Lightning Talk – 4th EuCAPT Annual Symposium

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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ECIU university

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Gravitational Wave
Sources

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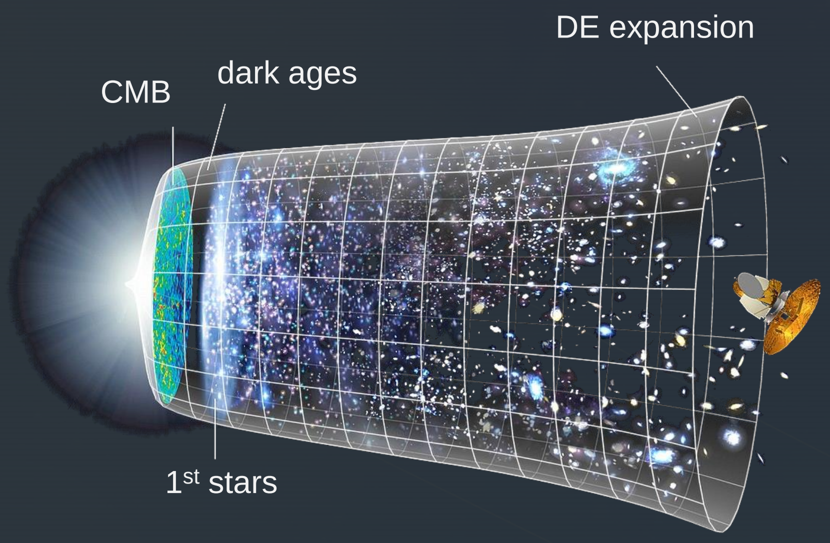

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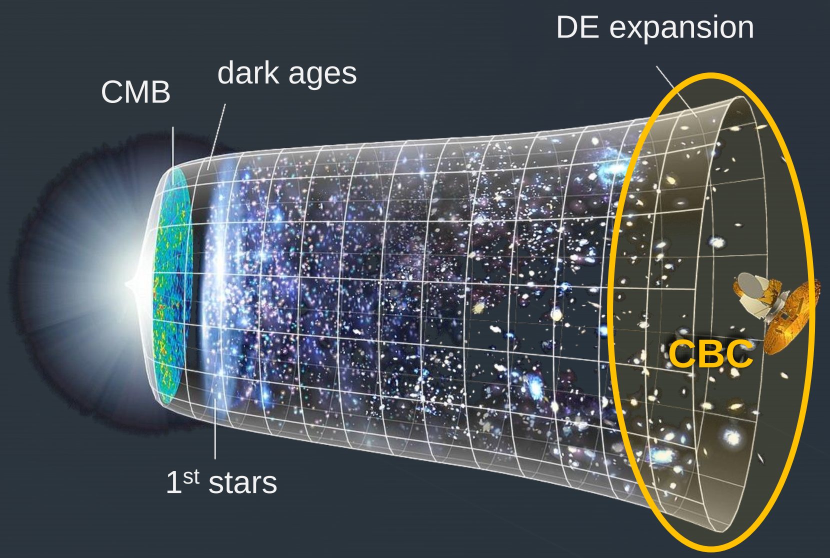

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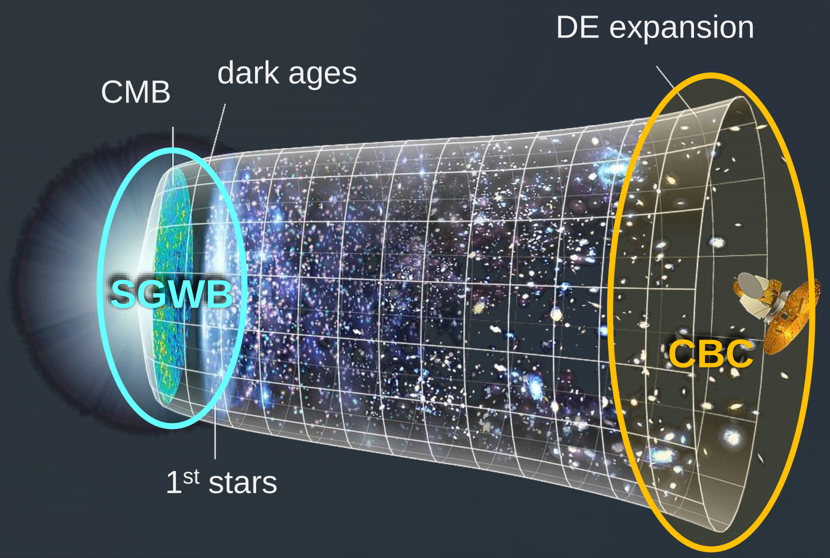

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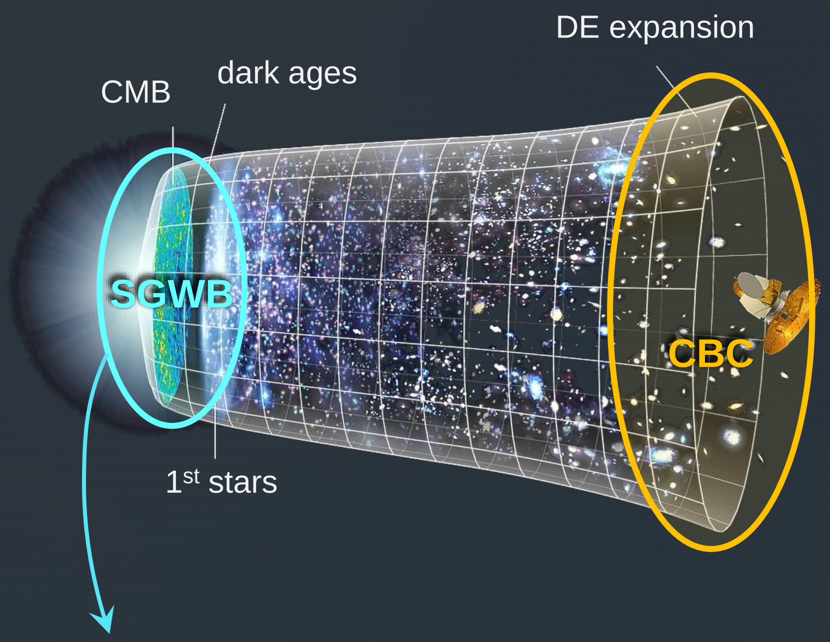

Main Sources	Frequency (Hz)
Inflation & preheating	??
Cosmic defects	$10^{-12} - 10^{-10}$ (strings)
Supermassive BH binaries	$10^{-10} - 10^{-7}$
Phase transitions	$\sim 10^{-5} - 10^{-3}$ (EW)
Primordial BHs	$\sim 10^{1} - 10^{2}$

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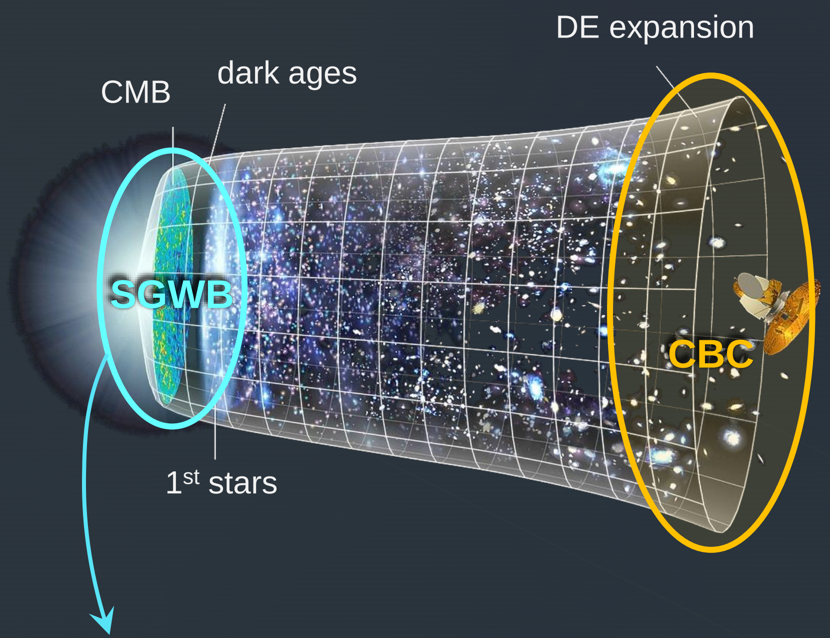

