Detecting Gravitational Waves from Cosmological Phase Transitions

Jonathan Kozaczuk (UMass Amherst)

KICP, 10/14/16

Preface

Primary focus of this talk: **gravitational waves from the electroweak phase transition**

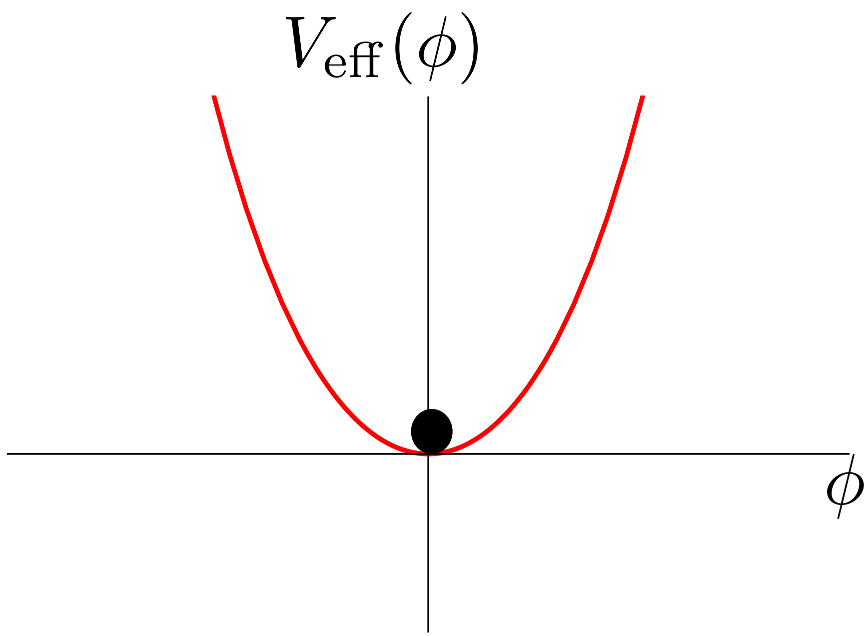
(I'll comment on some other PT scenarios not related to electroweak symmetry breaking as well)

Most of this talk based on work with members of LISA Cosmology Working Group:

Caprini, JK et al**, JCAP 1604 (2016) no.04, 001**

Motivation

The standard picture of electroweak symmetry breaking:



At high temperatures, a background field with electroweak quantum numbers stabilized at the origin

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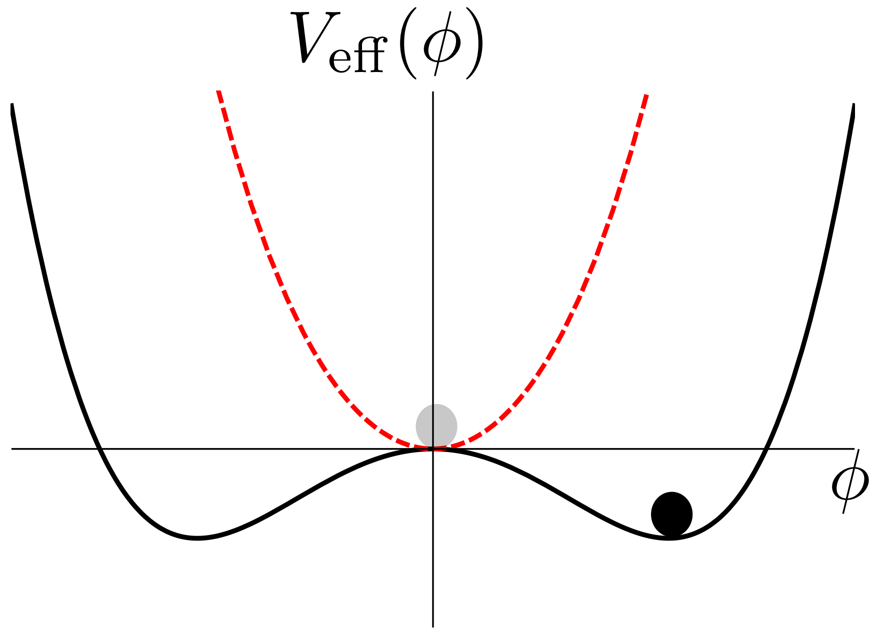
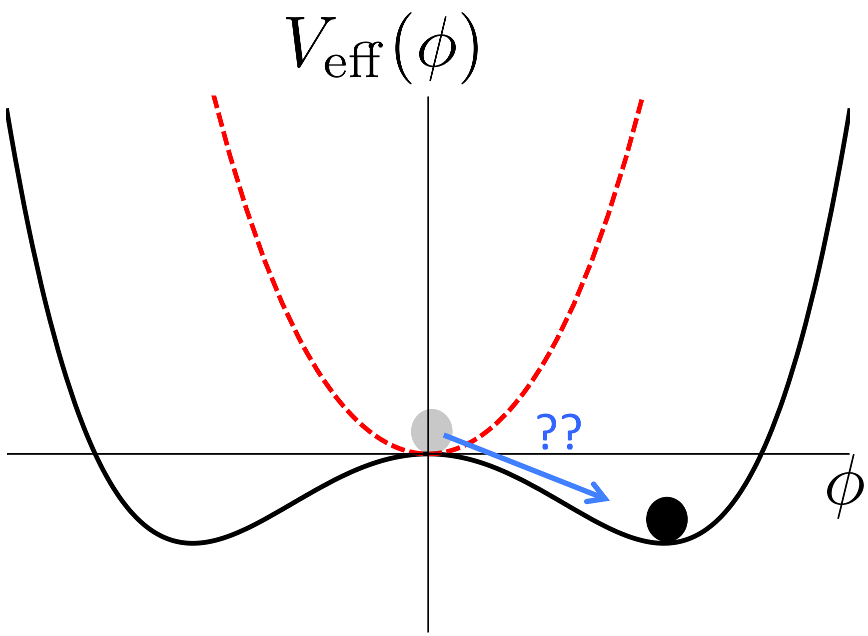


At zero temperature, the background field is stabilized away from the origin and EW symmetry is broken

Motivation

What happened in between?

