Gravitational waves from first-order phase transitions: Approaching reliable predictions

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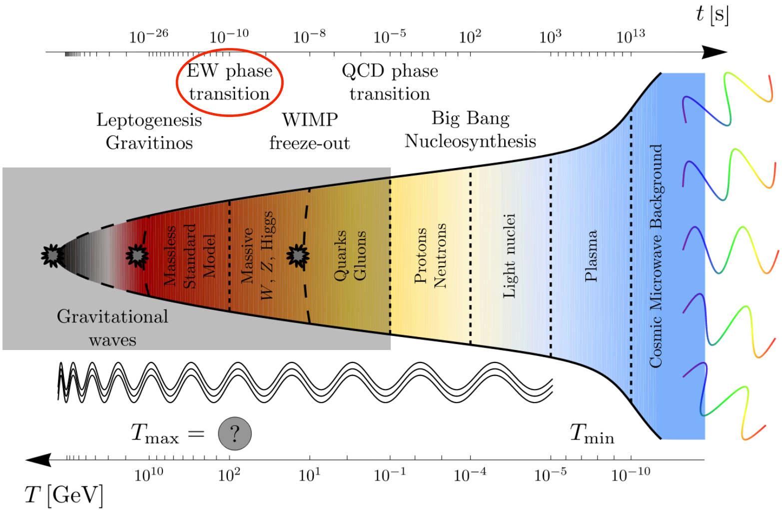
ICHEP 2024