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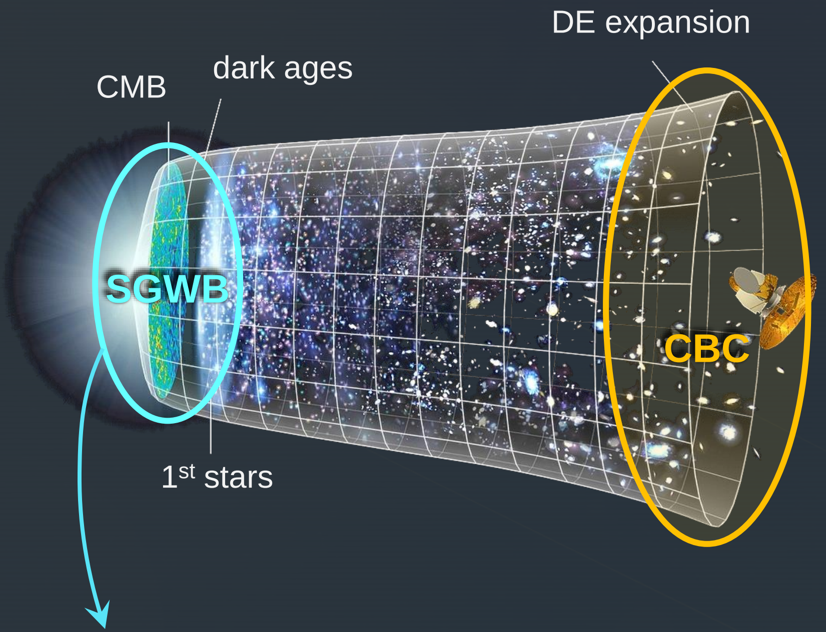

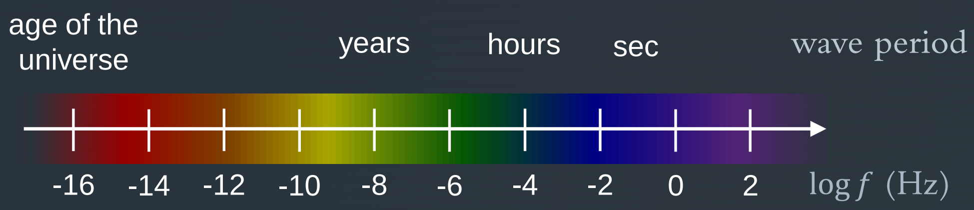

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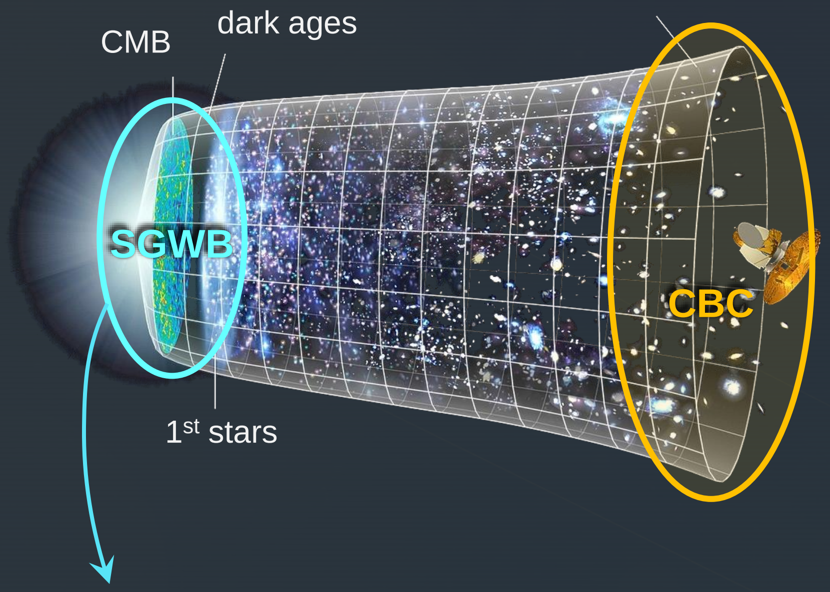

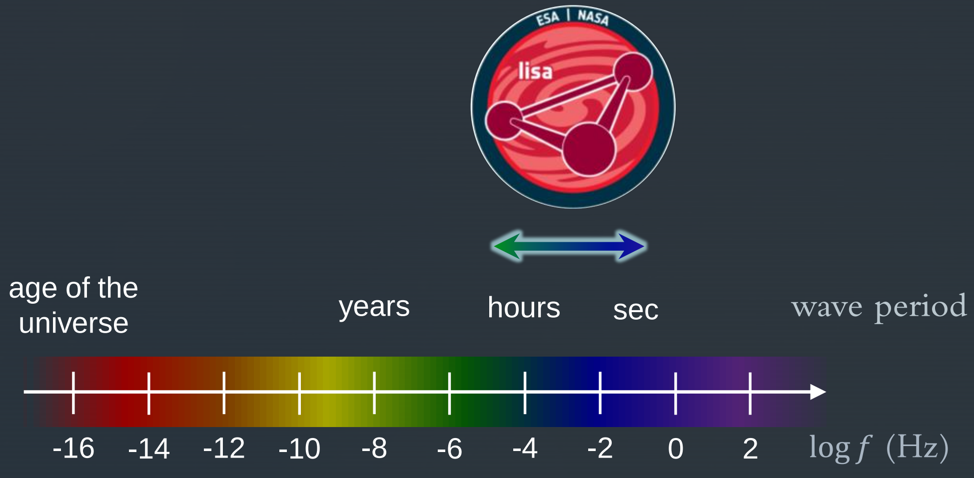

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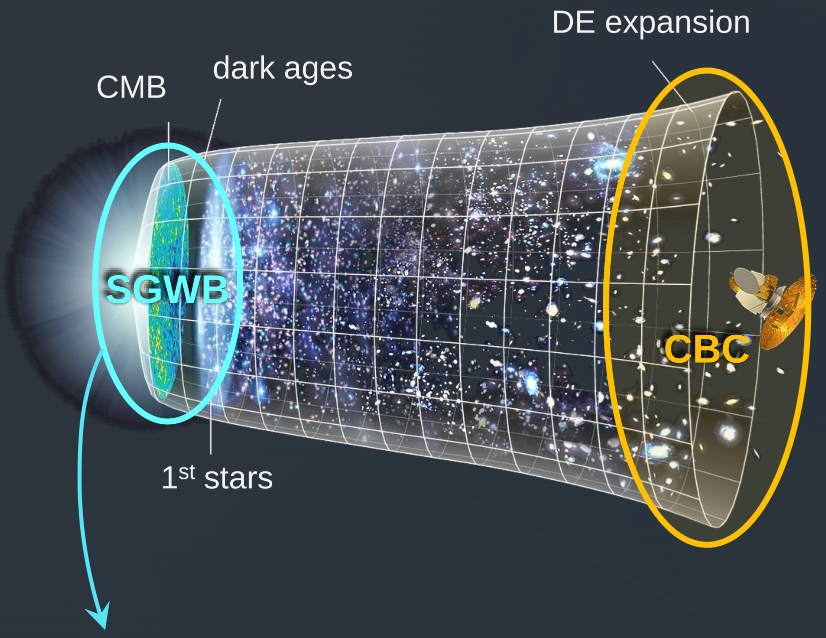

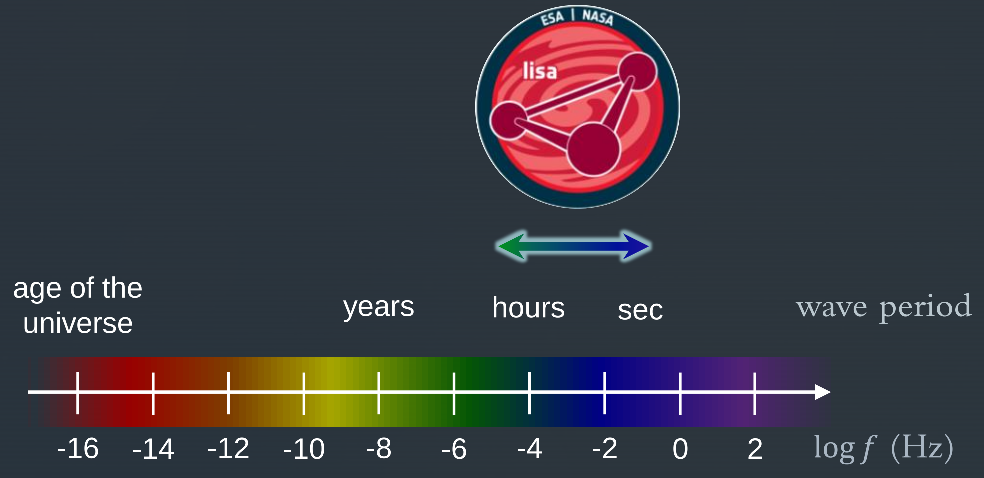

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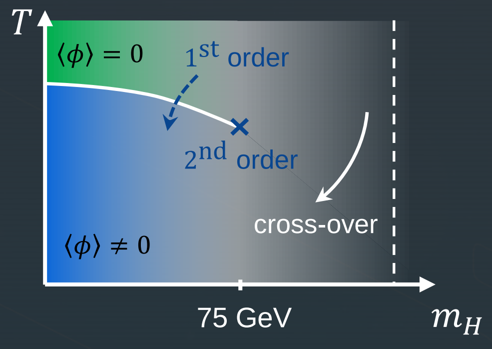

