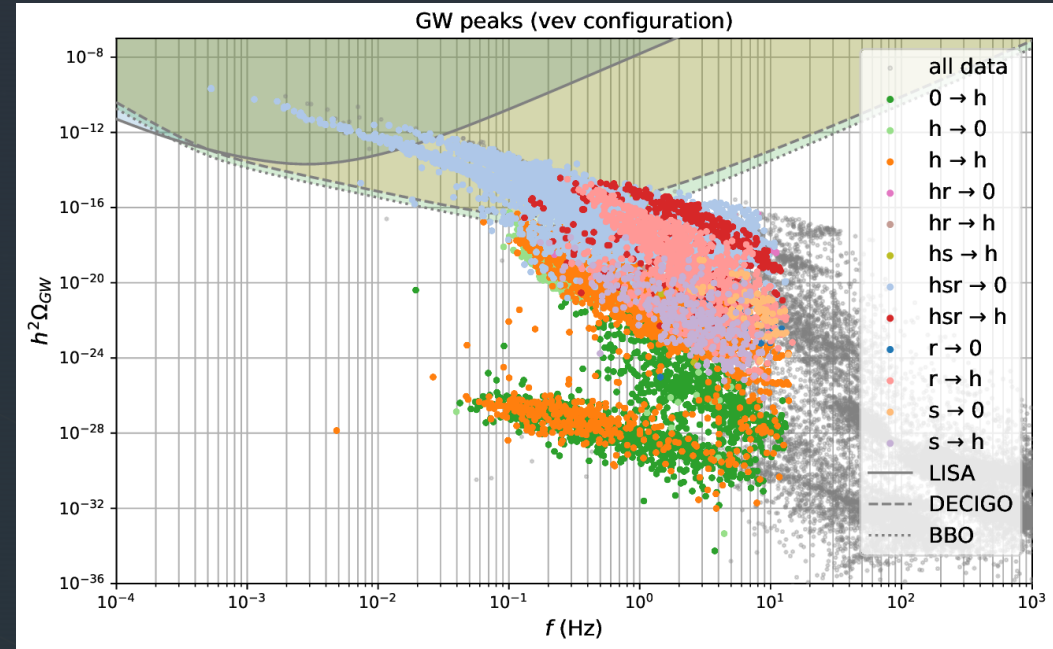
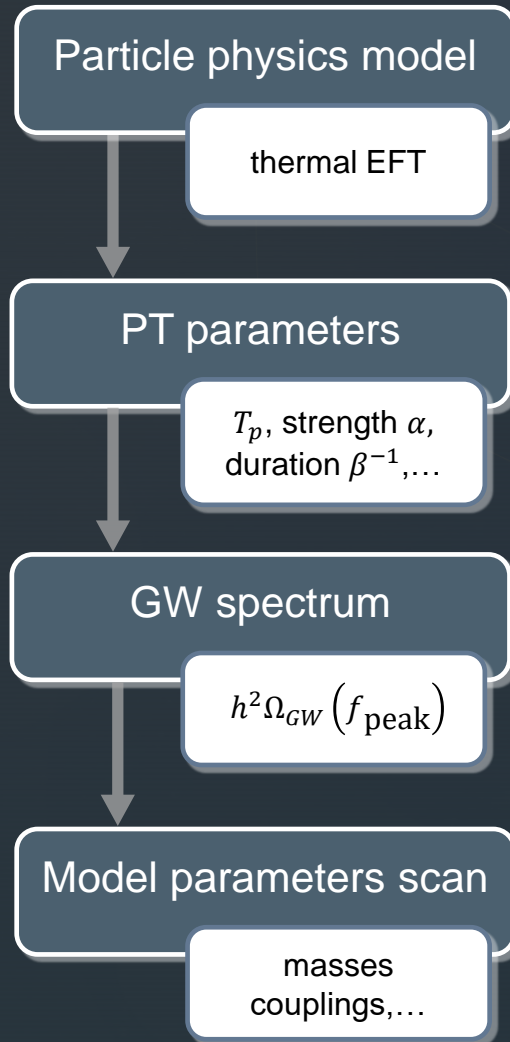
# Outcome