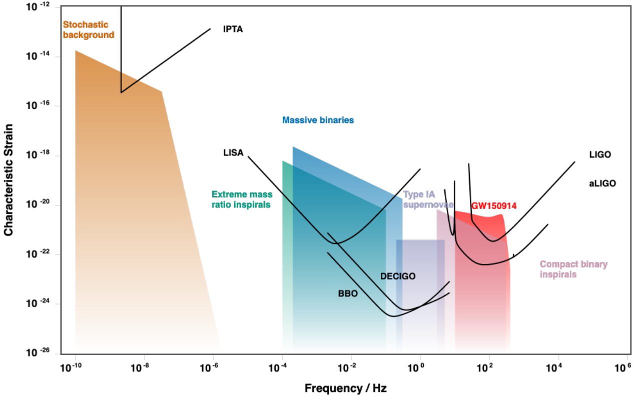
2024.07.19

Our cosmological history in a nutshell

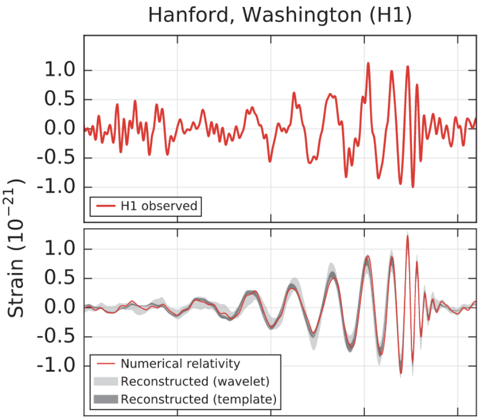


Adapted from 1307.3887

Gravitational waves—A new frontier



See gwplotter.com

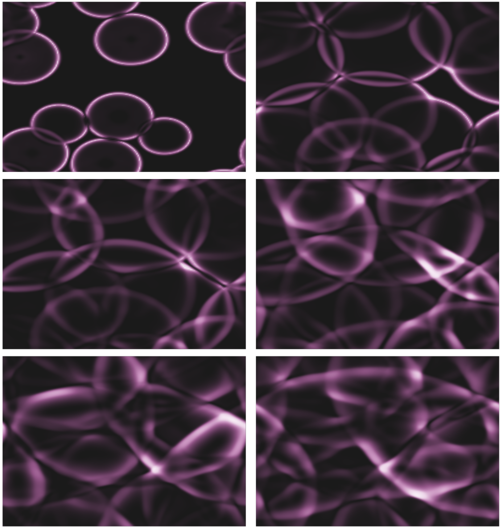


See 1602.03837

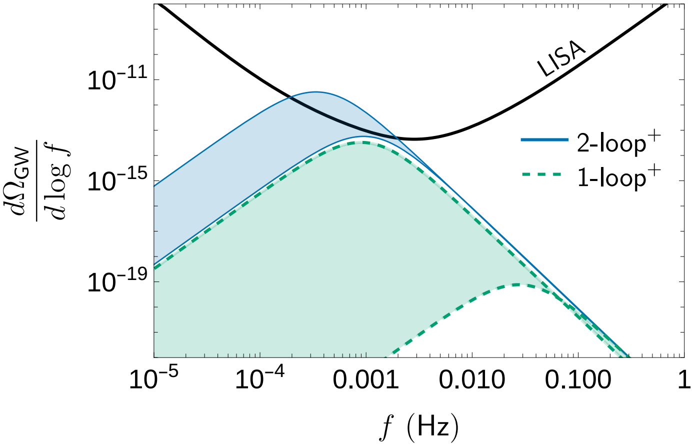
The electroweak phase transition

If the transition is first-order:

- Latent heat is released $\rightarrow$ α_N
- Bubbles nucleate and expand $\rightarrow$ T_N, β_N
- Sound waves generate a signal $\rightarrow$ Ω_{GW}



Alas, theory uncertainties



2104.04399

Green band—What most computations give
Blue band—Probably the best that we can do

Where we are at

Low-temperature phase transitions: $m \gg T_N, T_c$
$\rightarrow$ **Very hard** to get precise predictions

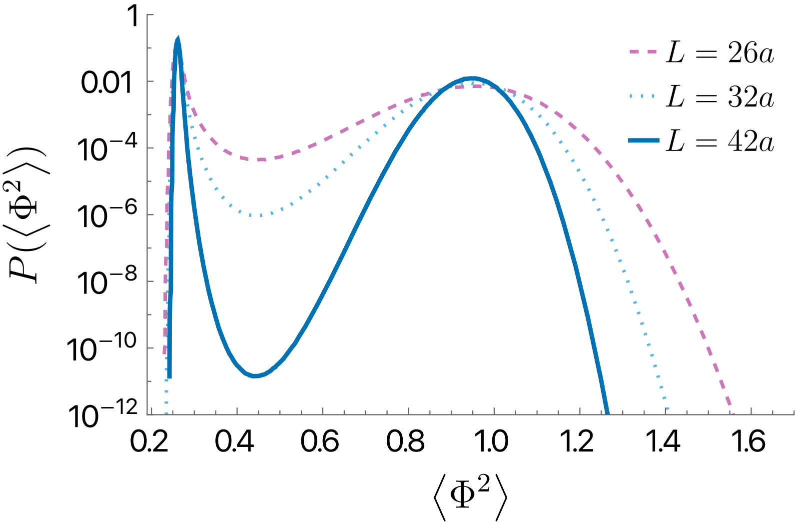
High-temperature phase transitions: $m \lesssim T_N, T_c \rightarrow$ A lot of progress:

- Nucleation rates (T_N, β_N): One-loop corrections ✓ $\leftarrow$ This talk
- Latent heat (α_N) : Three-loop calculations ✓ $\leftarrow$ This talk

What remains to be done:

- The wall-speed : $v_w \sim 1$ or $v_w \sim v_J$? ✗
- Dissipative effects: Hydrodynamics with friction, viscosity etc ✗

Lattice vs perturbation theory at thermal equilibrium



Comparison for a SM-like theory 2405.18349, 2205.07238

$V \sim y\phi^2 - \phi^3 + x\phi^4$

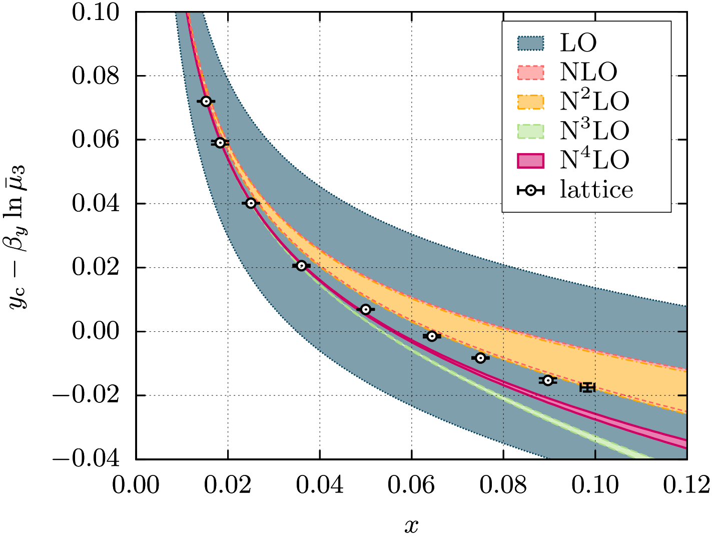
$y_c \sim T_c^2$

$x \sim m_H$

NLO $\sim$ 1-loop

N^{2}LO $\sim$ 2-loop

N^{4}LO $\sim$ 3-loop



Nucleation rates: $A \approx T^4$ is an **awful** approximation

The nucleation rate (Γ) is controlled by the bounce:

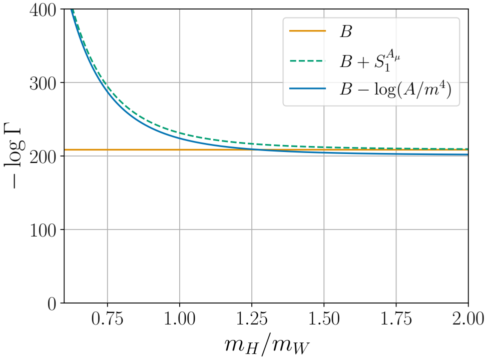
$$\nabla^2 \phi_B(r) = V'_{\text{eff}}[\phi_B] \to \Gamma = A e^{-E_B/T}$$

In field theory the prefactor, A, is **exponentially** important

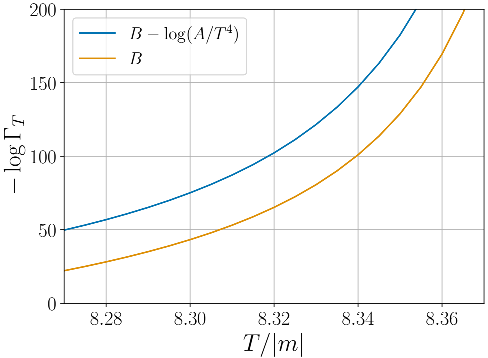
- The prefactor is basically the entropy: Contributes $\mathcal{O}(1)$ for **each** mode
- The huge number of modes in QFT add up to an exponential

Do **not** trust dimensional arguments for quantitative predictions!

One-loop rates are mandatory 2308.15652, 2104.11804

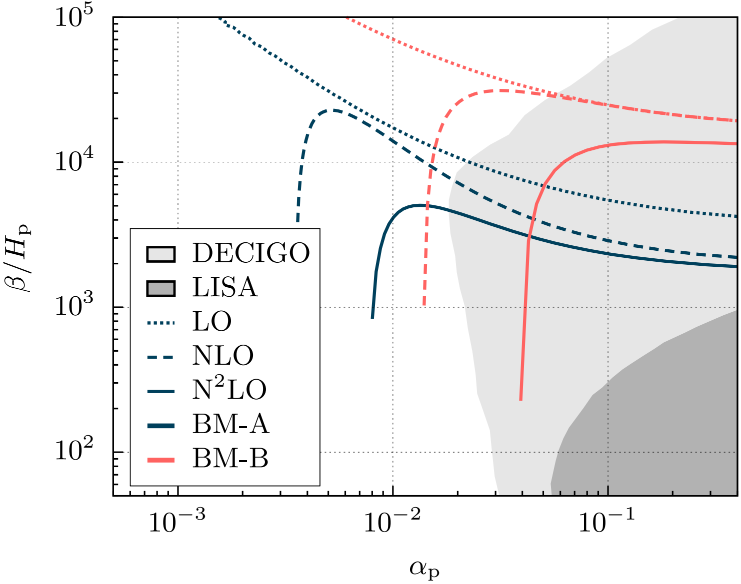


SM+ϕ^6



A Yukawa-Scalar model

Three-loop latent heat + (two) one-loop nucleation rates



In summary

Theory has made great leaps:

- Robust resummations at **high** temperatures 9508379, 2108.04377
- One (and two!) loop nucleation rates 2312.04482, 2104.11804
- Three-loop equilibrium predictions 0510375,2405.18349
- Fast hydrodynamic simulations 2209.04369
- More and more comparisons with lattice 2405.01191, 2205.07238

The minimum requirements for decent predictions:

- Two-loop thermal resummations
- Two-loop effective potentials
- One-loop nucleation rates: **Functional determinants**