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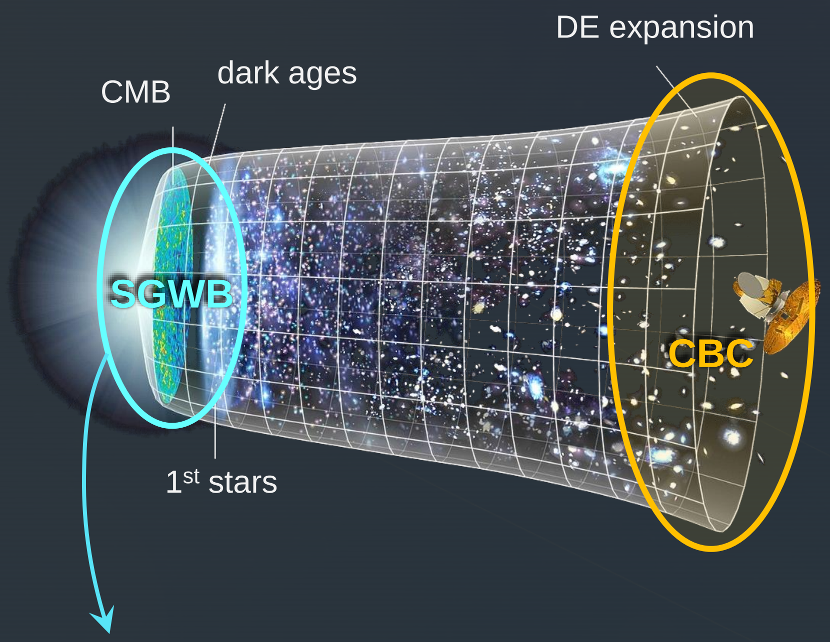

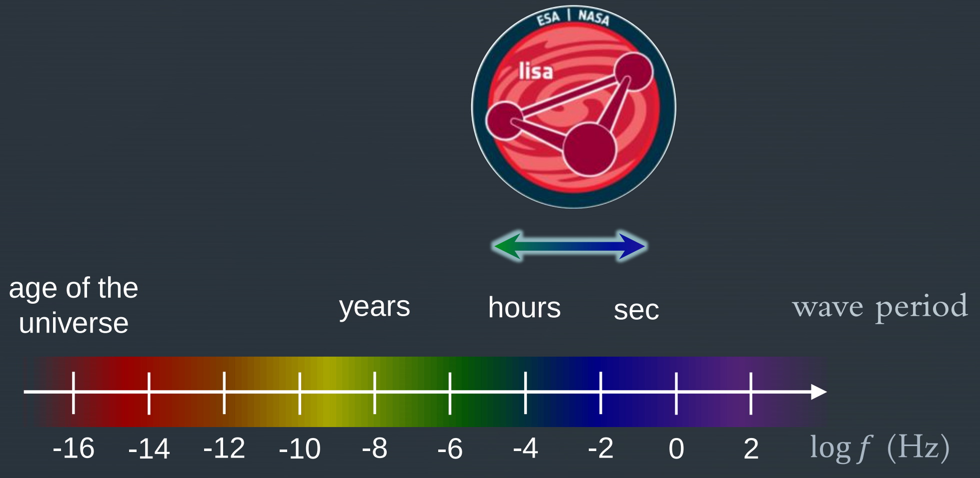

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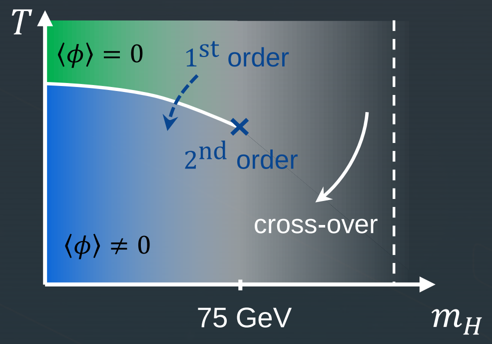

Is colour-restoration observable ?

Leptoquarks
A minimal 2-LQ model

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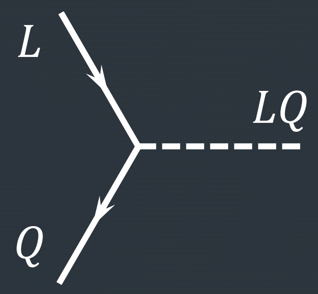

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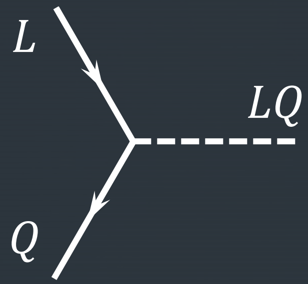

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$$V_{LQ}^{(0)} = \mu_H^2\, H^\dagger H + \mu_S^2\, S^\dagger S + \mu_R^2\, R^\dagger R$$
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Model based on F. Freitas, J. Gonçalves, A. P. Morais, R. Pasechnik, W. Porod (2023, PRD 108.115002)

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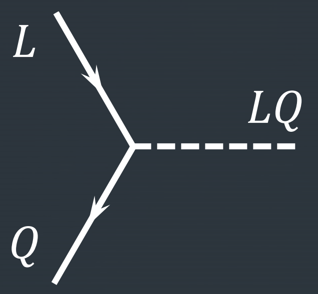

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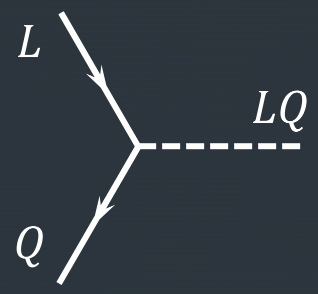

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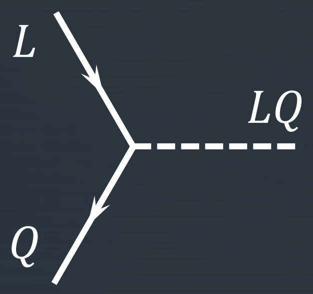

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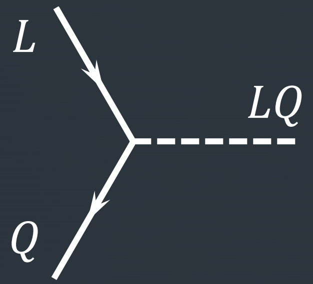

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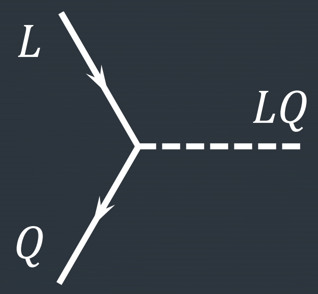

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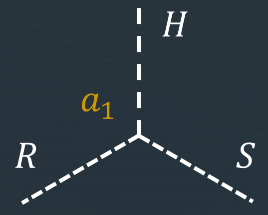

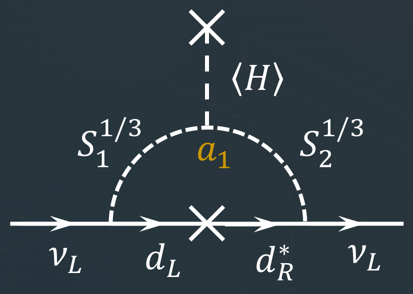

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An improved recipe for thermal EFTs

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  Linde problem: non-perturbative massless vector bosons

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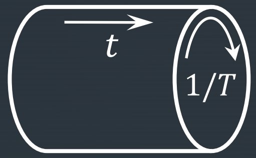
$$\boxed{4d \xrightarrow{t\to i/T} 3d\ \text{EFT}}$$