From Particle Physics to Cosmology

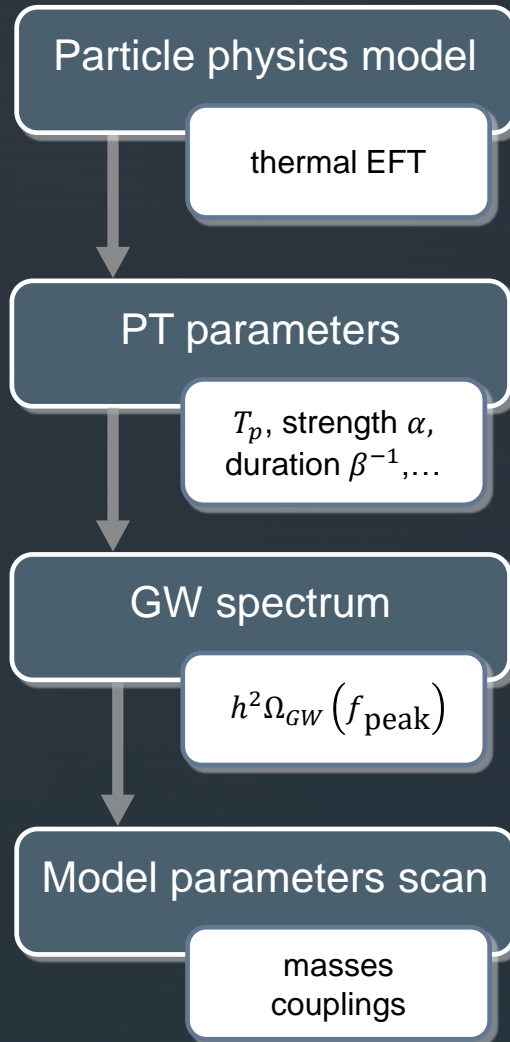


## Outcome

From Particle Physics to Cosmology

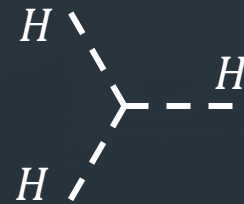
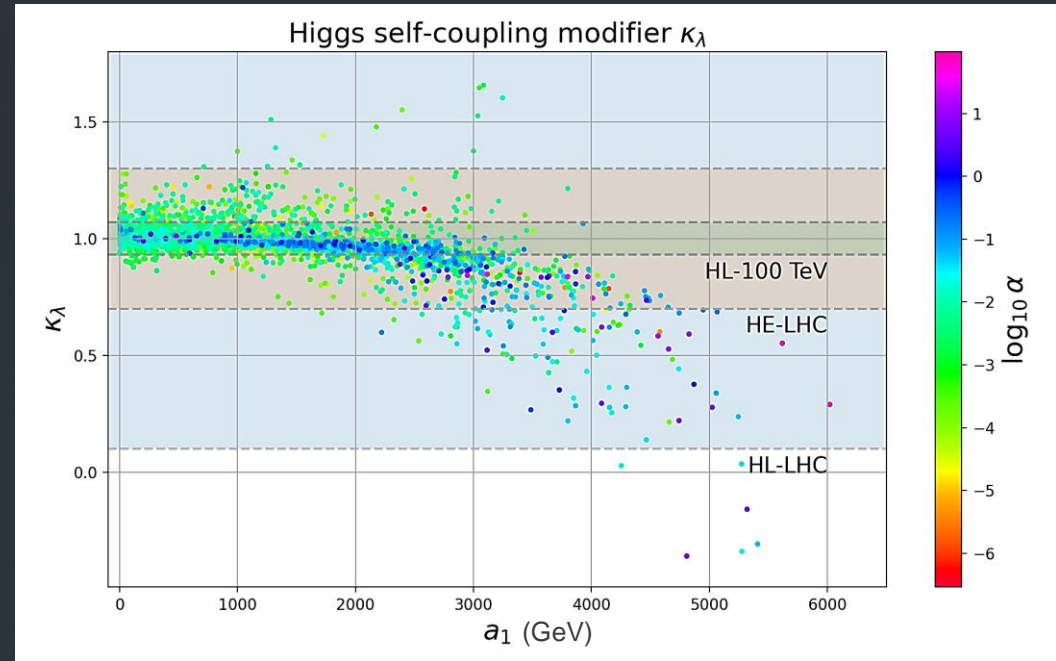


Colour breaking  
and restoration!



