

Gravitational waves from cosmological phase transitions

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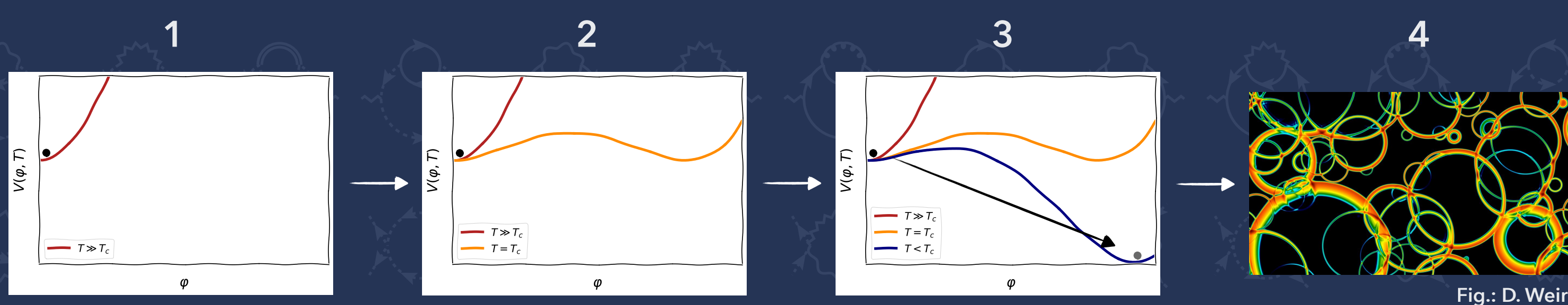
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Based on: Kierkla, Lewicki, Schicho, DS, Swiezewska 2607.18233



Cosmological first-order phase transitions (FOPTs) are a prime target of future gravitational-wave (GW) observatories. A primordial GW background would be a smoking-gun signature of new physics and provide a unique window into the very early Universe shortly after the Big Bang.

Dynamics.



1. Scalar field in symmetry-breaking potential. Thermal effects restore the symmetry at high temperature.
2. The Universe cools and a second minimum forms.
3. The true minimum becomes energetically favored and the false vacuum becomes metastable.
4. Bubble nucleation converts the entire Universe to the true vacuum. Bubble interactions generate large anisotropies in the primordial plasma that act as a source of stochastic GWs.