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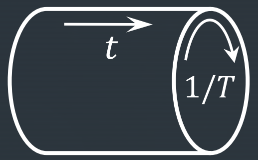

Boltzmann suppression: $> \pi T$ → hard: $\sim \pi T$ → semisoft: $\sim \left(\frac{g}{4\pi}\right)^{\frac{1}{2}} \pi T$ → soft: $\sim \frac{g}{4\pi} \pi T$ → supersoft: $\sim \left(\frac{g}{4\pi}\right)^{\frac{3}{2}} \pi T$ → ultrasoft: $\sim \left(\frac{g}{4\pi}\right)^{2} \pi T$

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

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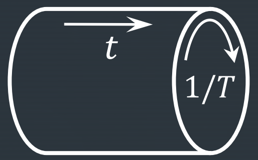

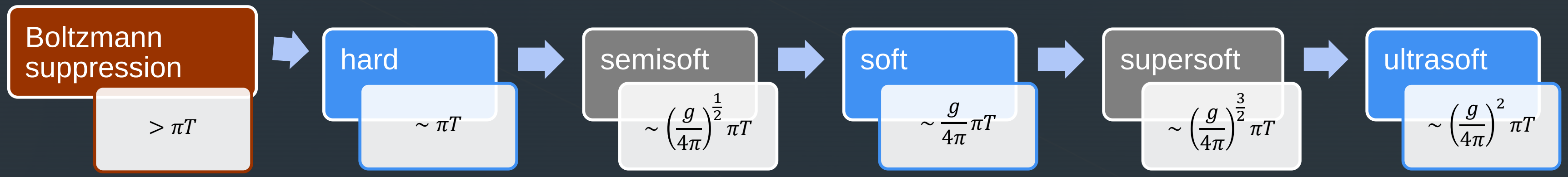

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  Automated, model-independent routine `DRalgo` → `CosmoTransitions`, including

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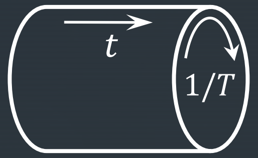

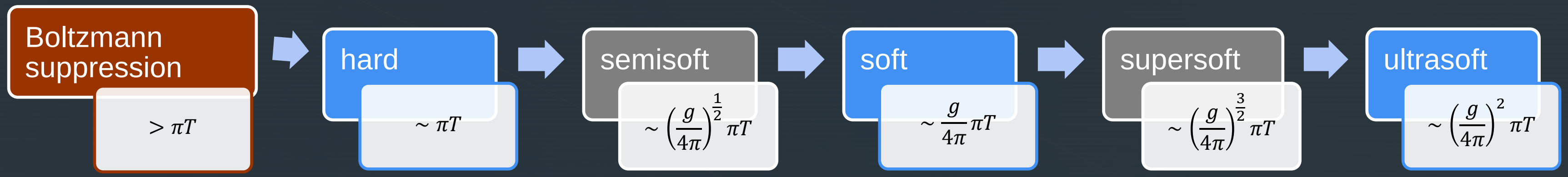

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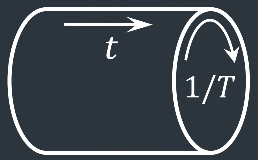

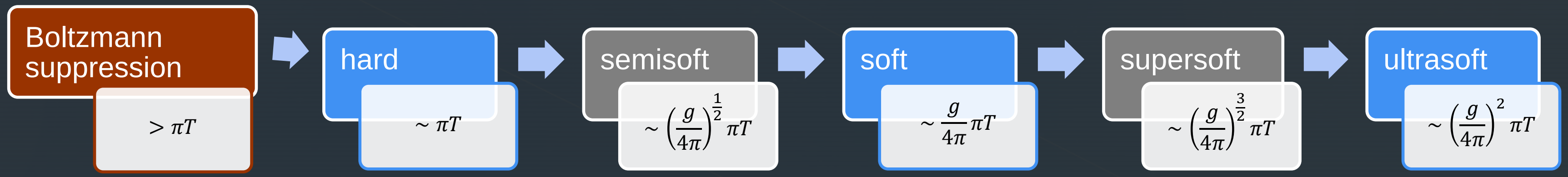

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  - export of DR quantities (soft and ultrasoft couplings)
  - high-T-adapted `CosmoTransitions`

Dimensional Reduction

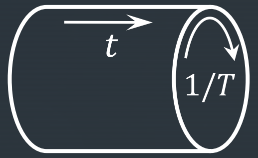
An improved recipe for thermal EFTs

- 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)
  - include systematically higher-order resummations
  - time → temperature ⇒ high-T approach
  - Weakly-coupled EFTs → thermal scale hierarchy

$$4d \xrightarrow{t\to i/T} 3d\ \text{EFT}$$



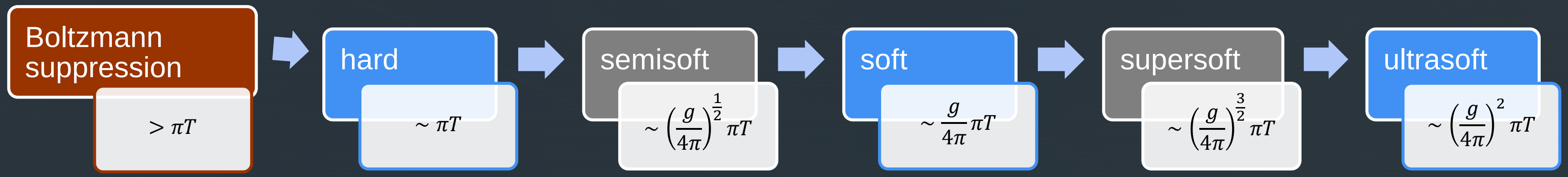


Figure inspired by eq. (2.1) of O. Gould and T.V.I. Tenkanen (JHEP01(2024)048)

- DR implementation
  Automated, <u>model-independent</u> routine `DRalgo` → `CosmoTransitions`, including
  - export of DR quantities (soft and ultrasoft couplings)
  - high-T-adapted `CosmoTransitions`
  - RG resolution, high-T consistency check, …