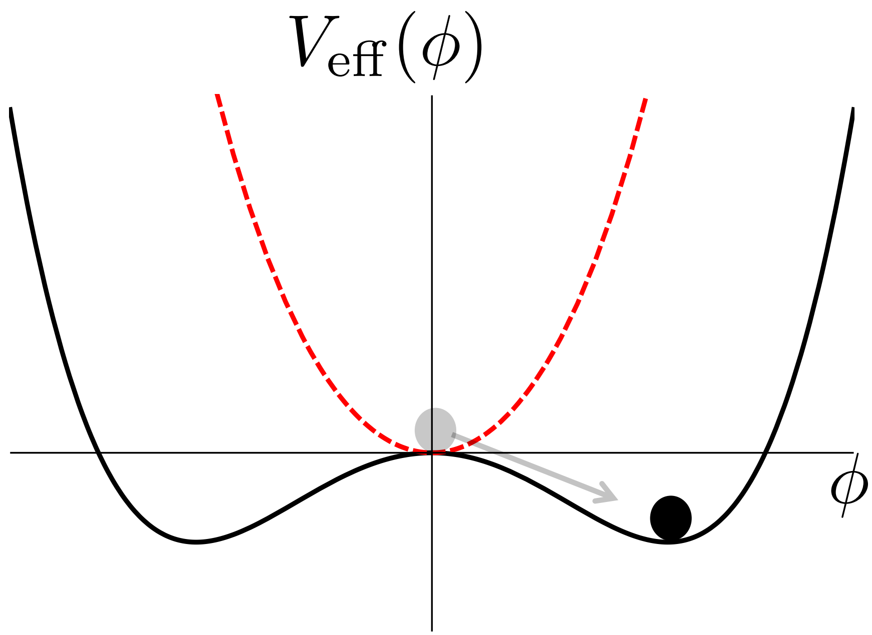


First or second order transition? At what temperature? Other fields involved? …

Motivation

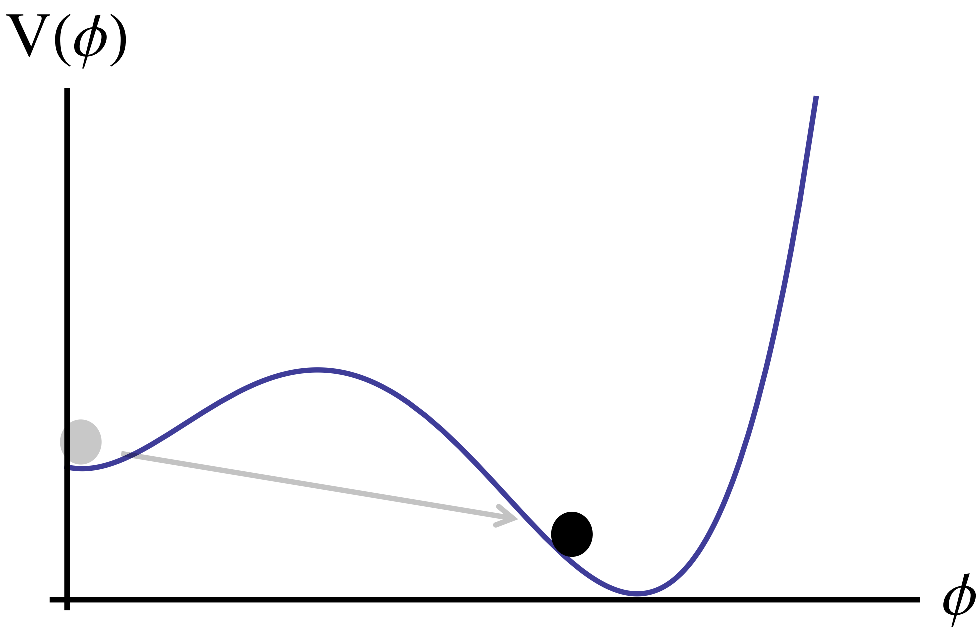
The SM features a smooth cross-over

Kajantie et al, hep-ph/9605288



Motivation

Scenarios beyond the SM can instead accommodate a first order EWPT



Motivation

Understanding the electroweak phase transition is important!

- First order PT can allow for successful electroweak baryogenesis

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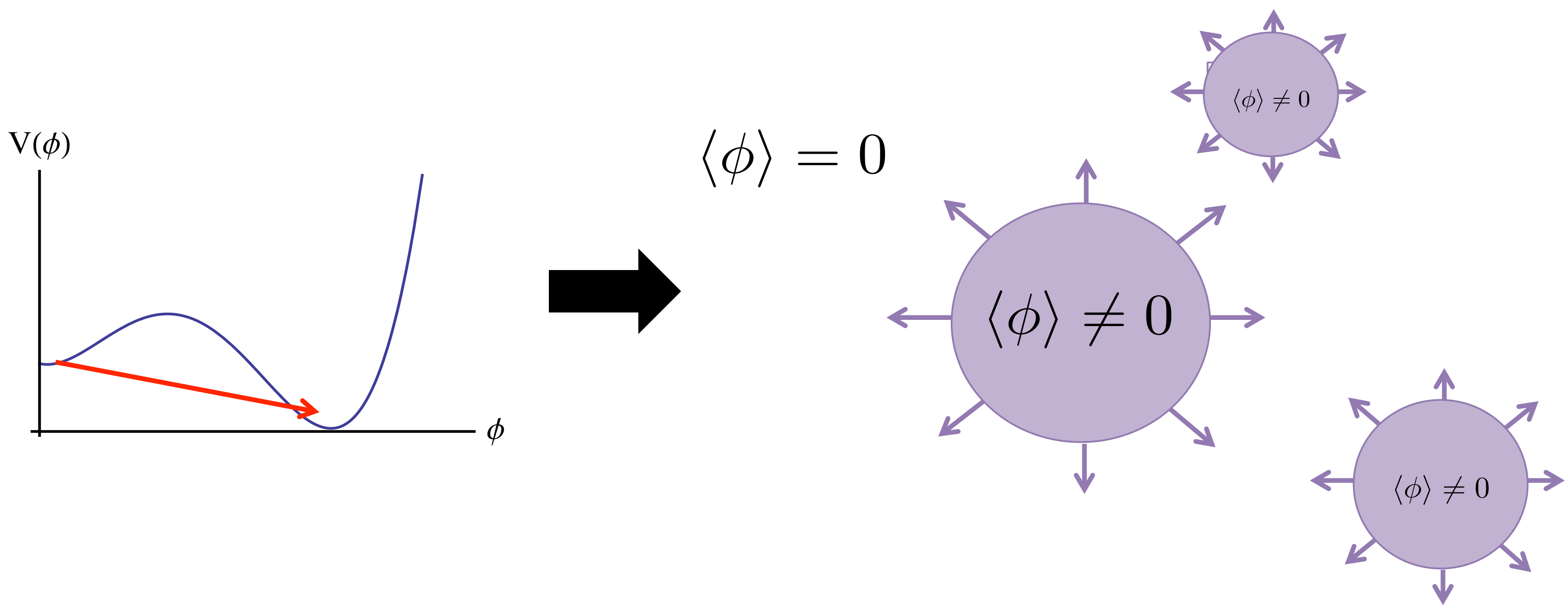

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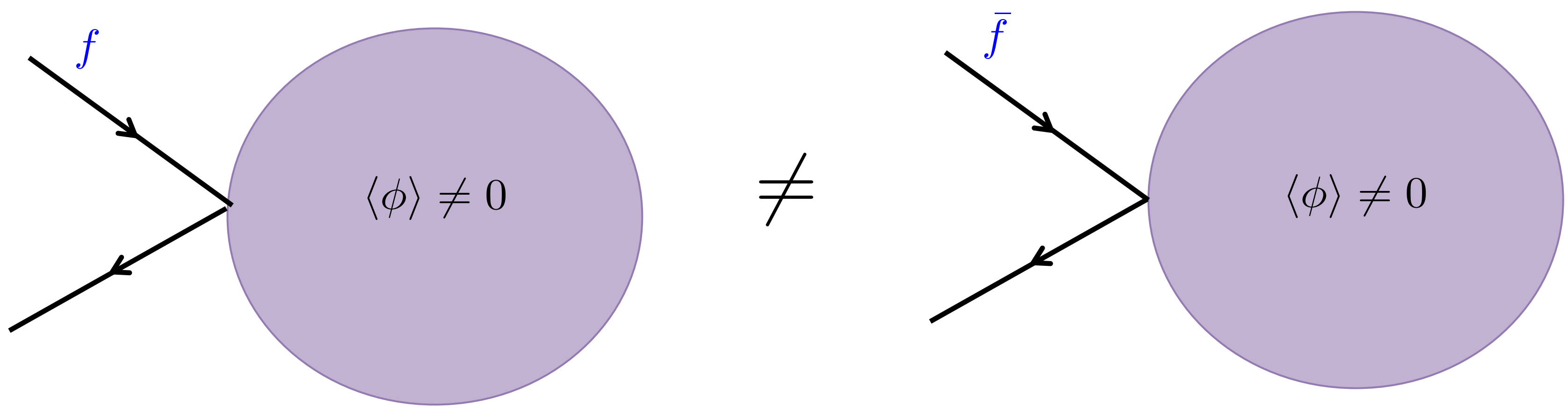