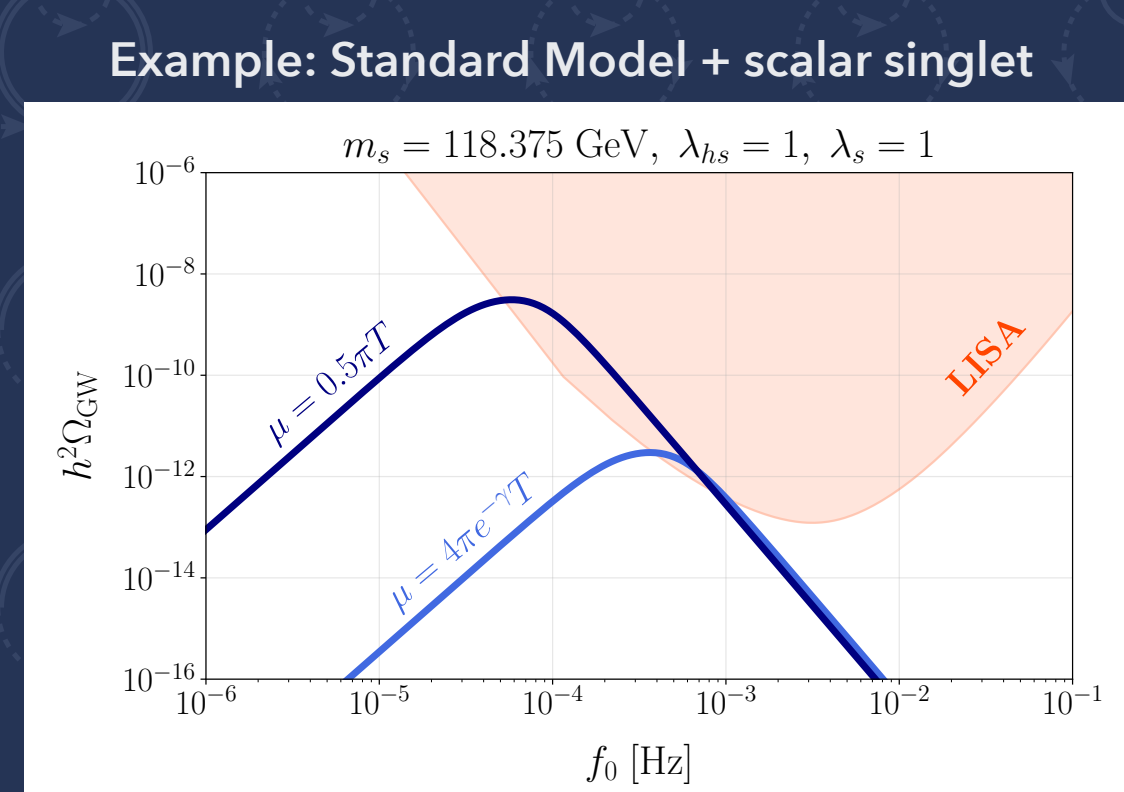
Key quantity: Bubble nucleation rate

$$\Gamma(T) \propto \exp(-S_E) \quad \text{with} \quad S_E = 4\pi \int dr r^2 \left[\frac{1}{2} (1 + Z_{\text{NLO}}(\varphi_b)) (\partial_r \varphi_b)^2 + (V_{\text{eff}}^{\text{LO}}(\varphi_b) + V_{\text{eff}}^{\text{NLO}}(\varphi_b)) \right]$$

Phenomenology.

Leading-order renormalization scale dependence leads to order-of-magnitude uncertainty in GW spectrum.

What is the impact on the reconstruction of model parameters from a benchmark signal?



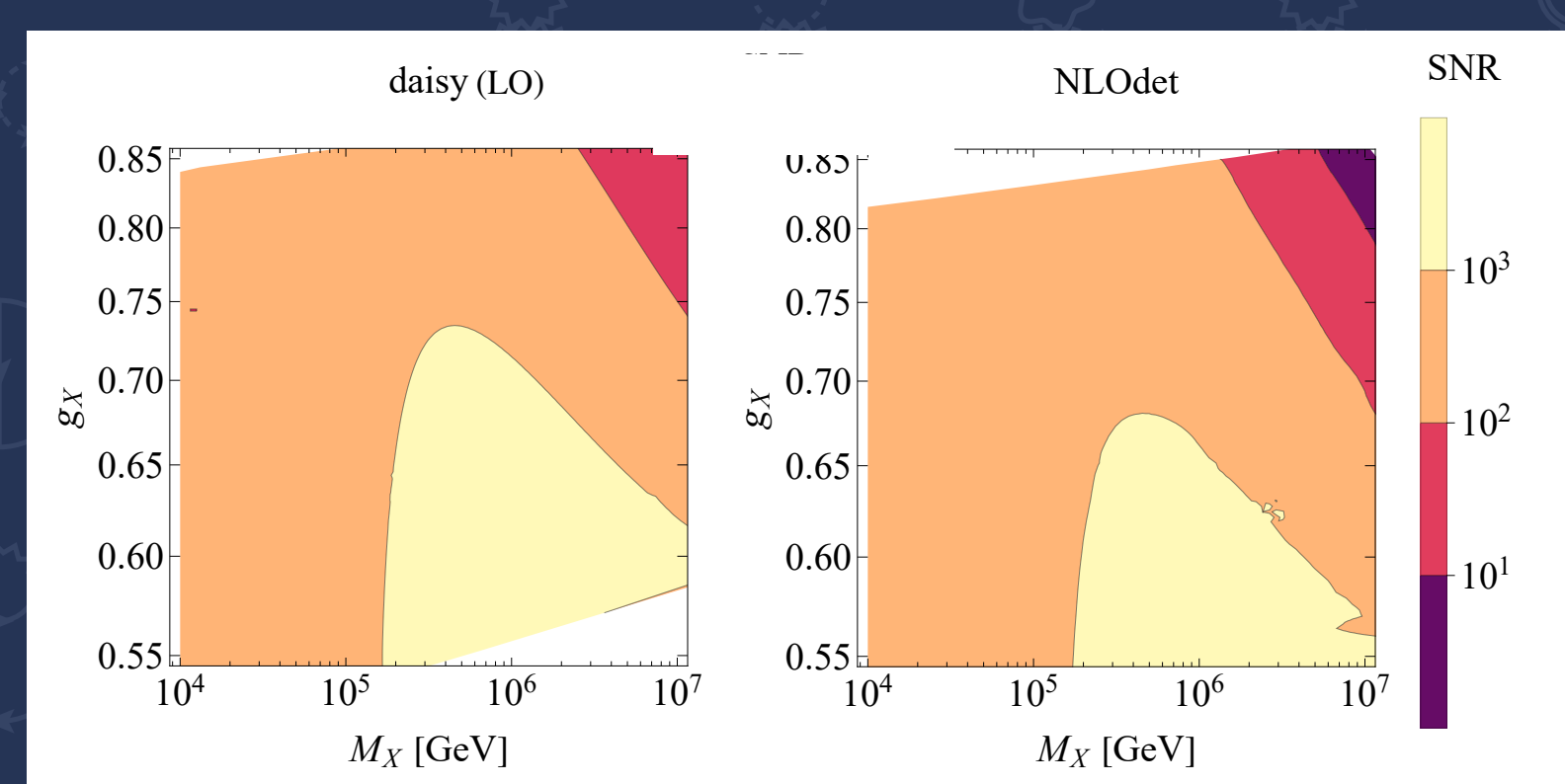
Benchmark model: Classically scale-invariant $U(1)_X$ Standard Model extension.