## Outcome

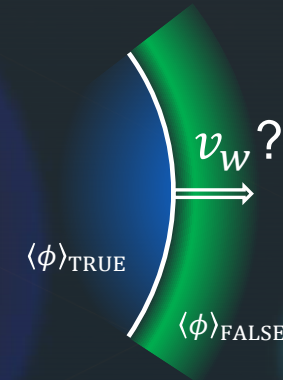
From Particle Physics to Cosmology



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

- Model
  - ✓ flavour-consistent LQ model generating  $\nu$  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 leptoquark model

Andreas Ekstedt<sup>1\*</sup>, Mårten Berntson<sup>2</sup>, Marco Finelli<sup>3</sup>, António P. Morais<sup>4</sup>,  
Roman Pasechnik<sup>5</sup> and Johan Rathsman<sup>6</sup>

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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 (FOT). Leptoquark (LQ) models offer an alternative to conventional mass scenarios for the generation of Majorana neutrino masses at UV scale, and can induce strong FOTs 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


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

The scalar content of the theory reads

$$V_{\text{tree}} = \mu_D^2 |H|^2 + \mu_S^2 |S|^2 + \mu_\Delta^2 |\Delta|^2 + \lambda_D |H|^4 + \lambda_S |S|^4 + \lambda_\Delta |\Delta|^4 + m_D |H|^2 |S|^2 + m_\Delta |H|^2 |\Delta|^2 + m_{\Delta S} |H|^2 |S|^2 + (h.c.)$$

At low energies, the Higgs doublet acquires a vacuum expectation value (vev)  $v \approx 246$  GeV. One of the  $S$ -doublet components mixes with the  $S$ -singlet via the  $a_1$  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  $a_1$  coupling, providing mixing between leptoquarks and thus enabling to generate both the neutrino masses and strong FOTs, via stable cube terms.



#### Matching to the SM

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

$$v^2 \text{tr}(M) = \mu_D^2 |S|^2 + \lambda_D |S|^4, \quad (2)$$

we run SM parameters up to the LQ scale ( $\sim 1$  TeV) and match the theories (1)+(2) at 1-loop, in the dimensional-regularization approach. This is tantamount to equating  $\mu^2$  and  $\lambda^2$  derivatives of the two theories:

$$\frac{d\mu^2}{d\ln\mu} = \frac{d\mu^2}{d\ln\mu} \Rightarrow \mu^2 = \mu_{UV}^2 + \beta_\mu^{(1)} \ln(\mu/\mu_{UV}) \quad (\text{LQ param})$$


$$\frac{d\lambda^2}{d\ln\mu} = \frac{d\lambda^2}{d\ln\mu} \Rightarrow \lambda = \lambda_{UV} + \beta_\lambda^{(1)} \ln(\mu/\mu_{UV}) \quad (\text{LQ param})$$

We then invert these relations to obtain  $\mu_{UV}$  and  $\lambda_{UV}$  in terms of  $\mu$ ,  $\lambda$  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  $\mathcal{D}[\text{tagge}]$  [5], which matches the hard-scale full theory to a soft-scale  $\mathcal{M}$  theory, and thereafter integrates out temporal modes to lower an effective  $\mathcal{M}$  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

$$\int_{t_c}^{\infty} dt \frac{H}{T} \frac{V}{T^4} = 1, \quad (3)$$

to determine the nucleation temperature  $T_c$ , with  $H(T) = T^2 (\frac{d^2 V}{d\phi^2})^{1/2} e^{-S_4/T}$  the nucleation rate. Crucially for strongly-supersaturated transitions, the Hubble parameter  $H = \dot{\phi}$  includes contributions from both the radiation and vacuum energies

$$\rho(T) = \frac{\pi^2}{30} g_* T^4 + \frac{\Delta V}{\text{volume}} \quad (4)$$

Phase transition parameters are computed at the production temperature  $T_p$ , which - for uniformly nucleated spherical bubbles - matches the false vacuum fractional volume condition  $P(T) = e^{-c} e^{-\rho(T)/T^4} \approx 0.1$ , where

$$H(T) = \frac{d\phi}{dt} \approx \int_{\phi}^{\phi_c} \frac{d\phi'}{\sqrt{2V(\phi')}} \left( \int_{\phi'}^{\phi_c} \frac{d\phi''}{H(\phi'')} \right)^{-1/2}, \quad (5)$$

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

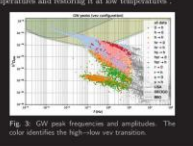
Parameter	Range	Log scale
$\lambda_{D,S}$	$[10^{-3}, 2]$	✓
$g_{D,S}, m_{D,S}$	$\pm [10^{-3}, 2]$	✓
$m_{\Delta,S}$	$[0.8, 3]$ TeV	✗
$\theta$	$[-\pi, \pi]$	✗