Outcome

From Particle Physics to Cosmology

Particle physics model

thermal EFT

Outcome

From Particle Physics to Cosmology

Particle physics model

thermal EFT

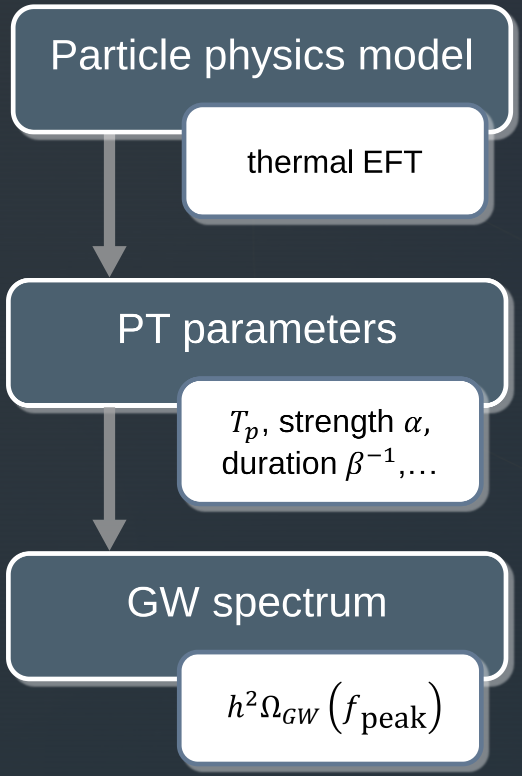
↓

PT parameters

T_p, strength α, duration β^{-1},…

Outcome

From Particle Physics to Cosmology



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↓

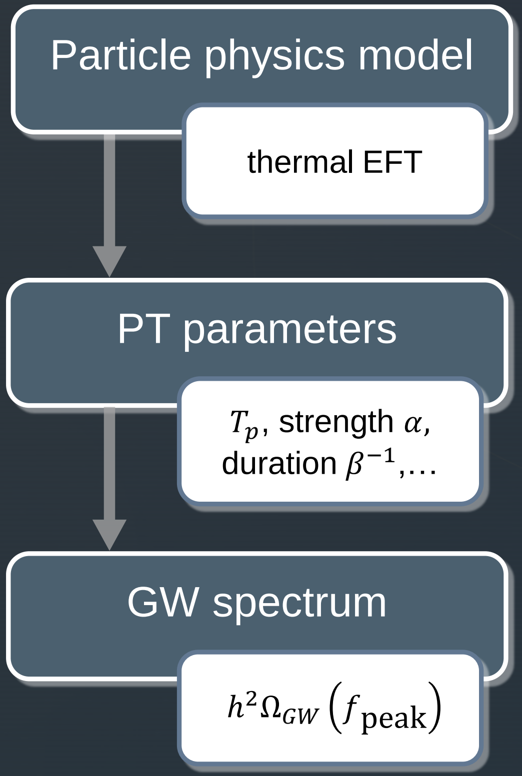
GW spectrum

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

— collisions

Outcome

From Particle Physics to Cosmology

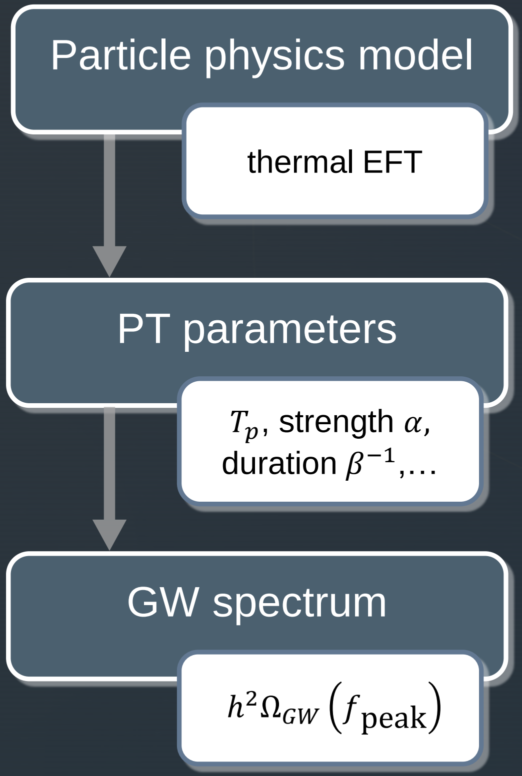


collisions

soundwaves

Outcome

From Particle Physics to Cosmology



collisions

soundwaves

turbulence

Outcome

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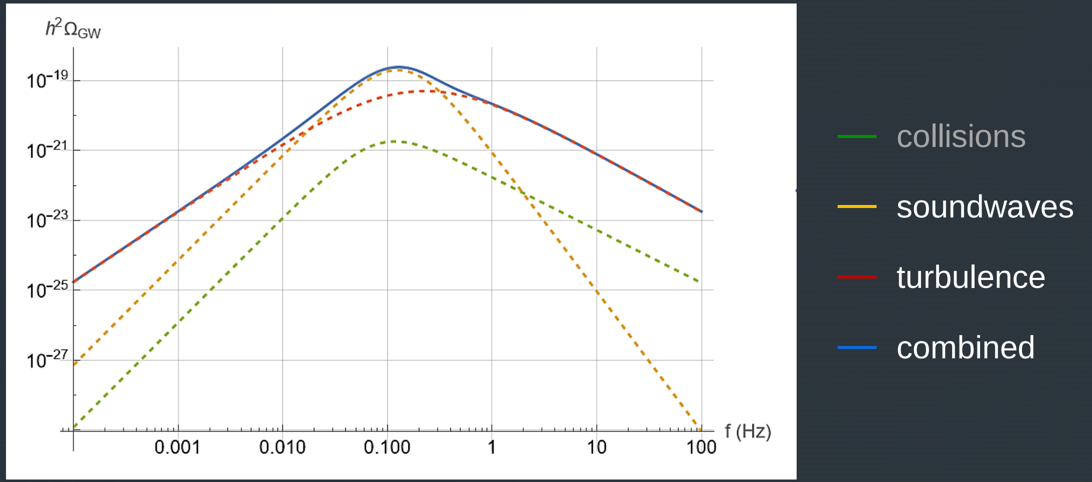

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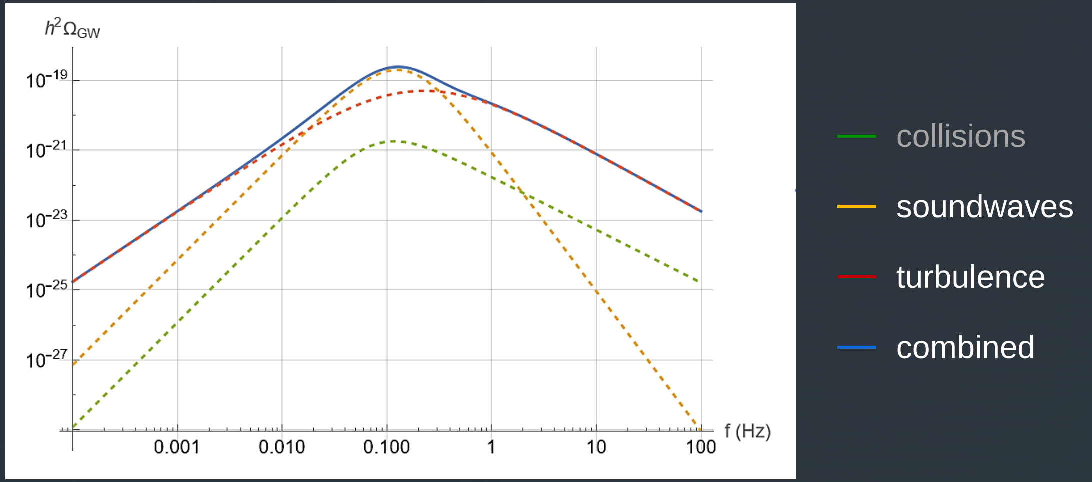

M. Hindmarsh, S. Huber, K, Rummukainen, D.J. Weir (2015, PRD 92.123009)

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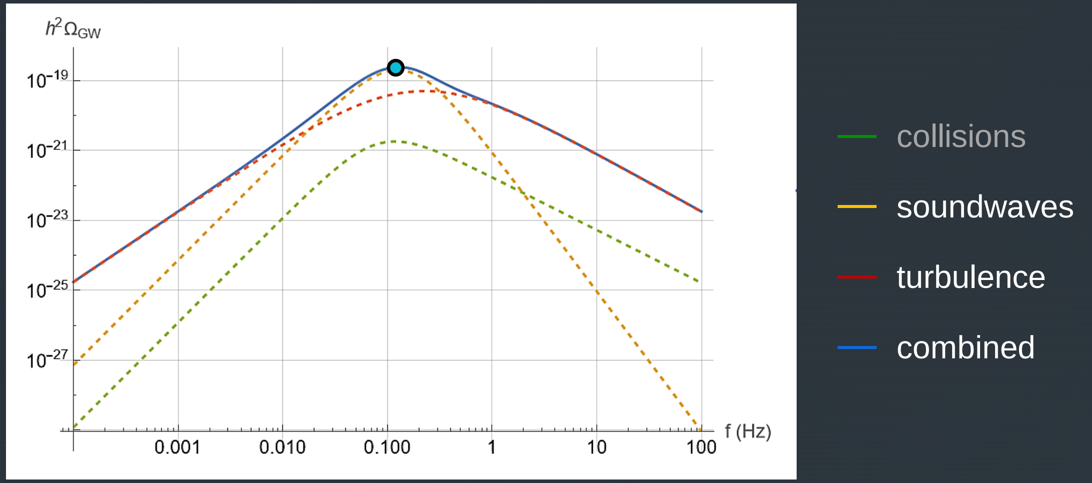

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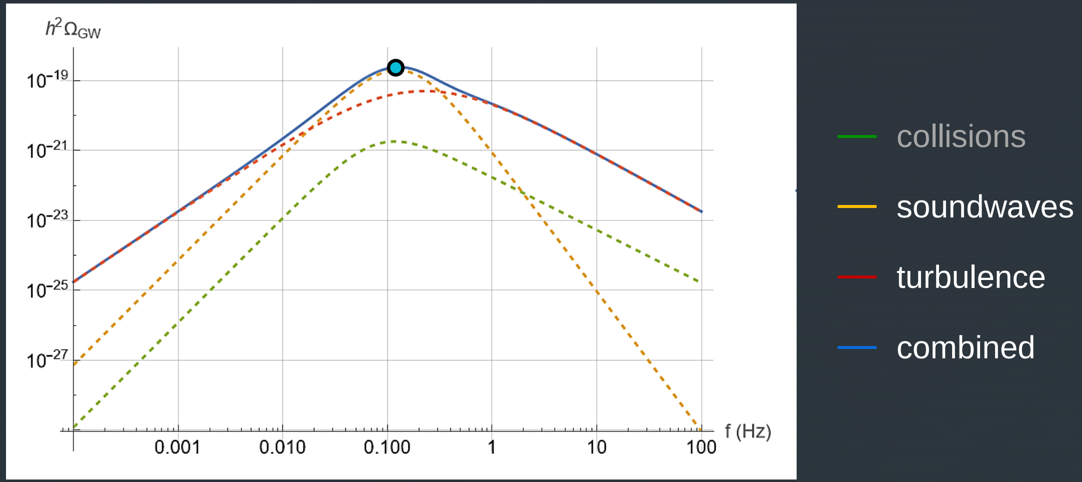
Model parameters scan
masses
couplings



