Gravitational waves from a prolonged electroweak phase transition and their detection with pulsar timing arrays

Cyril Lagger

THE UNIVERSITY OF SYDNEY

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Archil Kobakhidze, CL, Adrian Manning, Jason Yue [arXiv:1703.06552]

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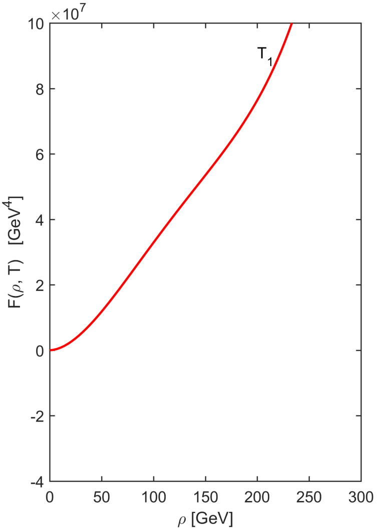
Introduction

First-order phase transition and GWs

Hot Big Bang scenario:

- early Universe $\sim$ hot plasma (high T)
- scalar field(s) behaviour dictated by their free energy density $\mathcal{F}(\rho, T)$
- depends on the underlying particle physics model



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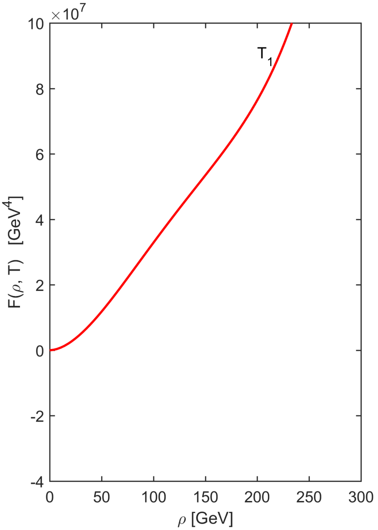
- bubble nucleation
- bubble collision
- stochastic GW background



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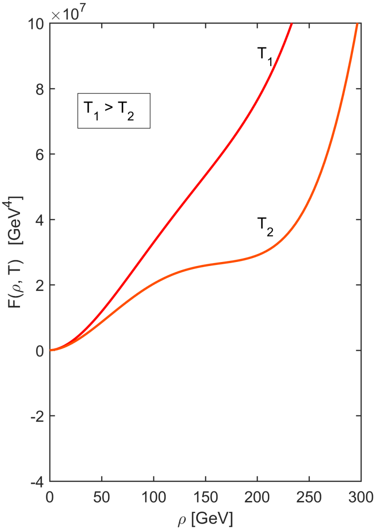

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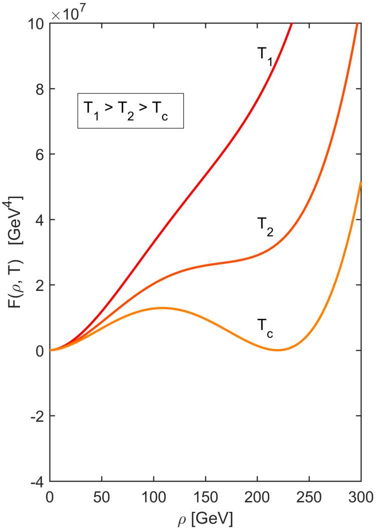

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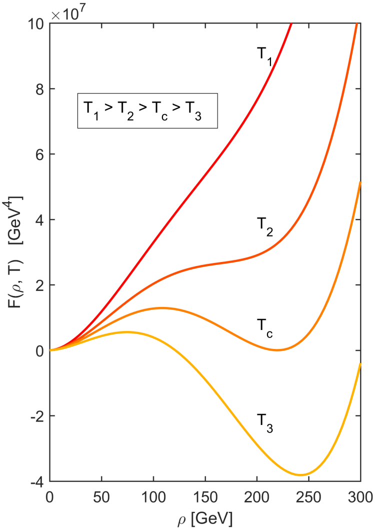