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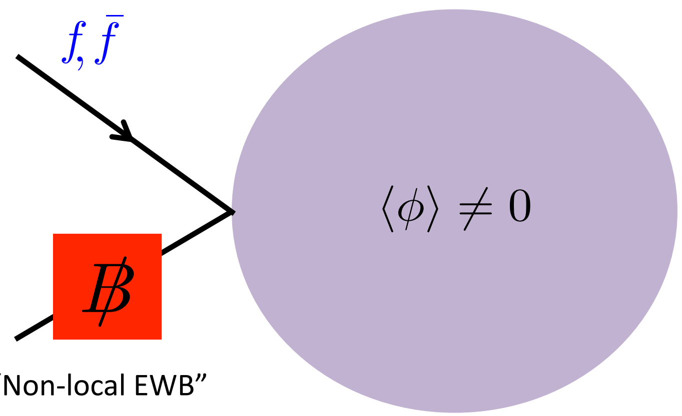

"Non-local EWB"

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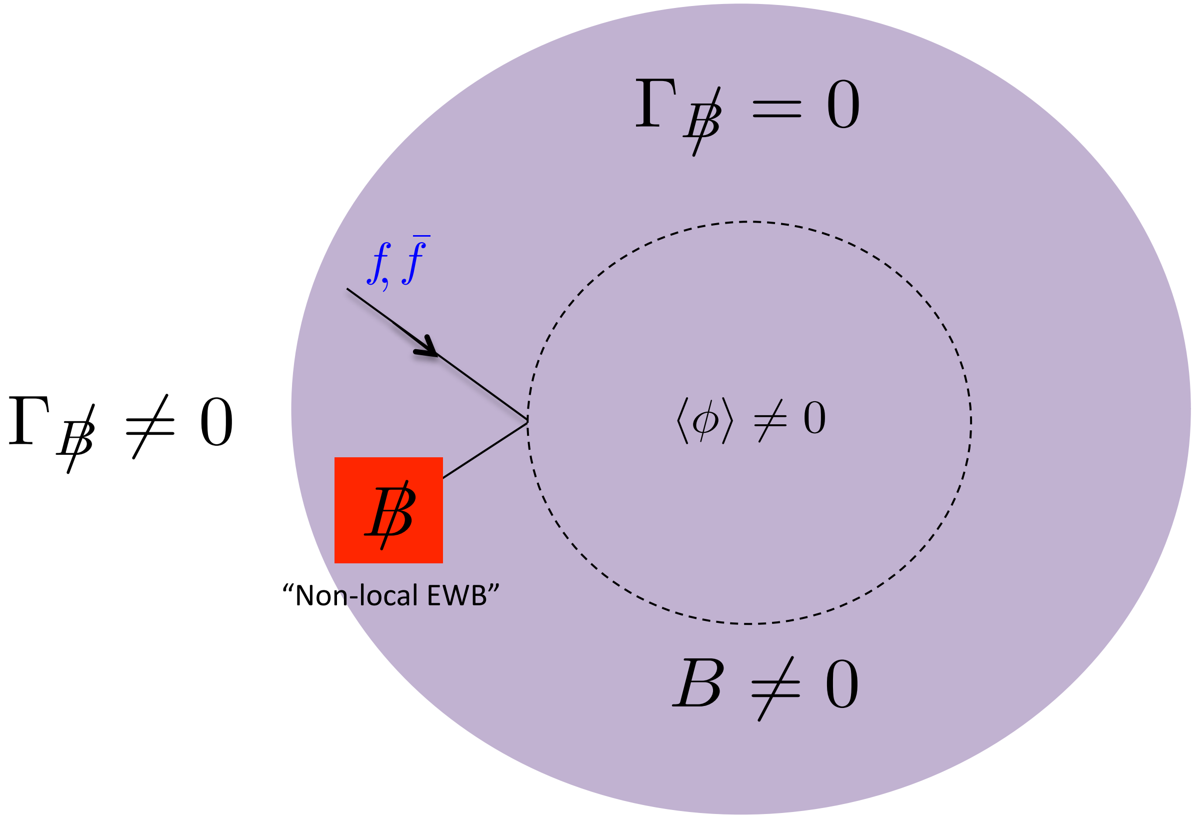

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Understanding the electroweak phase transition is important!

- First order PT can allow for successful electroweak baryogenesis

- Can affect cosmology (e.g. the abundance of thermal relics)

  See e.g. Profumo + Wainwright, 0909.1317

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- We should understand where we are on the EW phase diagram

Motivation

How might we test for a strong first-order (electroweak) phase transition in our past?

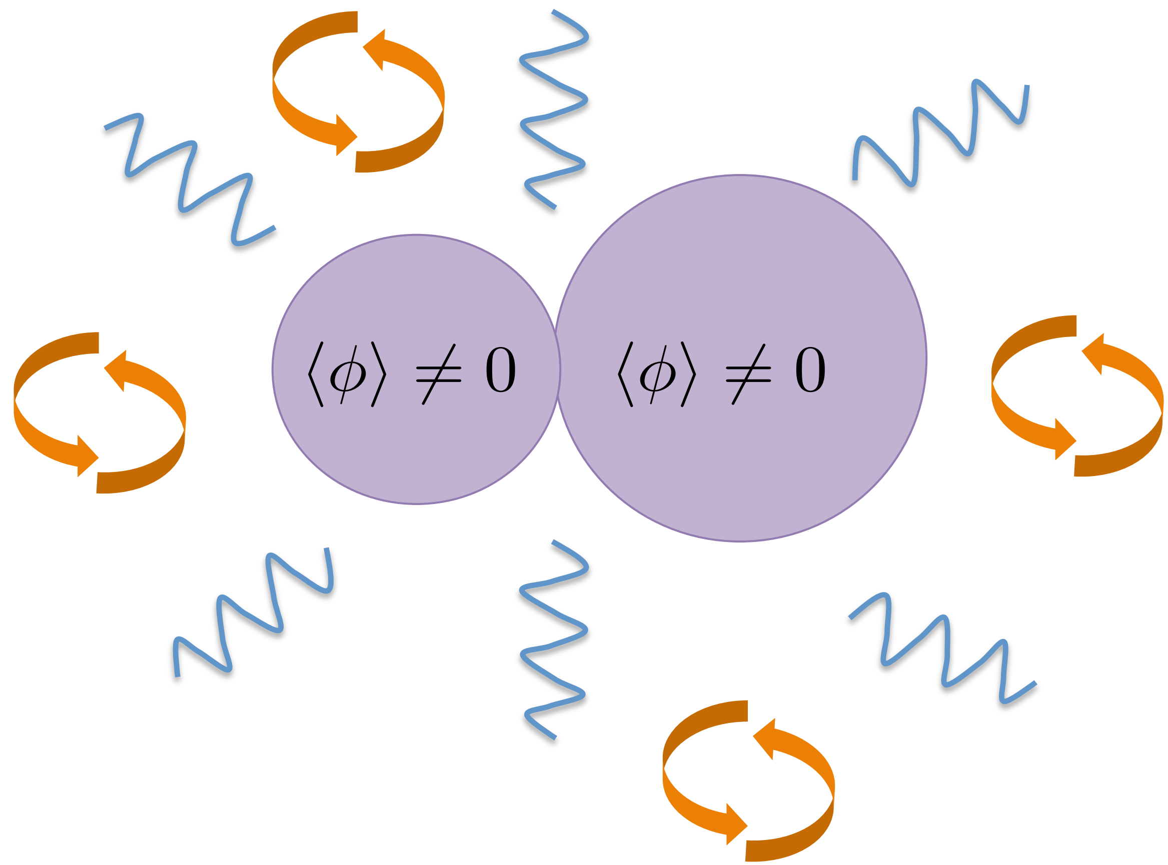
Two arenas: gravitational wave astronomy and colliders

(This talk) (Ask me later!)