#### Observables

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

$$\lambda_{3HS} = \lambda_{3HS}^{\text{SM}} + \frac{\lambda_{3HS}^{\text{LQ}}}{\Lambda_{UV}} \sqrt{\frac{\Lambda_{UV}}{\mu}} \rightarrow \alpha_3 = 1 + \frac{\lambda_{3HS}^{\text{LQ}}}{\lambda_{3HS}^{\text{SM}} + \lambda_{3HS}} \quad (6)$$

where the tree-level contribution is  $\lambda_{3HS}^{\text{SM}} = 3m_t^2/v$ . At large values of  $\alpha_3$ , we notice stronger modifications to  $\alpha_3$ , leaving 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. Jaeckel, A. P. Morais, B. R. Pedersen, and M. Reuter, *Simultaneous neutrino production and axionogenesis*, *Phys. Rev. D* **102**, 075011 (2020).  
 [2] A. Ekstedt, M. Berntson, and J. Rathsman, *Origin of baryon asymmetry through thermal production of thermal photons*, *Phys. Rev. D* **102**, 075012 (2020).  
 [3] G. 't Hooft, *Dimensional Reduction in Quantum Gravity*, *Phys. Lett. B* **183**, 171 (1986).  
 [4] G. 't Hooft, *Dimensional Reduction in Quantum Gravity*, *Phys. Lett. B* **183**, 171 (1986).  
 [5] D. Harlow and J. Rathsman, *Dimensional reduction: A fast theory generator for cosmological phase transitions*, *Phys. Rev. D* **102**, 075013 (2020).  
 [6] M. Reuter, *Dimensional Reduction in Quantum Gravity*, *Phys. Lett. B* **183**, 171 (1986).

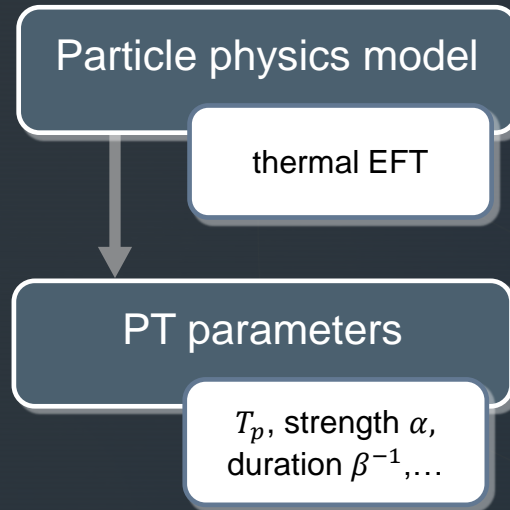
#### Acknowledgments

This project was supported by CIDMA through projects FEDER/2014/00001 (UIDB/04029/2020) and CIDP/2020/2020.  
 CIDMA is supported by FCT through UIDB/04029/2020 and CIDP/2020/2020.  
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#### More Information