Outcome
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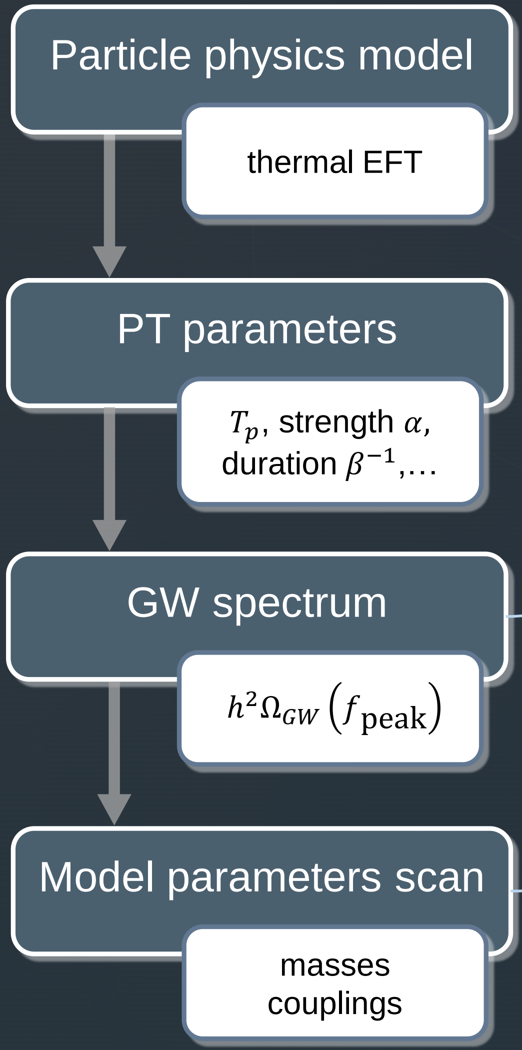

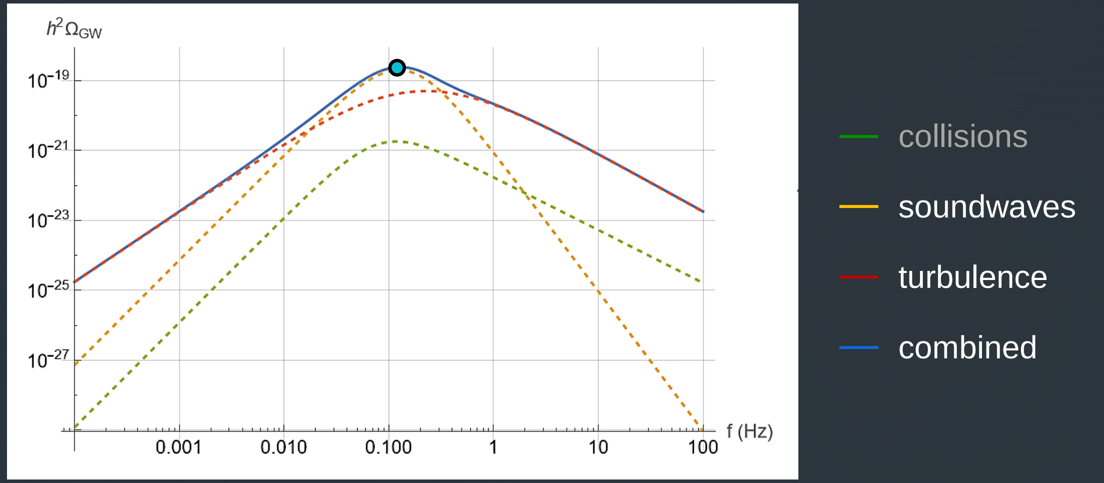

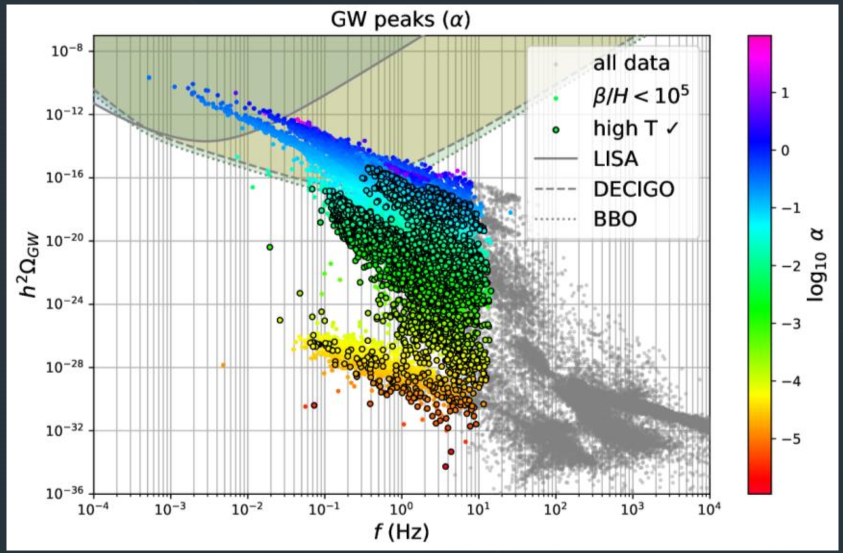

Outcome

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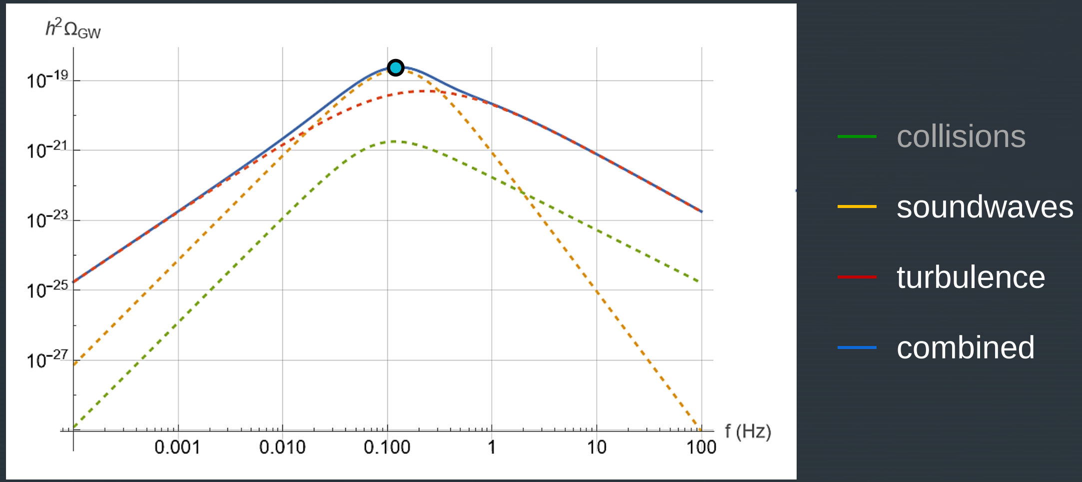
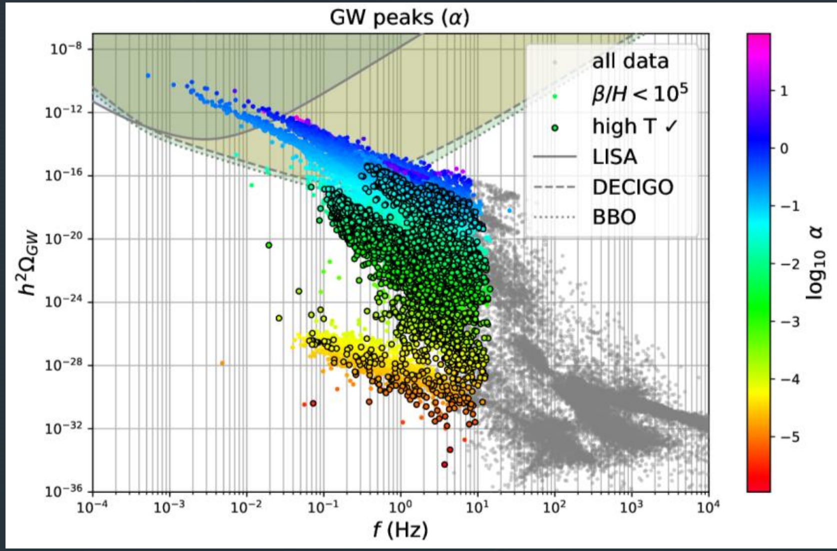
Model parameters scan
- masses
- couplings