Gravitational Waves from Strong PTs

A first-order cosmological phase transition can source a stochastic gravitational wave background in different ways:

- Bubble Collisions
- Sound Waves
- Turbulence



Gravitational Waves from Strong PTs

Various contributions to the gravitational wave spectrum depend on the phase transition properties

$$h^2\Omega_{\rm GW} \simeq h^2\Omega_\phi + h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$$

Bubble Collisions:

Efficiency factor; Bubble wall velocity

$$h^2\Omega_{\rm env}(f) \;=\; 1.67\times 10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11\,v_w^3}{0.42+v_w^2}\right)S_{\rm env}(f)$$

Duration of the PT; Latent heat; Frequency dependence

$$\beta \equiv -\left.\frac{dS}{dt}\right|_{t=t_*} \simeq \frac{\dot\Gamma}{\Gamma}$$

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Sound Waves:

$$h^2\Omega_{\rm sw}(f) = 2.65\times 10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}} v_w\, S_{\rm sw}(f)$$

Turbulence:

$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

Gravitational Waves from Strong PTs

Which contributions dominate depends on the PT dynamics

Three general scenarios:

1. Non-runaway bubbles

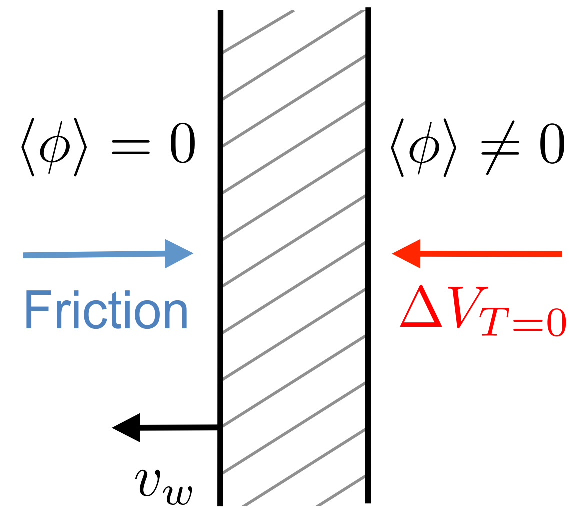
$$h^2\Omega_{\rm GW} \simeq h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$$

2. Runaway bubbles in plasma

$$h^2\Omega_{\rm GW} \simeq h^2\Omega_{\phi} + h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$$

3. Runaway bubbles in vacuum

$$h^2\Omega_{\rm GW} \simeq h^2\Omega_{\phi}$$

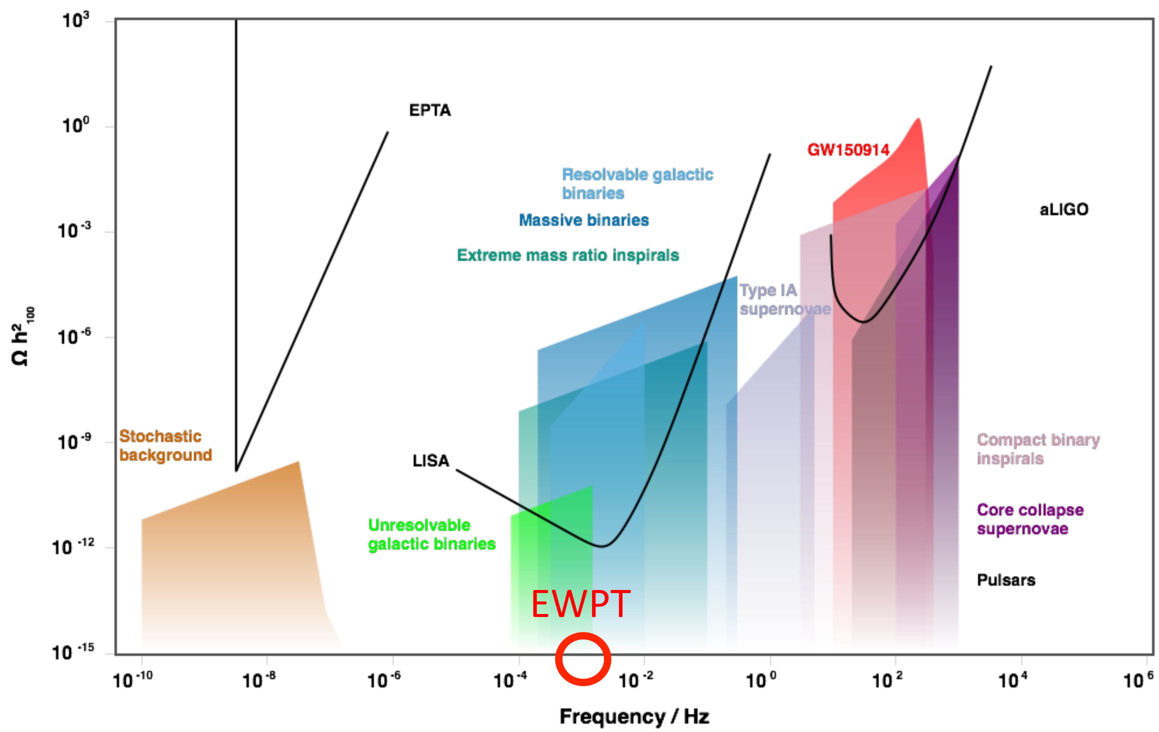


When considering specific BSM scenarios, it's important to know which applies!

Gravitational Waves from Strong PTs

How should we look for this signal?

