# A link between gravitational waves and collider physics

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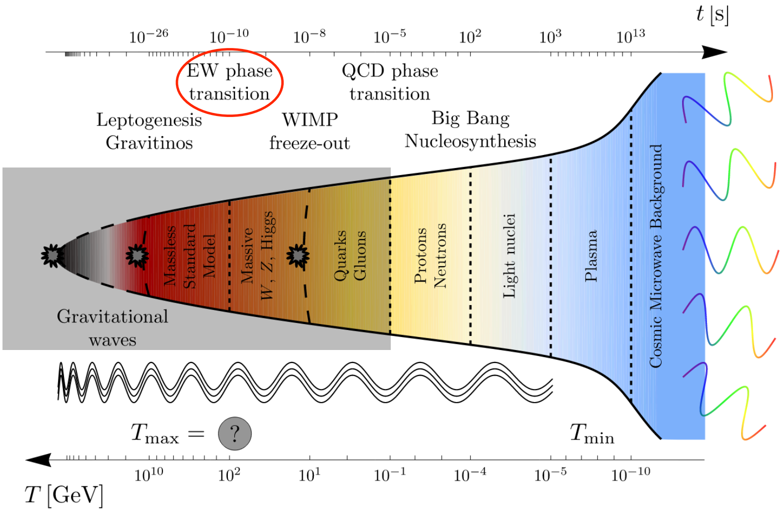
# The Cosmological History

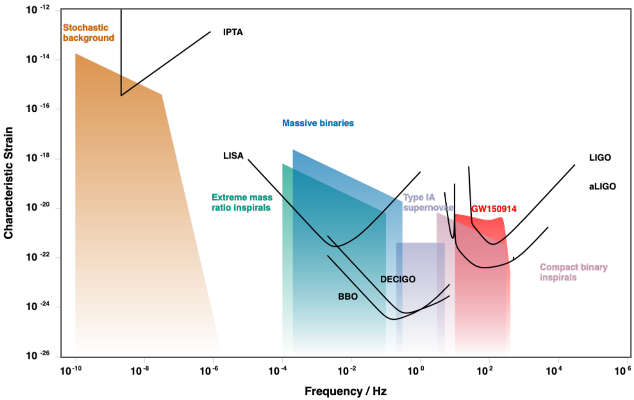



Adapted from 1307.3887

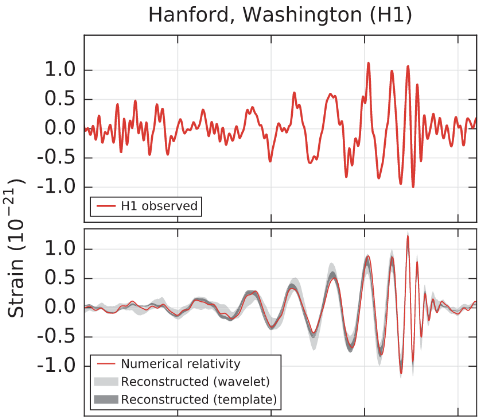
# Gravitational waves—A new game in town

Gravitational waves observed by LIGO/VIRGO

New experiments are coming




See gwplotter.com




See 1602.03837

# This talk

The Electroweak phase transitions

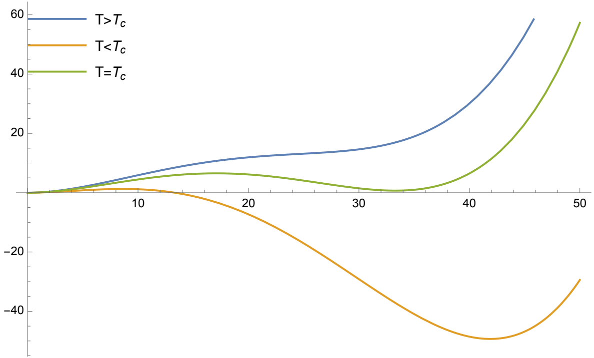
How to get phase-transitions constraints

Connecting phase transitions to simplified models

# The Electroweak phase transition in a nutshell

The Electroweak symmetry was (**probably**) exact at $T \gtrsim 1$ TeV

A phase transition at $T_c \sim 100$ GeV.




