Gravitational waves from bubble collisions

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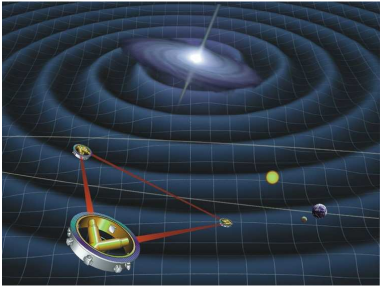
Outline

Why are gravitational waves interesting? - experiment

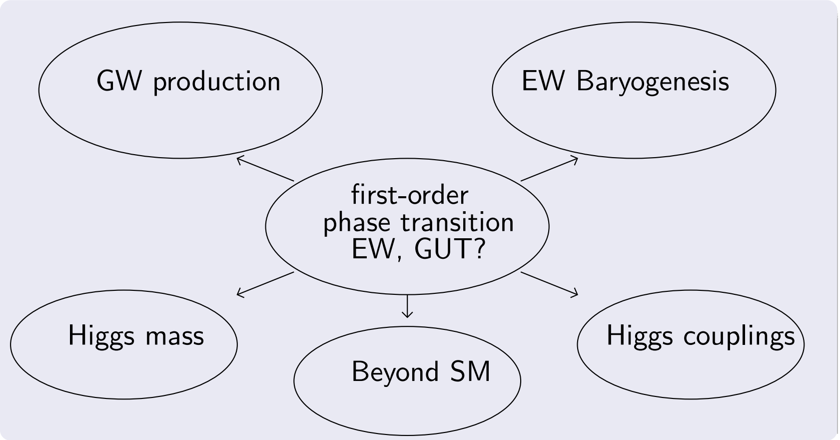
With LIGO a ground based experiment is operational that can observe black hole merger.

With LISA a satellite experiment is under way that might be sensitive enough to measure not only GWs from localized sources (*e.g.* binaries) but also the stochastic GW background (*e.g.* inflation).



Why are gravitational waves interesting? - Particle physics

If a GW background is produced by a strong first-order electroweak phase transition, some information about the Higgs sector can be inferred:



GW production

EW Baryogenesis

first-order
phase transition
EW, GUT?

Higgs mass

Beyond SM

Higgs couplings

Bubble nucleation

A first-order phase transition proceeds by bubble nucleation

During the first-order phase transition, the latent heat is transformed into

- Reheating of the plasma
- Kinetic energy of the Higgs walls
- Bulk motion
- Turbulent motion at the end of the phase transition

The last three contributions can source gravitational wave radiation.

Relevant parameters

In the production of GWs by bubbles collisions, basically only three relevant parameters enter

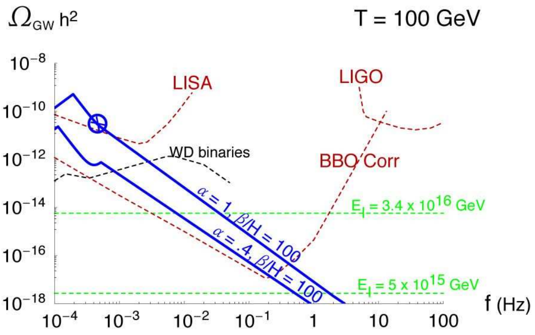
- The temperature of the phase transition T.
- The parameter β that parametrizes the nucleation probability of bubbles and hence the duration of the phase transition and the typical bubble radii.
- The latent heat normalized to the radiation energy $\alpha = \Lambda/\rho_{radiation}$.

Typical parameters are $\alpha \lesssim 1$, $\beta \approx 100H$, $T \approx 100$ GeV, but depend on the specific model under consideration. In the SM no first-order phase transition occurs (cross over).

Stochastic GWs

Different sources of stochastic GWs are: Inflation, binaries or a strong first-order phase transition

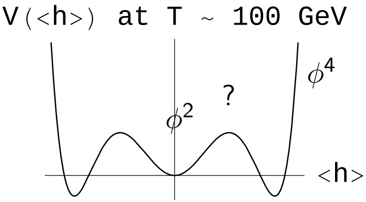
Grojean, Servant ('06)



Outline

Barriers in the free energy

A first-order phase transition proceeds by tunneling.