Christopher Moore, Robert Cole and Christopher Berry
http://rhcole.com/apps/GWplotter/



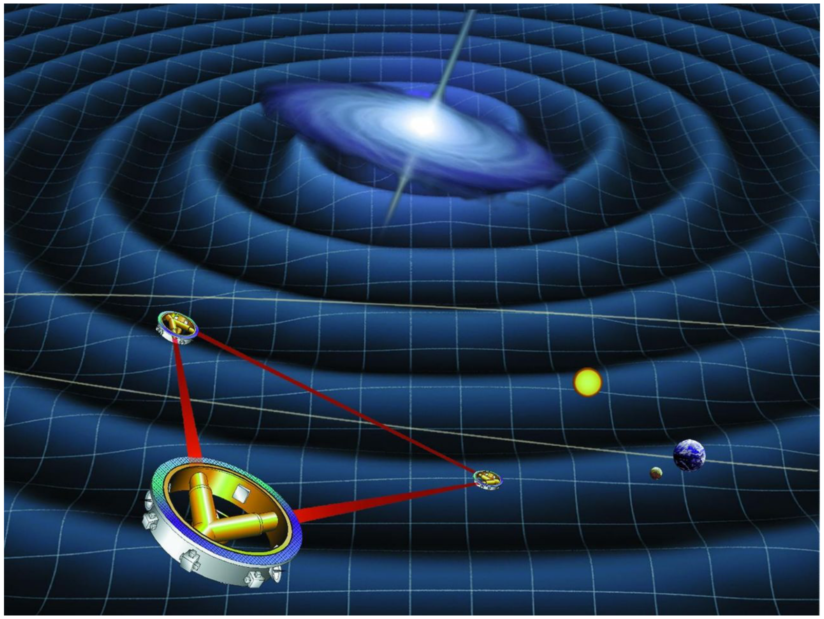
Characteristic frequency set by H. For EWPT, $f_{peak} \sim 10^{-3}$ Hz so

LISA is the way to go

Gravitational Waves from a Strong EWPT

LISA (**Laser Interferometer Space Antenna)**, formerly known as eLISA

http://lisa.jpl.nasa.gov/gallery/lisa-waves.html



Leading candidate for the ESA's *Cosmic Vision* Program L3 experiment

Proposed launch in 2034

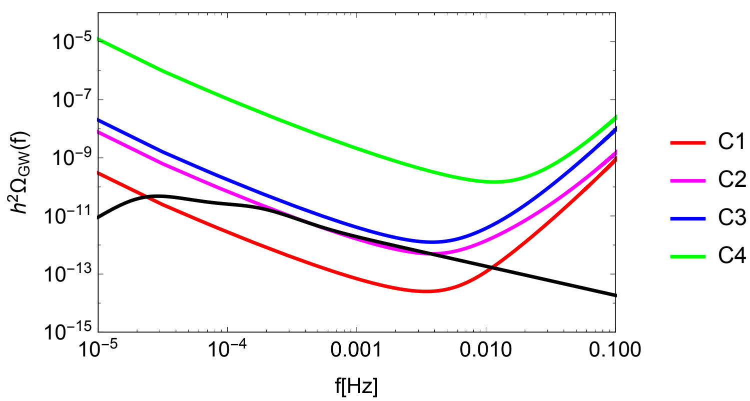
LISA Pathfinder launched last year, demonstrating feasibility of LISA technology

Gravitational Waves from a Strong EWPT

How well can LISA observe a stochastic background originating from cosmological phase transitions?

Study commissioned by the Gravitational Observatory Advisory Team (GOAT): Caprini, JK et al, **JCAP 1604 (2016) no.04, 001**

Answer depends on the experimental configuration and mission timeline



Name	C1	C2	C3	C4
Full name	N2A5M5L6	N2A1M5L6	N2A2M5L4	N1A1M2L4
# links	6	6	4	4
Arm length [km]	5M	1M	2M	1M
Duration [years]	5	5	5	2
Noise level	N2	N2	N2	N1

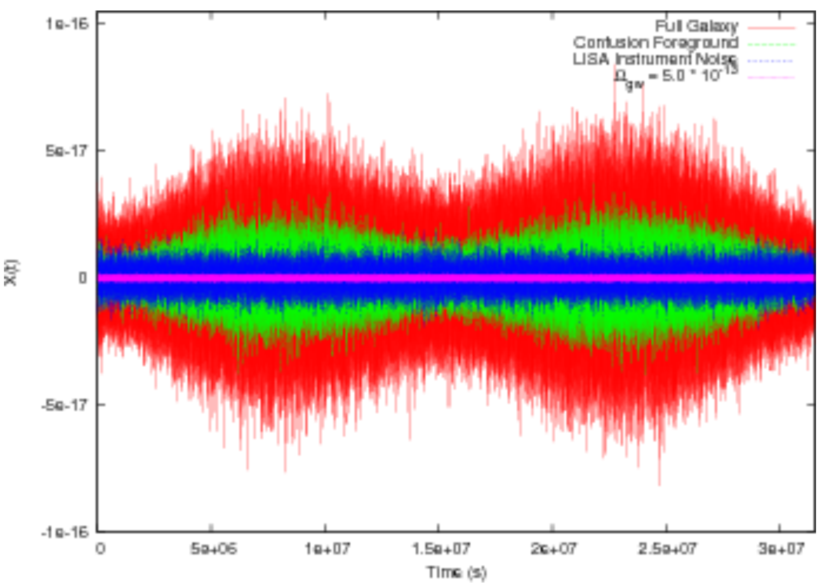
Preliminarily confirmed by LISA Pathfinder

LISA Sensitivity to Stochastic Background

Primary astrophysical foreground expected to be unresolved galactic white dwarf binaries

Distinguish between primordial and unresolved background using spectral differences and annual modulation

Adams + Cornish, 2013



Extra-galactic sources can also be isolated from anisotropies in the foreground

Gravitational Waves from a Strong EWPT

Prospects for LISA are model-dependent. Strategy: consider several representative BSM scenarios

New physics can yield a strong 1st order PT through several different mechanisms:

$$V_{\rm eff}^{1-{\rm loop}} = \underline{V_0} + \underline{V_1^{T=0}} + \underline{V_1^{\rm thermal}}$$

New bosonic DOFs can contribute a sizeable thermal cubic term

Loop effects can reduce the energy difference between vacua

BSM physics can give rise to new terms in the scalar potential

New physics can also produce a first-order PT via strong dynamics

Gravitational Waves from a Strong EWPT

Representative scenarios

Higgs portal: $$V(H,S) = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 + \frac{1}{2}a_2(H^\dagger H)S^2 + \frac{1}{2}b_2S^2 + \frac{1}{4}b_4S^4$$

NMSSM: $$V = V_F + V_D + V_{\rm soft}$$

2HDM: $$\begin{aligned} V(H_1,H_2) &= \mu_1^2\,|H_1|^2 + \mu_2^2\,|H_2|^2 - \mu^2\left[H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}\,|H_1|^4 + \frac{\lambda_2}{2}\,|H_2|^4 \\ &+ \lambda_3\,|H_1|^2\,|H_2|^2 + \lambda_4\left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]. \end{aligned}$$

Dim-6 EFT: $$V(\phi) = \mu^2|\phi|^2 - \lambda|\phi|^4 + \frac{|\phi|^6}{\Lambda^2}$$

Dilaton: $$V(\sigma,\phi) = V_\sigma(\sigma) + \frac{\lambda}{4}(\phi^2 - \xi\,\sigma^2)^2$$