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

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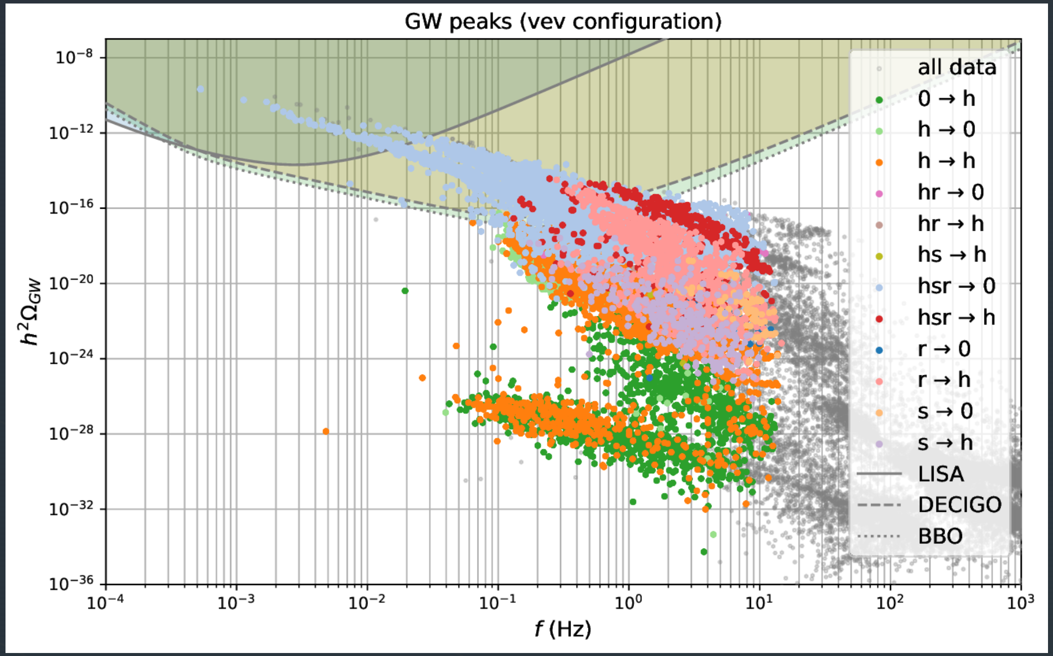
Model parameters scan

masses couplings,…



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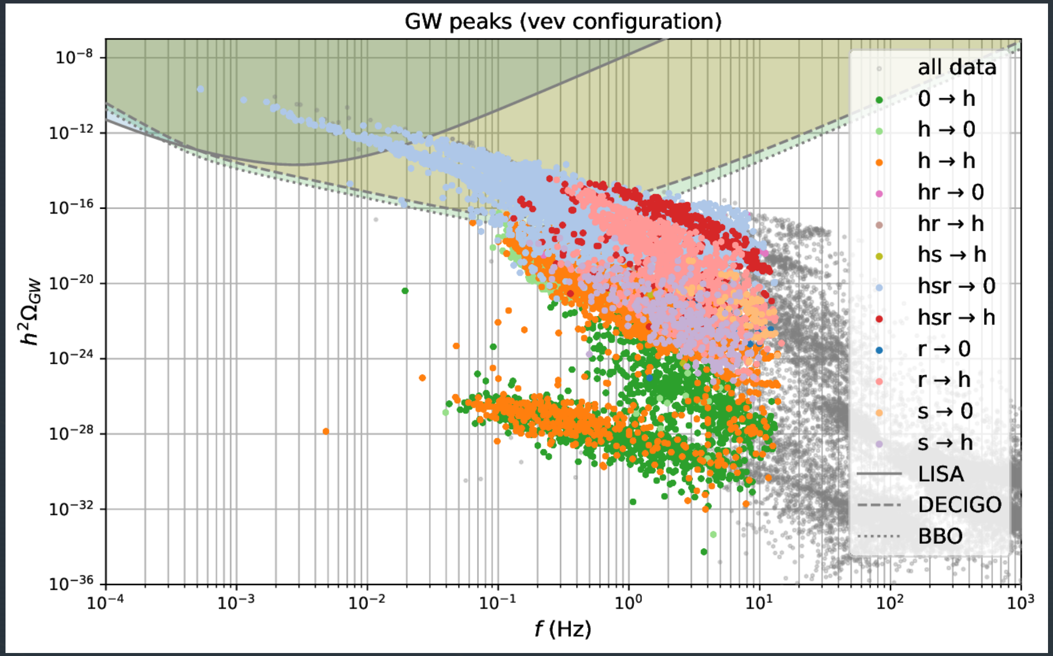

Colour breaking and restoration!

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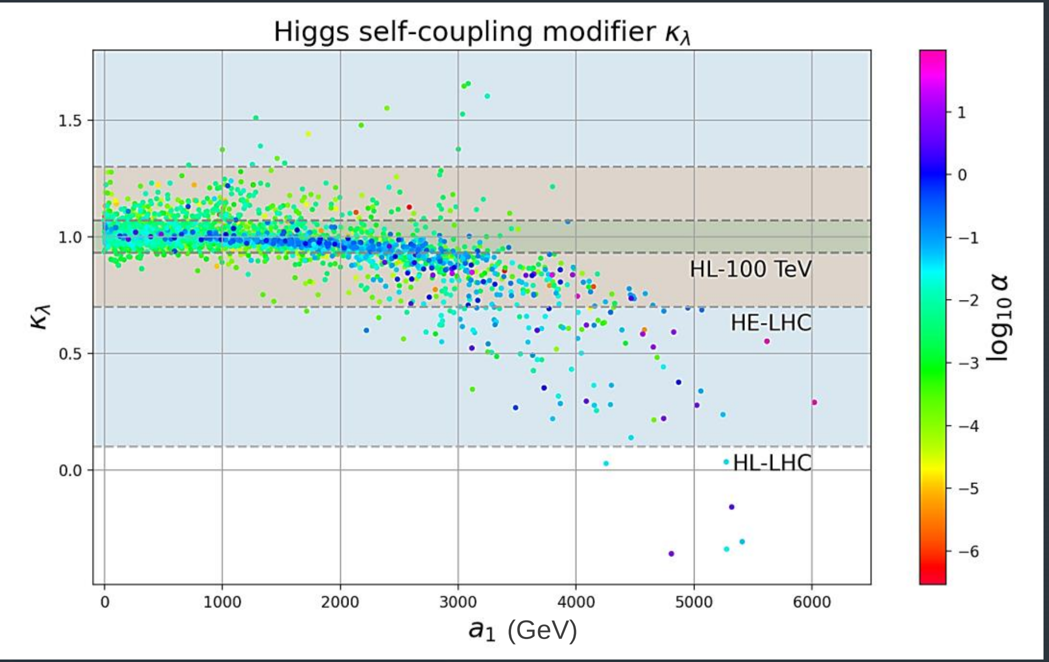
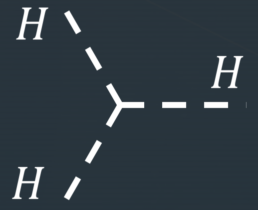




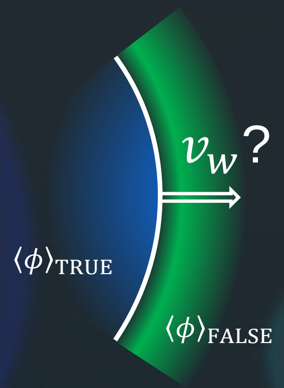
$$\kappa_\lambda \equiv \frac{\lambda_{hhh}^{BSM}}{\lambda_{hhh}^{SM}} = 1 + \frac{\lambda_{hhh}^{LQ}}{\lambda_{hhh}^{(0)} + \lambda_{hhh}^{t}}$$