$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu H)^\dagger (D^\mu H) + (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

$$V(\Phi, H) = \lambda_\Phi \Phi^4 + \lambda_H H^4 - \lambda_p \Phi^2 H^2$$

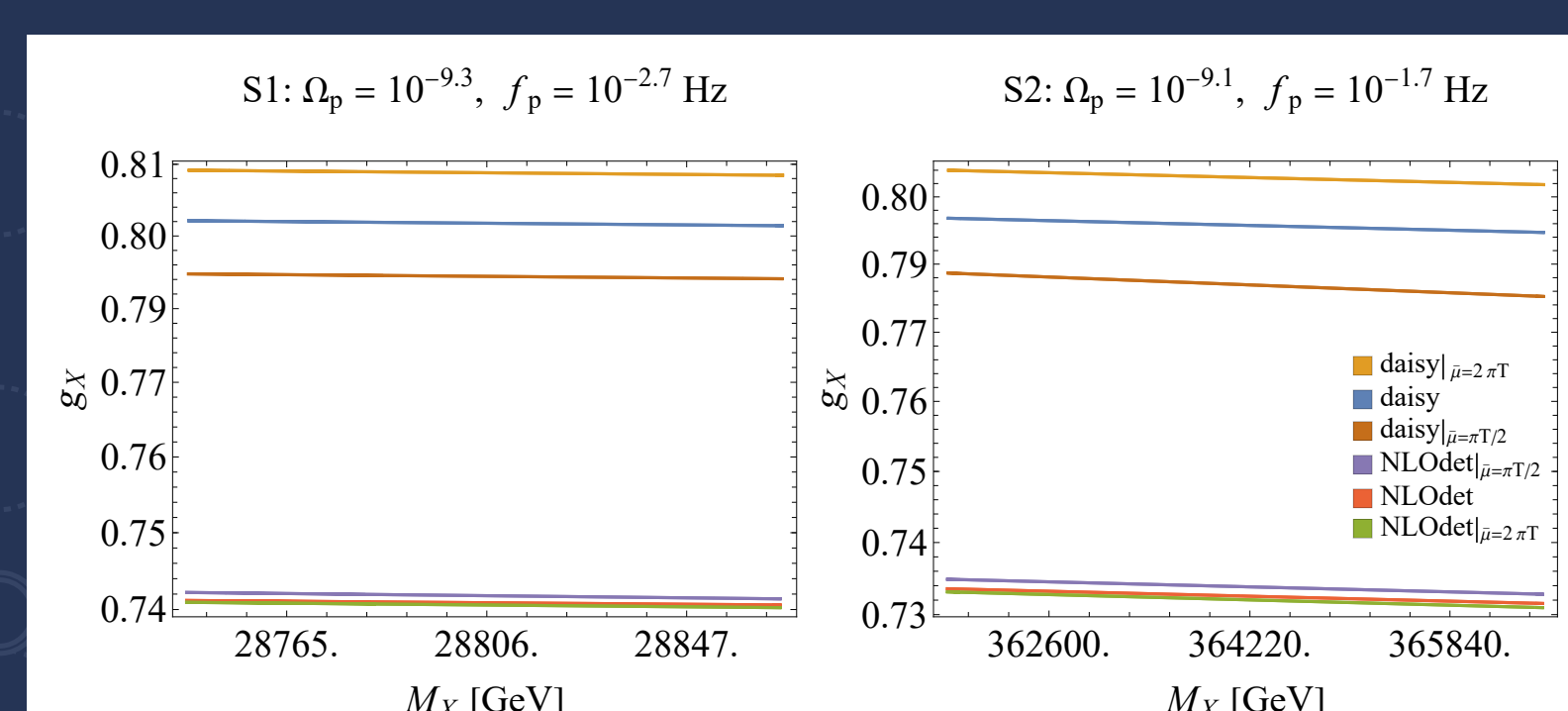
Overall strong signals and great detection prospects in LISA.