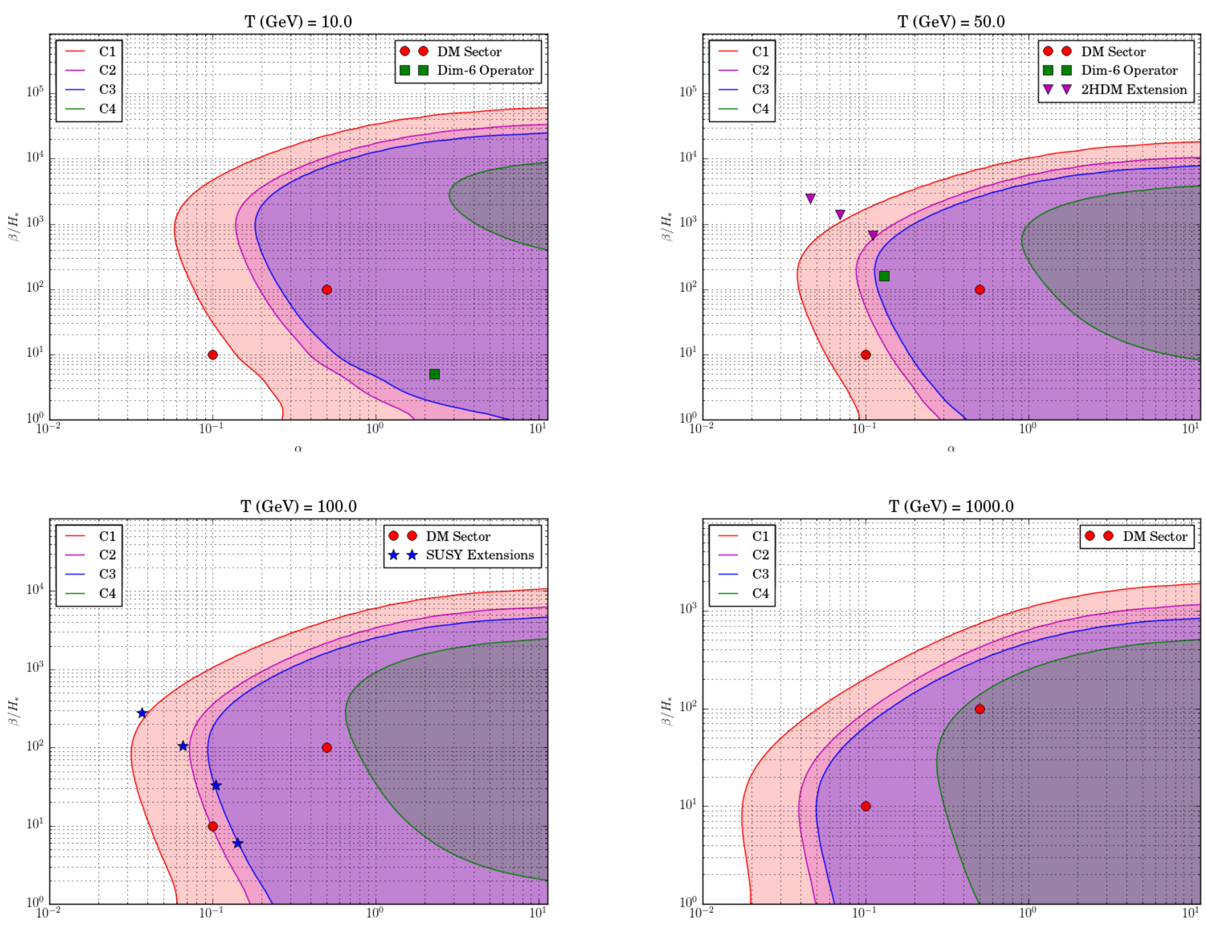
Also consider strongly coupled dark sectors not related to EWSB (more speculative)

These scenarios also span the different possibilities for bubble expansion (non-runaway, runaway in plasma, runaway in vacuum)

Gravitational Waves from a Strong EWPT

Results (Case 1: Non-Runaway Bubbles)

Representative models: 2HDM, NMSSM, Dark Sector (?), Dim-6 EFT

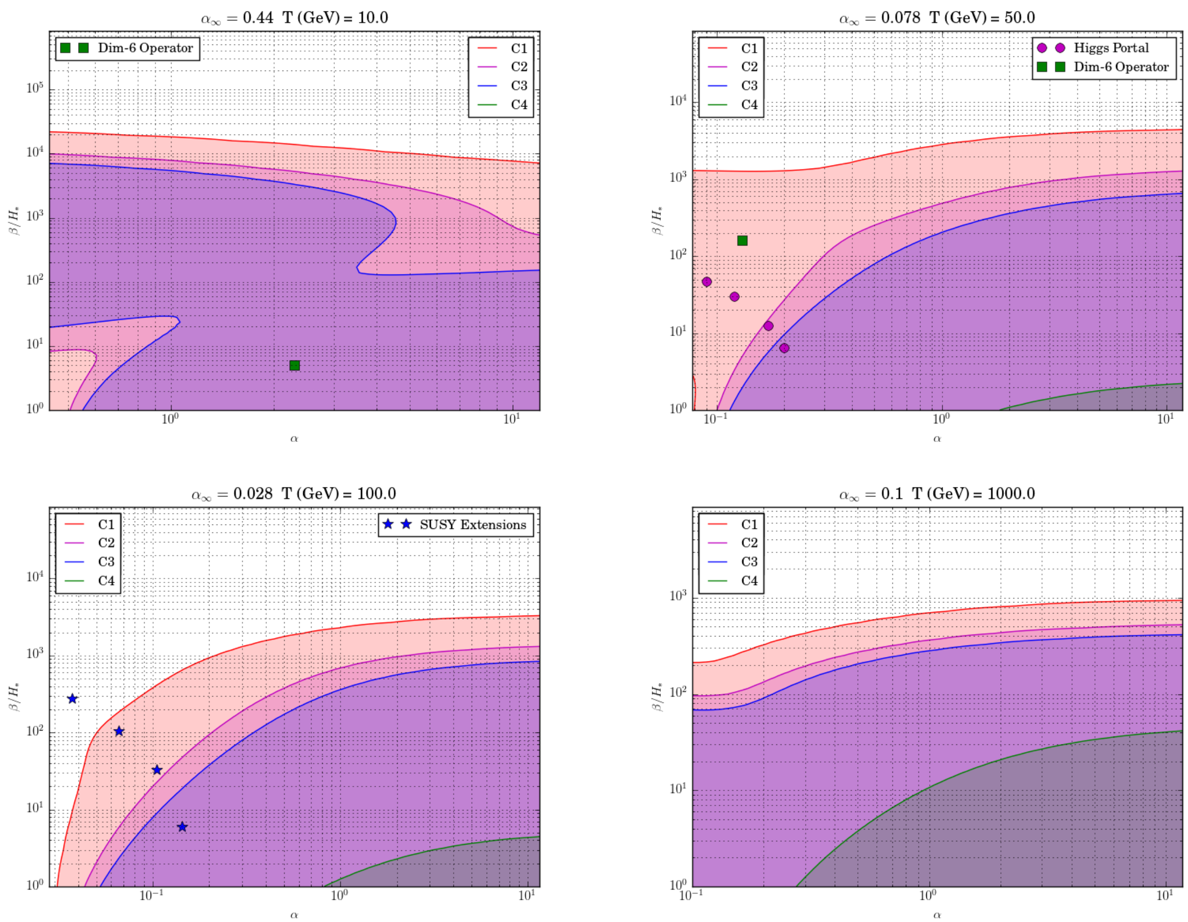


Primary source:
sound waves

Gravitational Waves from a Strong EWPT

Results (Case 2: Runaway Bubbles in Plasma)