Marco Finelli  
 University of Aveiro - Physics  
 CIDMA | Collo group





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

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

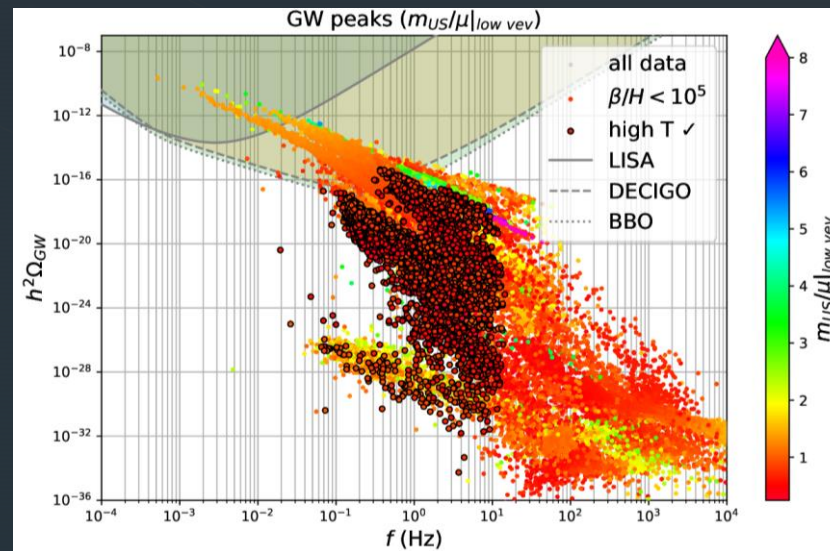
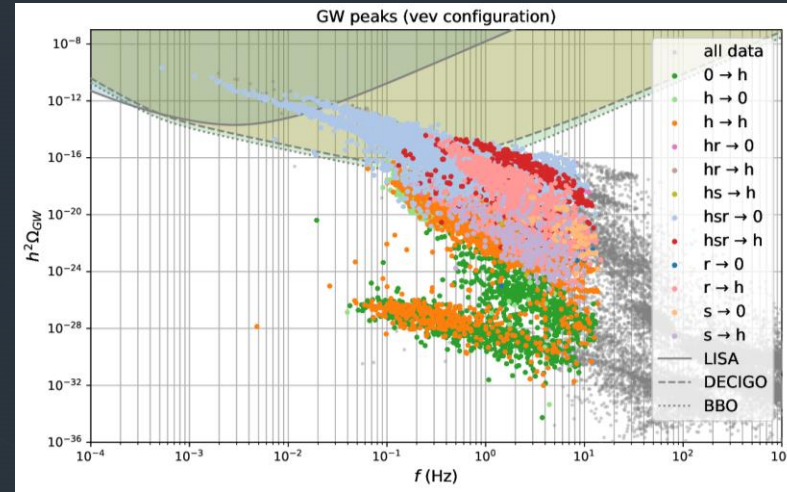
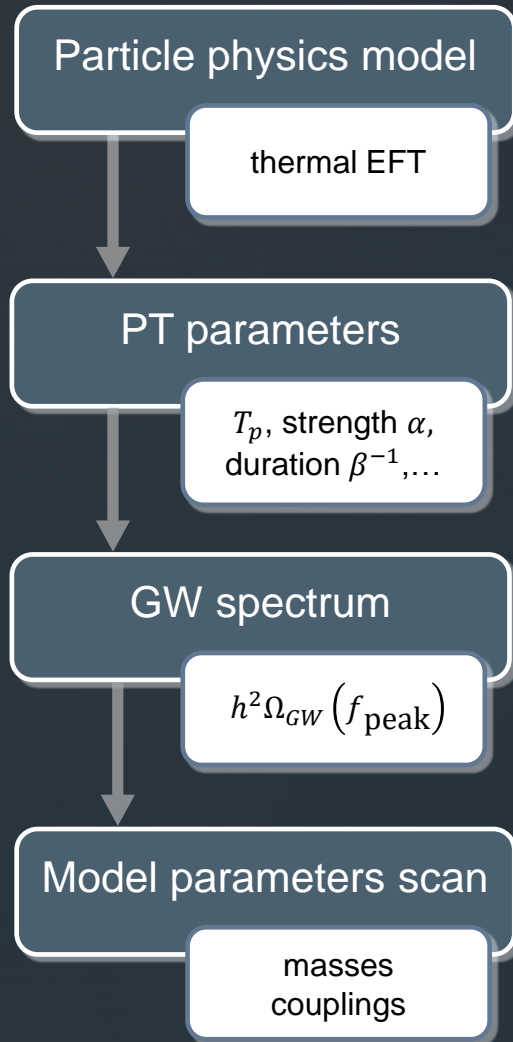
percolation criterion:  $I(T_p) \approx 0.34$

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

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<sup>-1</sup>  $\frac{\beta}{H} = T \frac{d}{dT} \left( \frac{S_3}{T} \right)$

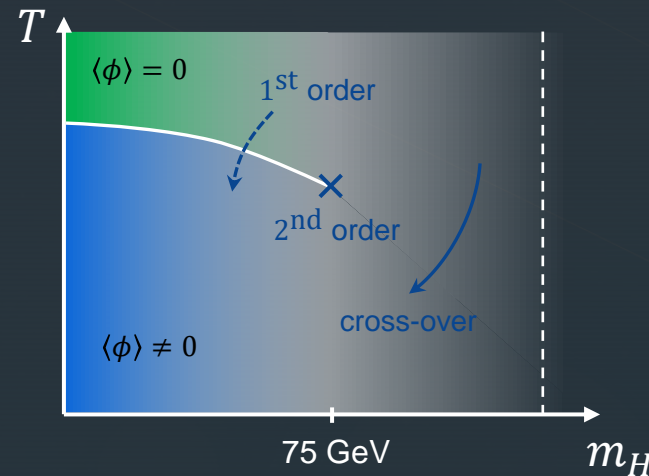
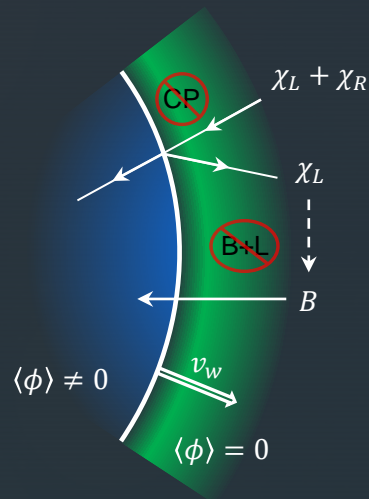


## EW Baryogenesis

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!