Next-to-leading order effects result in shift of parameter space.



Model parameter reconstruction via Fisher matrix analysis.

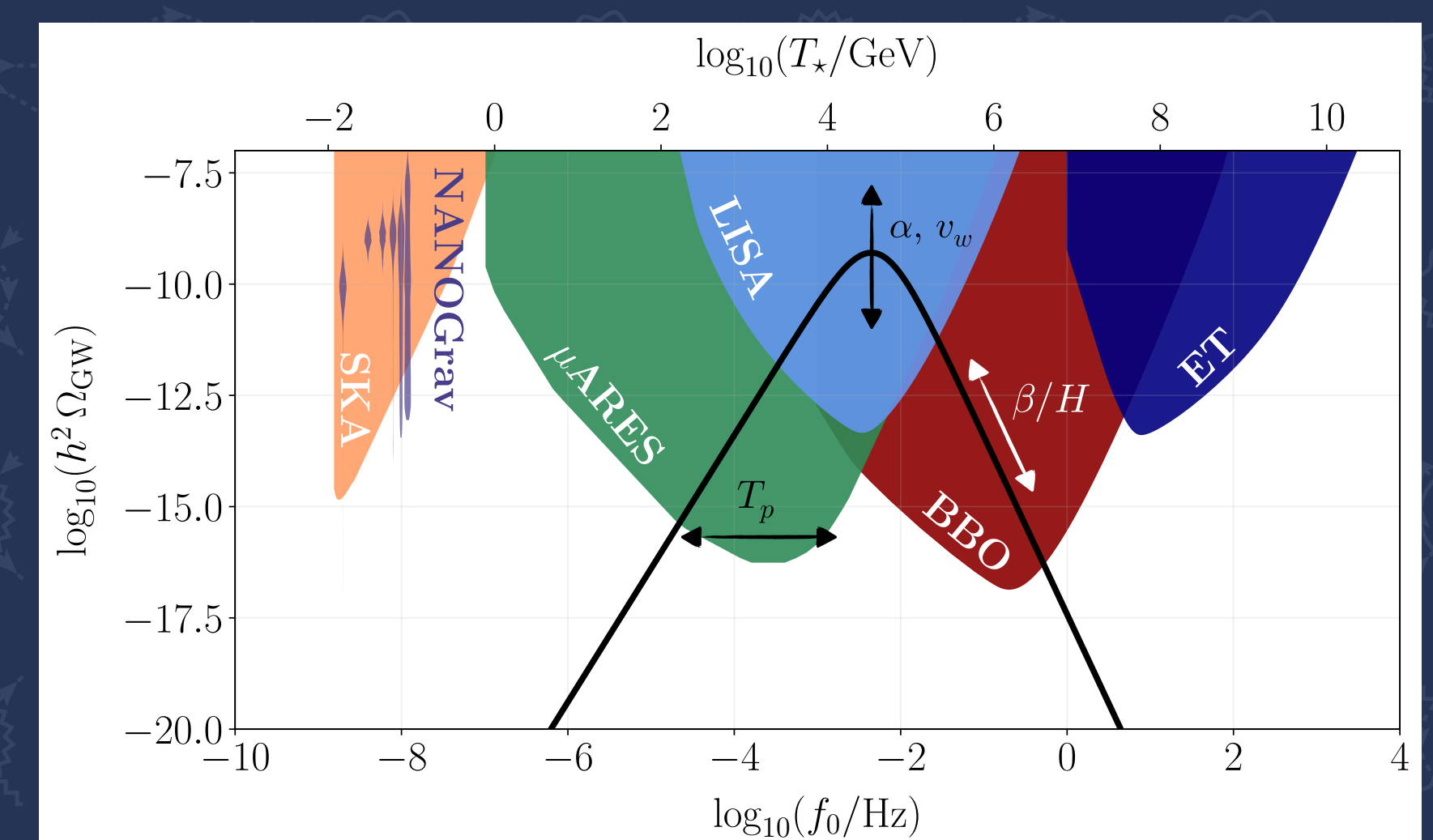
Only NLO computation reduces theoretical uncertainty to a level comparable with experimental uncertainty.