**What if the transition was first-order?**

**Electroweak Baryogenesis**

$\rightarrow$ Can explain the Baryon asymmetry

**Gravitational waves**

$\rightarrow$ Window into the early Universe

$\rightarrow$ Access to the Higgs potential

# The connection with collider studies

At **zero** temperature:

$$V \subset \underbrace{\frac{1}{2} m^2 h^2}_{\text{Measurement}} + \underbrace{\gamma h^3}_{\text{Higgs pair production}} + \underbrace{\lambda h^4}_{\text{Vacuum stability}} + \ldots$$

At high temperatures:

$$V_{\text{eff}} \subset \underbrace{\frac{1}{2} m_{\text{eff}}^2(T) h^2 + \gamma_{\text{eff}}(T) h^3 + \lambda_{\text{eff}}(T) h^4 + \ldots}_{\text{Electroweak phase transition}}$$

**In a nutshell**

Fundamental theory at zero temperature $\rightarrow$ Classical theory at finite temperature

# A crash course in thermal field theory

**Phase transitions are fine tuned**

$E \sim m_{\text{eff}}(T) \ll T \rightarrow$ Everything is classical $n_B(E) \sim \frac{T}{E} \gg 1, \quad n_F(E) \sim 1$

**The general idea**

Long-range ($L \gg T^{-1}$) fluctuations are small: $\langle \Psi_F^2 \rangle / \langle \Phi_B^2 \rangle \sim n_F / n_B \ll 1$

$\rightarrow$ Fermions do not enter phase transitions directly

Fermions enter the classical description indirectly:

- Thermal masses and Couplings
- Collisions $\rightarrow$ Generates **Friction**
- Tiny $L \sim T^{-1}$ fluctuations keep pushing on the scalar field $\rightarrow$ Thermal noise

# From the LHC to the Electroweak phase transition

So say that you have a model with two fields and a potential:

$$V = \frac{1}{2}m^2 h^2 + \frac{1}{2}\mu^2 s^2 + \frac{1}{4}\lambda h^4 + \ldots + c_6 s^6 + \ldots$$

What do you need to make a phase-transition **prediction**?

$m^2, \ldots, \lambda, c_6, g_s, g_w, \ldots$+ Fermions $\rightarrow$ $V_{\text{eff}}$ (without fermions)

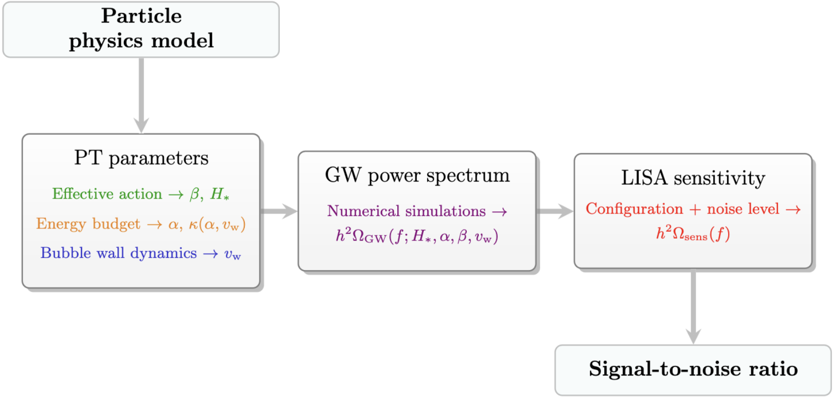
Cross-sections $\rightarrow$ Friction and viscosity

**We can go about it in a few ways**

1) Start with a fundamental theory $V_{T=0}$ , find $V_{\text{eff}}$, and get constraints
2) Consider a generic $V_{\text{eff}}$, get constraints, map to many different $V_{T=0}$
3) Consider a generic $V_{\text{eff}}$, get constraints, map to a simplified potential at $T = 0$

$\rightarrow$ Map the result to almost any models

# Typical pipeline




See 1910.13125

# Summary

Opportunities:

Only a few scenarios have been studied

Cross-sections enter both di-Higgs and the friction coefficients

Phase-transition predictions can be made (almost) model independently

$\rightarrow$Can use simplified models both at zero and at finite temperature

The Higgs potential can be probed in both settings

What's in store:

Automatized gravitational-wave predictions

LISA up and running ($\sim 2035 - 2040$)