The barrier can be produced by

- Thermal effects of light bosons $\sim T\phi^3$ (e.g. MSSM with light stops) Anderson, Hall ('91)
- Extended Higgs sectors (e.g. NMSSM) Huber, Schmidt ('01)
- Higher dimensional ϕ^6 operators Grojean, Servant, Wells ('05)
- Logarithmic contributions from scalars strongly coupled to the Higgs Espinoza, Quirós ('07)

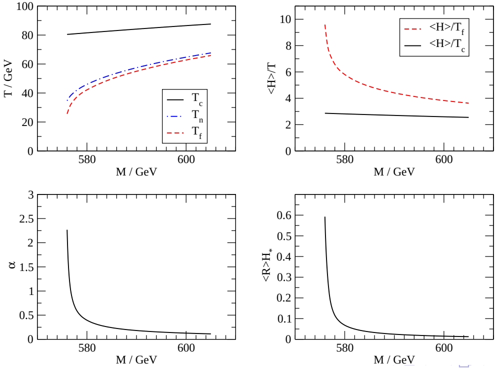
A strong electroweak phase transition requires beyond the SM physics at the TeV scale and favors a light Higgs.

Toy model ϕ^6

Consider the toy model with the following Higgs potential

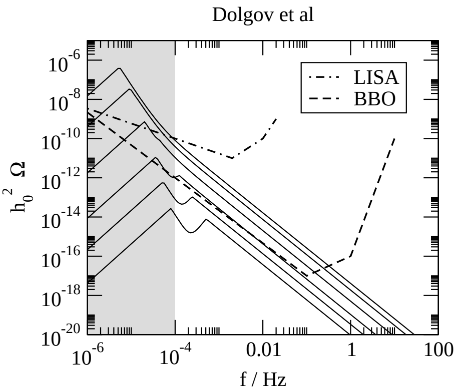
$$V(\phi) = m^2\,\phi^2 + \lambda\phi^4 + \frac{1}{M^2}\phi^6,$$

where M is a strong coupling regime (technicolor?), and the Higgs mass is fixed as $m_H = 120$ GeV ($\langle\phi\rangle \simeq 256$ GeV).



Toy model ϕ^6

Huber, Konstandin ('07)

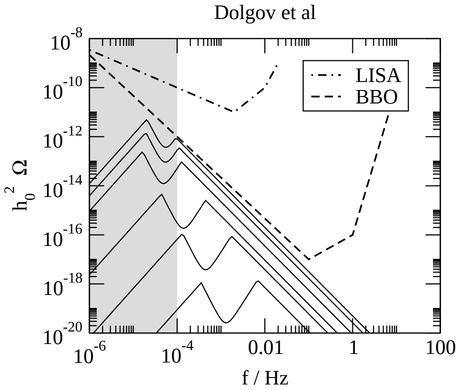


In the ϕ^6 model, stronger phase transitions (*larger* α) proceed at *lower* T and with *smaller* β, shifting to lower frequencies.

In the shaded region, the sensitivity of LISA and BBO drops significantly.

nMSSM

Huber, Konstandin ('07)



The nMSSM is a MSSM extension with additional singlet and the superpotential

$$\mathcal{L} \ni \lambda H_1 H_2 N - tN$$

The singlet field N obtains a vev, thus producing a strong phase transition and solving the μ-problem.

Stronger phase transitions (*larger* α) proceed at *lower* T and with *smaller* β, shifting to lower frequencies.

Lessons learnt from model studies

Analyzing explicit models one concludes that

- Very strong phase transition ($\alpha \approx 1$) are in some models possible but require tuning on the percent level.
- Stronger phase transitions proceed with larger bubbles and at lower temperatures, thus shifting the peak frequency beyond the best sensitivity of LISA (mHz)
- The peak frequency is decisive for observational prospects of GWs
- This gives the high frequency behavior of the GW spectrum special importance, which is so far poorly understood.

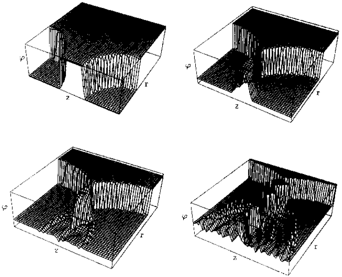
Outline

1. Introduction
2. Specific models
3. GWs from bubbles collisions
4. Conclusions

Two vacuum bubbles

Kosowsky, Turner, Watkins ('91)

Calculating the spectrum for two bubbles, one obtains:



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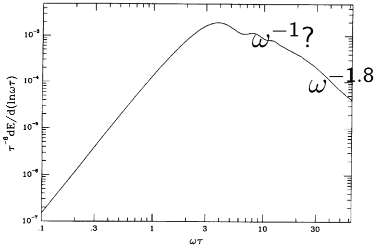
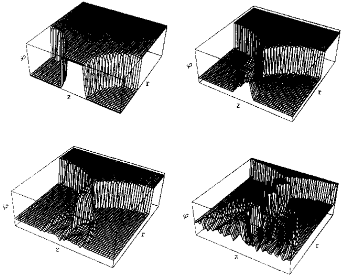


However, the phase transition has to ended by a cut-off what might influence the high frequency behavior.