GW spectrum.

GW spectrum described by few microphysical parameters.

- T_p : Percolation temperature
- α : Transition strength
- β : Inverse timescale
- v_w : Bubble wall velocity



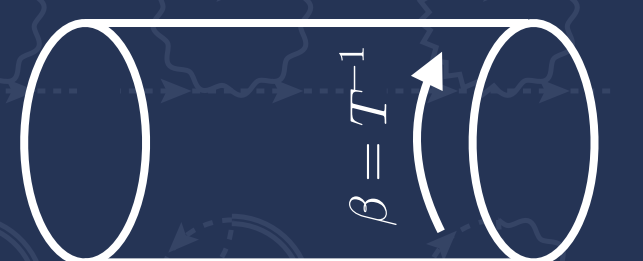
Goal: minimizing theoretical uncertainties in GW predictions.

Thermal resummation.

- Quantum fields at finite temperature live in compact time dimension with periodicity $\sim T^{-1}$

$$\phi(x) = T \sum_{n=-\infty}^{\infty} \int \frac{d^3 p}{(2\pi)^3} \phi(\omega_n, \mathbf{p}) e^{i\omega_n \tau} e^{-i\mathbf{p} \cdot \mathbf{x}}$$

- Matsubara frequencies $\omega_n = \begin{cases} 2n\pi T, & \text{bosons} \\ (2n+1)\pi T, & \text{fermions} \end{cases}$



- Expansion parameter of bosonic zero mode $\epsilon \sim \frac{g^2 T}{\pi m}$ non-perturbative for $m \rightarrow \frac{g^2 T}{\pi}$

- Use scale hierarchy $\underbrace{\pi T}_{\text{hard}} \gg \underbrace{gT}_{\text{soft}} \gg \underbrace{g^{\frac{3}{2}} T}_{\text{supersoft}} \gg \underbrace{g^2 T}_{\text{ultrasoft}}$ to construct 3d effective theory (EFT)

- Identify degrees of freedom (dofs) which live at the respective scales.
- Construct most general 3d Lagrangian involving dynamical infrared dofs.
- Find effective Lagrangian parameters by matching correlation functions at desired order, e.g.,

$$\underbrace{p^2 + m_{\text{eff}}^2}_{3\text{D}} + \underbrace{\bar{\Pi}_{\text{soft}}^{(1)}(p=0; m_{\text{eff}}^2)}_{3\text{D}} = \underbrace{p^2 + m^2}_{4\text{D}} + \underbrace{\bar{\Pi}_{\text{soft}}^{(1)}(p=0; m^2)}_{4\text{D}} + \underbrace{\bar{\Pi}_{\text{hard}}^{(1)}(p=0; m^2)}_{4\text{D}}$$

- Study PT dynamics within 3d EFT.

Conclusions.

- FOPTs are a promising GW source in the early Universe
- Predictions are subject to large theoretical uncertainties from thermodynamic treatment of primordial plasma
- Thermal effective field theory allows for consistent computation of higher orders
- Leading-order computations carry uncertainties that exceed experimental ones
- Next-to-leading order required for robust model parameter reconstruction