Representative models: Higgs Portal, NMSSM, Dark Sector (?), Dim-6 EFT

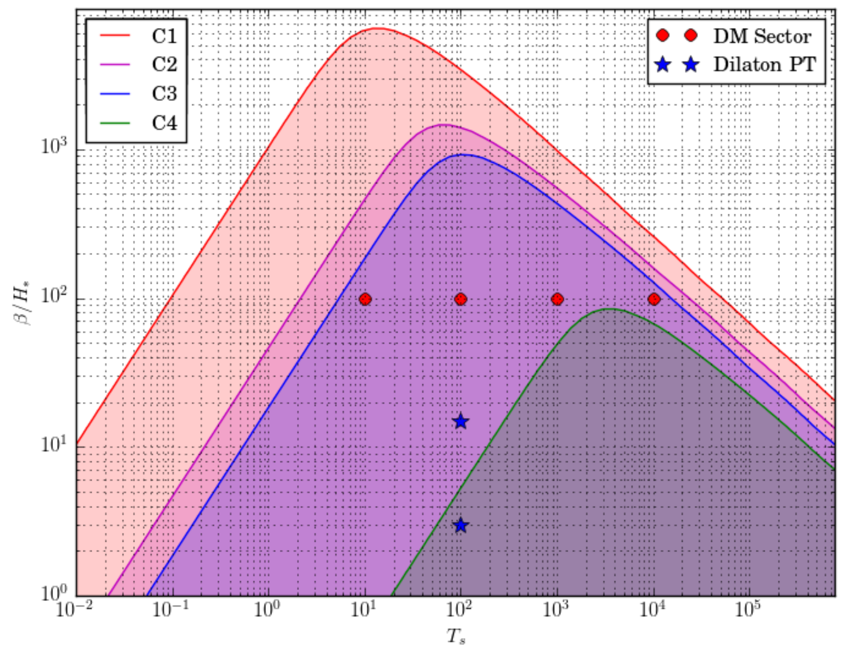


Primary source:
sound waves + scalar field

Gravitational Waves from a Strong EWPT

Results (Case 3: Runaway Bubbles in Vacuum)

Representative models: Dilaton, Dark Sector (?)



Primary source:
scalar field

Gravitational Waves from a Strong EWPT

Conclusions of our study: Caprini, JK et al, **JCAP 1604 (2016) no.04, 001**

- For typical electroweak phase transitions, in which all relevant dimensionful parameters are near the electroweak scale, the configuration C1 is definitively better than the others, while the configuration C4 is decisively unsatisfactory. The performances of the configurations C2 and C3 are similar, but C2 has the ability to test a larger fraction of the considered benchmark points.
- For phase transitions not strictly related to electroweak symmetry breaking, e.g. involving a dark sector or a dilaton, the predicted characteristics of the phase transitions exhibit more variation. Larger GW signals are allowed than in the electroweak case. For certain scenarios, the resulting GW spectrum can be probed by all considered eLISA designs. The C1 configuration, however, has the potential to test a much wider region of the parameter space in such models than do C2–C4.

Gravitational Waves from a Strong EWPT

"C1 configuration" is similar to the original LISA design. Feasible if NASA decides to participate

The takeaway:

LISA will likely have a real chance at detecting gravitational waves from a strong first-order phase transition, providing valuable information about our cosmic history. In some cases (e.g. for highly decoupled new physics), LISA is likely the only option.

Gravitational Waves from a Strong EWPT

Only very strong phase transitions yield observable gravitational radiation.

What would a signal imply for models electroweak baryogenesis?

Can electroweak baryogenesis source both detectable gravitational waves and the observed baryon asymmetry?

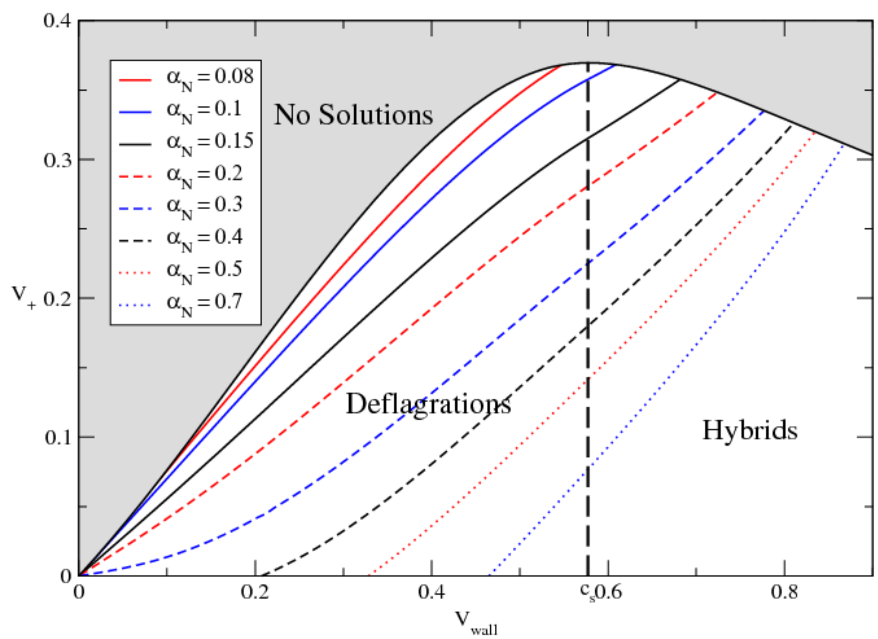
Depends on the scenario…

Implications for Electroweak Baryogenesis

Usual charge transport mechanism could produce both, provided significant plasma velocity in front of the bubble

J.M. No, 2011

v_w-v_+ relevant for EWB



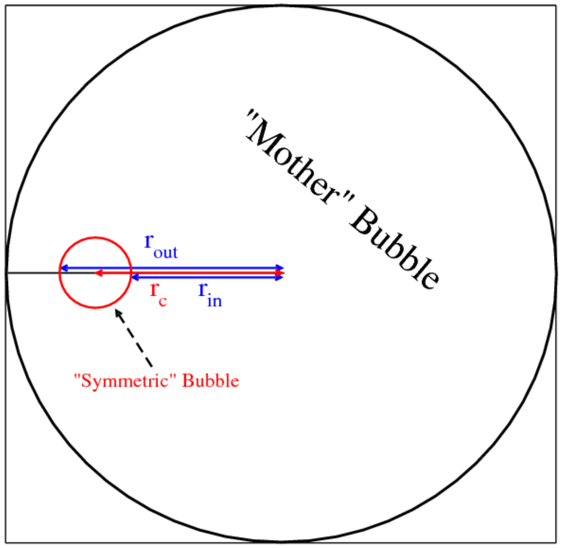
Not very generic, but possible

v_w relevant for gravitational waves

Implications for Electroweak Baryogenesis

Other possibilities:

Bubbles inside bubbles (Caprini + No, 2011)