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(B)SM and GW detection

A possible probe of new physics:

- no 1st-order PT in the Standard Model [K. Kajantie et al., Phys. Rev. Lett. 77 (1996) 2887]

  $\Rightarrow$ no stochastic GW background predicted in the SM

- various BSM models account for a 1st-order EWPT (e.g. motivated by electroweak baryogenesis)

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GW detection:

- background peak frequency vs. detectors sensitivity band

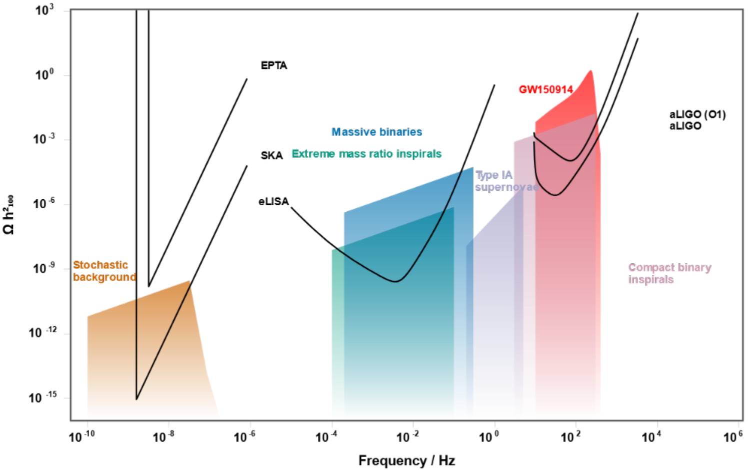
- common scenario: EWPT around $T_{EW} \sim 100$ GeV

  $\Rightarrow f_{\text{peak}} \sim$ milliHertz $\Rightarrow$ range of eLISA [C. Caprini et al., JCAP 1604 (2016) no.04 001]

- we discuss here a prolonged EWPT $\Rightarrow f_{\text{peak}} \sim 10^{-8}$ Hz

  $\Rightarrow$ range of pulsar timing arrays (EPTA, SKA,...)

(B)SM and GW detection



[From rhcole.com/apps/GWplotter/]

A model: non-linearly realised electroweak gauge group

Realisation of $SU(2)_L \times U(1)_Y$

Main idea:

- $\mathcal{G}_{\text{coset}} = SU(2)_L \times U(1)_Y / U(1)_Q$ is gauged
- with broken generators $T^i = \sigma^i - \delta^{i3}\mathbb{I}$ and Goldstone bosons $\pi^i(x)$
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SM Higgs doublet identified as $H(x) = \frac{\rho(x)}{\sqrt{2}} e^{\frac{i}{2}\pi^i(x) T^i} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \qquad i \in \{1, 2, 3\}$

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Minimal setup (usual SM configurations except Higgs potential):

$$V^{(0)}(\rho) = -\frac{\mu^2}{2}\rho^2 + \frac{\kappa}{3}\rho^3 + \frac{\lambda}{4}\rho^4.$$

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For additional details, see e.g.: [M. Gonzalez-Alonso et al., Eur. Phys. J. C 75 (2015) 3, 128] [D. Binosi and A. Quadri, JHEP 1302 (2013) 020] [A. Kobakhidze, arXiv:1208.5180] [R. Contino et al., JHEP 1005 (2010) 089]

Early considerations

Model specified by one parameter: $\kappa = \bar{\kappa} \cdot \frac{m_h^2}{v} \sim 63.5 \cdot \bar{\kappa}$ GeV.