Outcome
& Future Endeavours

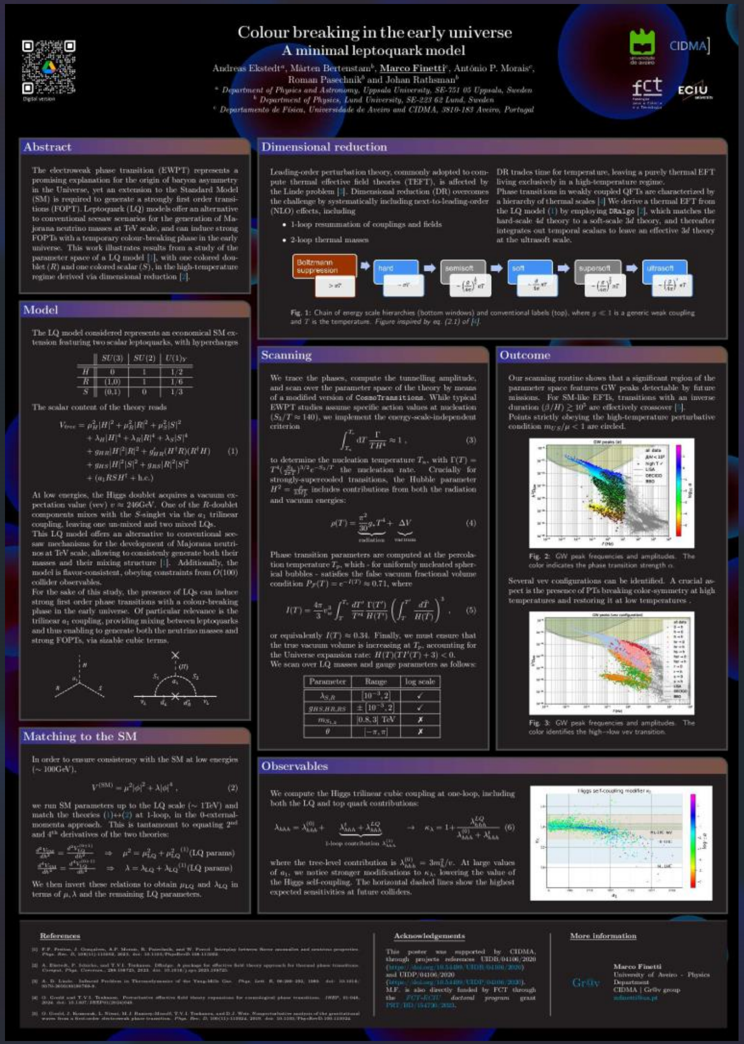
- Model
  - ✓ flavour-consistent LQ model generating ν masses
  - ✓ featuring colour-breaking at high-T
  - ✓ and colour-restoration at lower T

- 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 $\Gamma = A\, e^{-S_3/T}$

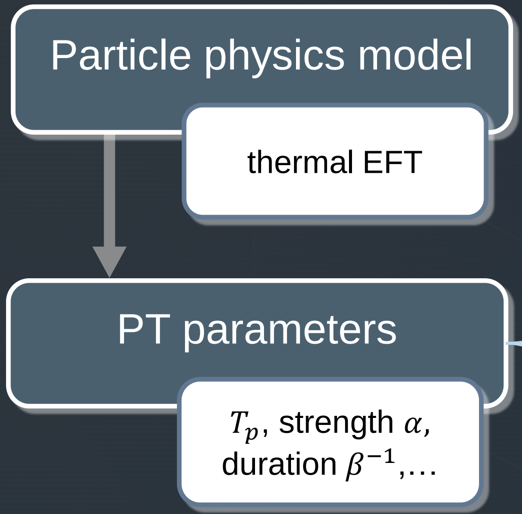


Thanks for listening!



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

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↓

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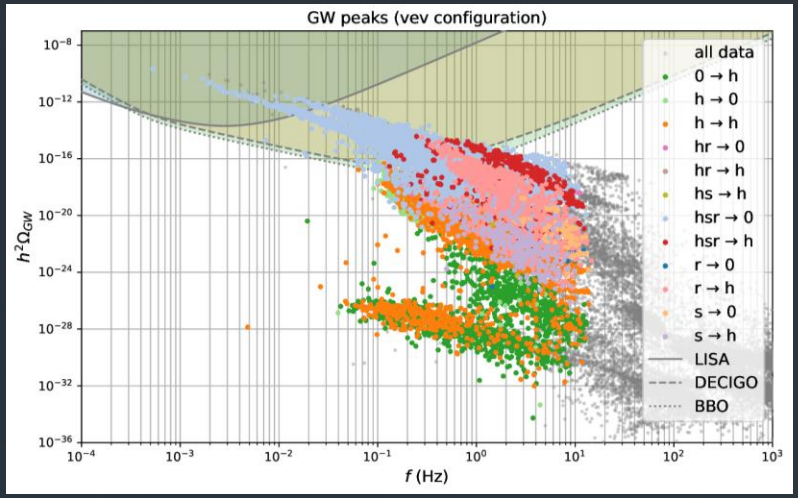
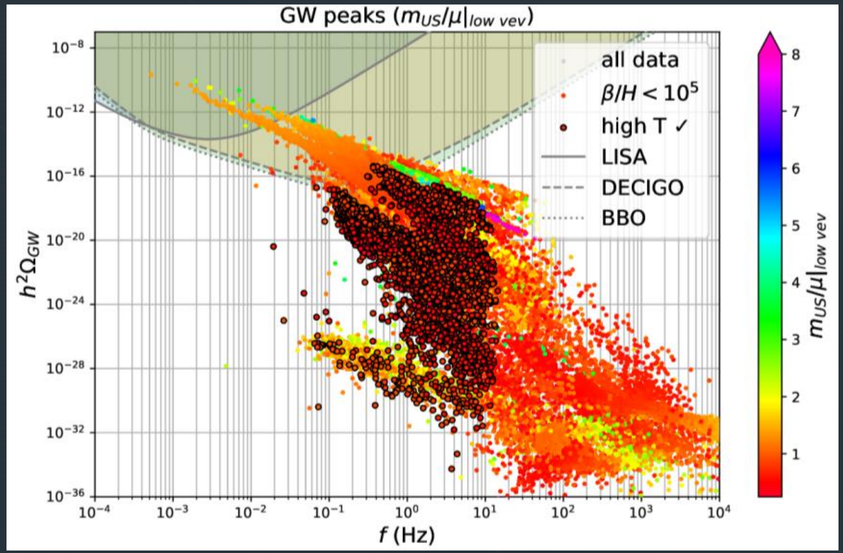
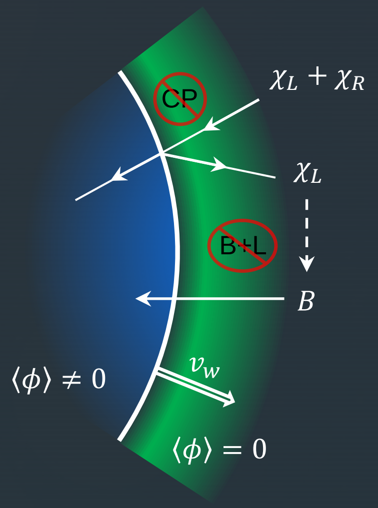


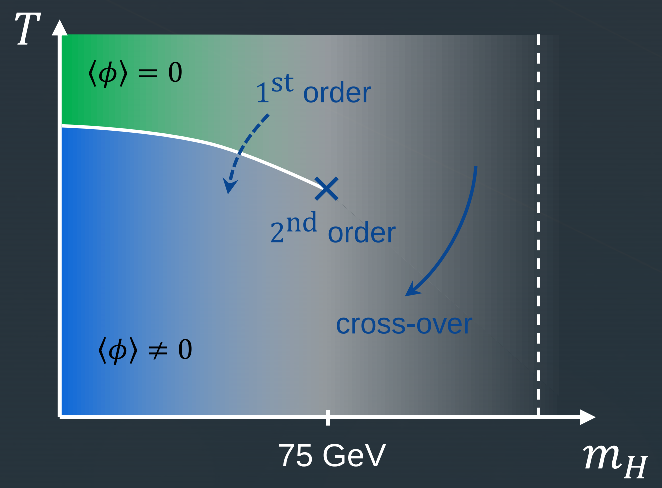


EW Baryogenesis
The matter-antimatter problem

- 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!