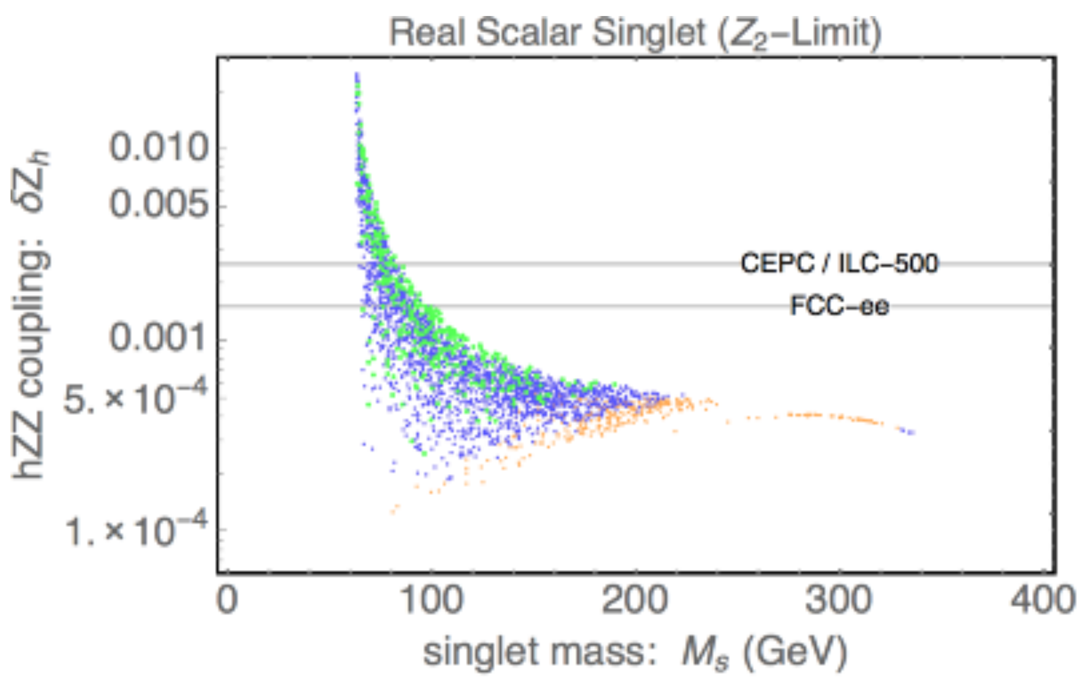
Baryogenesis from bubble collisions

-Natural Cold EWB (Konstandin + Servant, 2011)

-Particle production from elastic collisions (Katz + Riotto, 2016)

Complementarity

GW interferometers will complement collider searches in probing a strong first-order EWPT



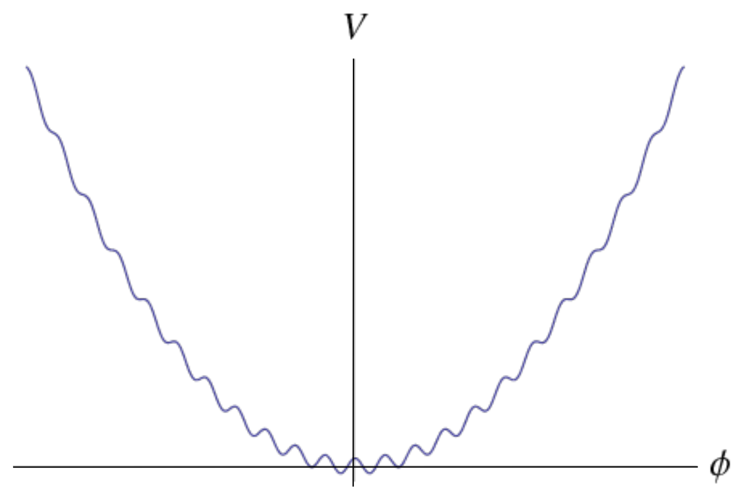
Huang et al, 2016

Beyond the EWPT

Other cosmological PT scenarios might also predict a signal at LISA and other GW experiments

E.g. Monodromy inflation

Hebeker et al, 2016

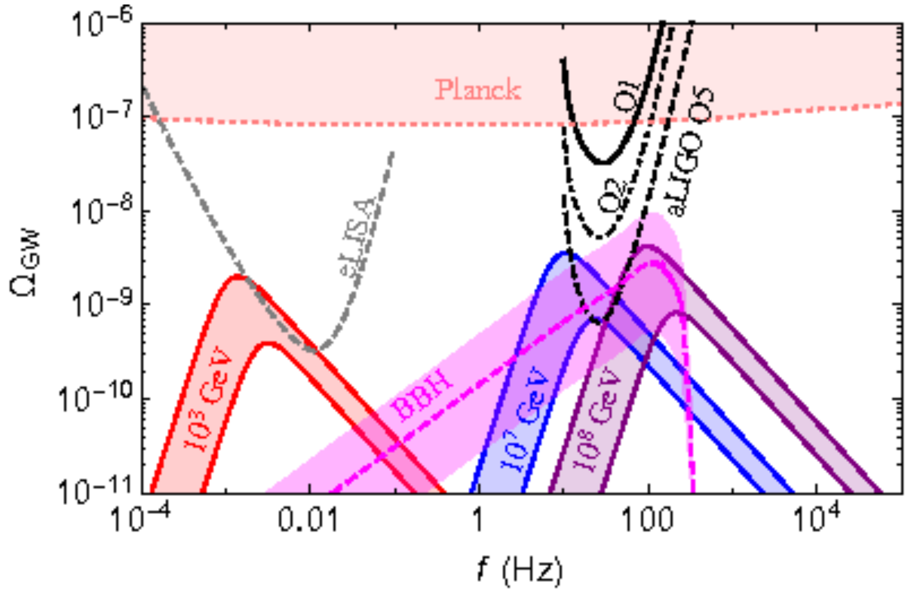


If more than one vacuum is populated in a Hubble patch, can give rise to a strong first order cosmological PT

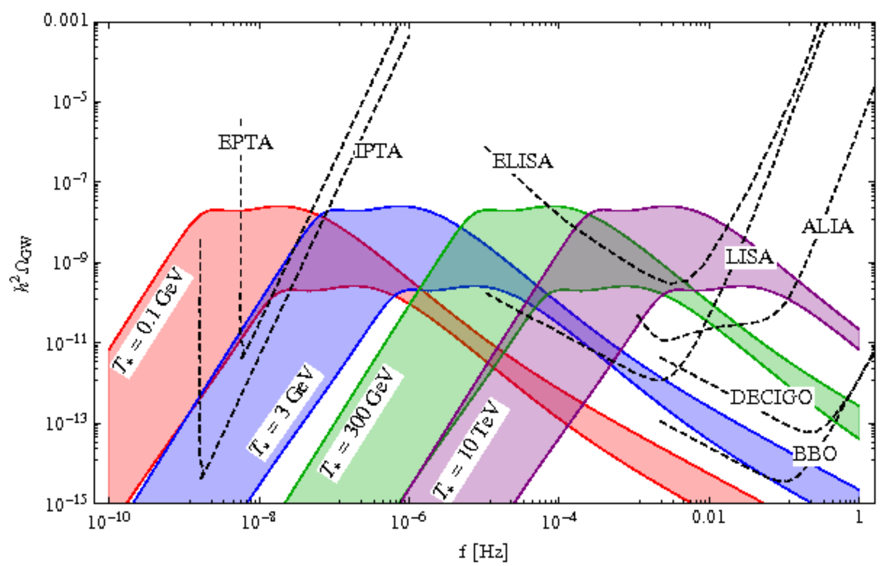
For other inflationary signals expected at LISA, see Garcia-Bellido et al, 2016 and Marco's slides

Beyond the EWPT

Other GW experiments can probe PTs at different scales



Dev et al, 2016



Schwaller, 2015

Higher temperature phase transitions can predict signal at aLIGO. Lower temperature phase transitions can predict signal at pulsar timing arrays

Takeaways

LISA can probe cosmological phase transitions in many BSM scenarios. The closer to the original LISA design the better.

A signal in LISA can be compatible with viable electroweak baryogenesis

PTs at other scales may yield a signal in advanced LIGO or pulsar timing arrays