Envelope approximation

KOSOWSKY, TURNER, WATKINS ('91)

The envelope approximation assumes that the energy is concentrated in a thin shell of the uncollided bubbles. Numerical simulations of the Higgs field show that this yields very accurate results.



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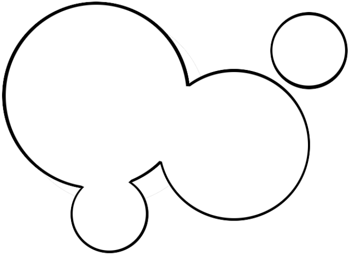


This makes the simulation of phase transitions with a large number of bubbles possible.

Many bubbles

Kamionkowsi, Kosowsky, Turner ('93)

Multi-bubble simulations have been so far rather inaccurate (especially for large frequencies and wall velocities) and the high frequency behavior is usually inferred from the two bubble case

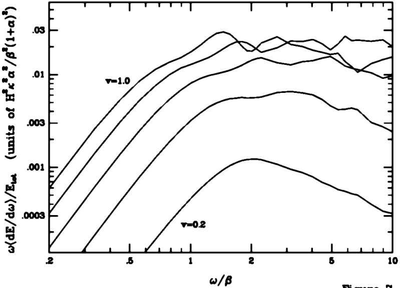


Figure 7

Also in this case, the result indicates that the high frequency tail might fall off more slowly

Numerical setup

For our simulation we chose the following parameters

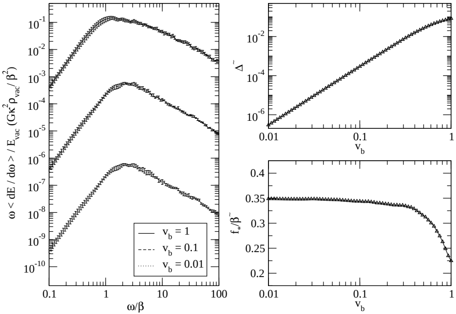
- Spherical volume with radius $7v_b/\beta$. This is motivated by the typical phase transition duration $\tau \approx 4/\beta$ and leads to ~ 140 bubbles
- Determine the spectrum two orders beyond the peak
- Ensure numerical accuracy on the percent level

With this setup the calculation takes around one week on three desktop PCs.

Numerical results

Huber, Konstandin ('08)

Simulations with higher statistics show that the spectrum indeed decreases as ω^{-1} for high frequencies.

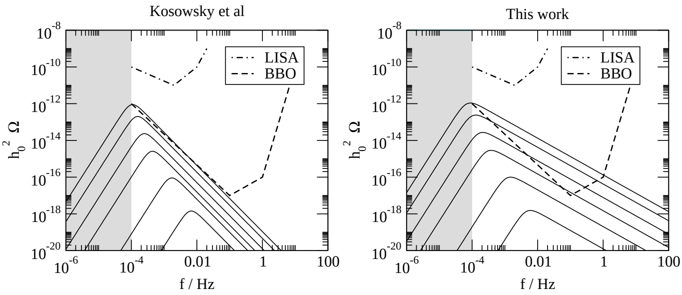


The error bars arise from averaging over eight different simulations.

Numerical results

Huber, Konstandin ('08)

This might be essential for the detection of GWs in many models, as e.g. the nMSSM



Outline

Conclusions

In contrast to earlier work, we find that the GW spectrum falls of as ω^{-1} for high frequencies. This is essential since stronger phase transitions lead generally to smaller peak frequencies.

To observe GWs from the electroweak phase transition with LISA is rather improbable.

BBO might observe GWs from a phase transition in case the phase transition is very strong. This way, the hopes for a smoking gun from inflation could be jeopardized.

GW observations from a first-order phase transitions allow to probe the underlying particle physics model. This is not necessarily the electroweak phase transition.