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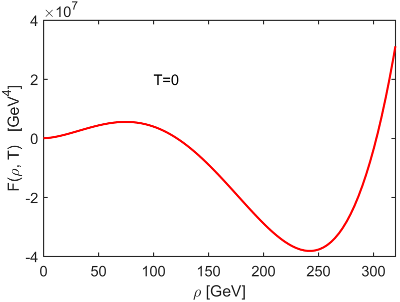

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Indeed confirmed by a previous study [A. Kobakhidze, A. Manning, J. Yue, arXiv:1607.00883]:

$$|\bar{\kappa}| \in [1.75, 1.85] \Rightarrow \text{GW signal detectable by eLISA}$$

General observation: higher $|\bar{\kappa}|$ $\Rightarrow$ lower bubble nucleation probability

However, unclear process at $|\bar{\kappa}| \sim 1.9$

Prolonged electroweak phase transition

A. Kobakhidze, CL, A. Manning, J. Yue [arXiv:1703.06552]

Qualitative description

Standard scenario (quick PT):

- $\mathcal{O}(1)$ bubbles produced per Hubble volume at $T_n \lesssim T_{EW}$
- they rapidly collide $\Rightarrow$ percolation temperature $T_p \sim T_n$
- time scale of the process much shorter than Hubble time

Qualitative description

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Long-lasting and supercooled scenario:

- weaker nucleation probability
- less bubbles produced $\Rightarrow$ more time needed for them to collide
- $\Rightarrow T_p \ll T_n \lesssim T_{EW}$
- requires to take into account expansion of the Universe and to check low-temperature nucleation probability

Bubble nucleation probability

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Computation of the Euclidean action:

$$S[\rho, T] = 4\pi \int_0^\beta d\tau \int_0^\infty dr\, r^2 \left[\frac{1}{2}\left(\frac{d\rho}{d\tau}\right)^2 + \frac{1}{2}\left(\frac{d\rho}{dr}\right)^2 + \mathcal{F}(\rho, T)\right]$$

$$\frac{\partial^2 \rho}{\partial \tau^2} + \frac{\partial^2 \rho}{\partial r^2} + \frac{2}{r}\frac{\partial \rho}{\partial r} - \frac{\partial \mathcal{F}}{\partial \rho}(\rho, T) = 0 \quad + \quad \text{boundary conditions}$$

$$S[\rho, T] \approx \begin{cases} S_4[\rho, T] = 2\pi^2 \int_0^\infty d\tilde{r}\, \tilde{r}^3 \left[\frac{1}{2}\left(\frac{d\rho}{d\tilde{r}}\right)^2 + \mathcal{F}(\rho, T)\right], & T \ll R_0^{-1} \\ \frac{1}{T} S_3[\rho, T] = \frac{4\pi}{T} \int_0^\infty dr\, r^2 \left[\frac{1}{2}\left(\frac{d\rho}{dr}\right)^2 + \mathcal{F}(\rho, T)\right], & T \gg R_0^{-1} \end{cases}$$

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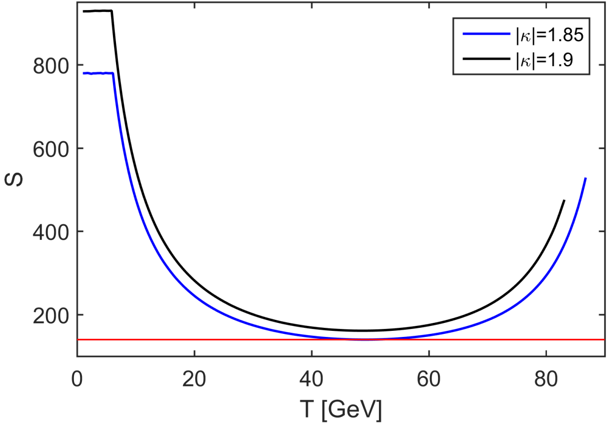
Some numerical results:



Standard scenario: number of bubbles $\sim \mathcal{O}(1)$ requires $\min S \lesssim 140$

Phase transition dynamics

General formalism in expanding universe: [M. Turner et al., Phys. Rev. D46 (1992) 2384].

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Nucleation temperature T_n: maximum of $\frac{dN}{dR}(t_p,t_R)$

Bubbles properties at collision

By definition:

- most bubbles collide at t_p
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Kinetic energy stored in bubble-walls:

$$E_{\text{kin}} = \kappa_v \cdot 4\pi \int_{t_n}^{t_p} dt \frac{dR}{dt}(t, t_n) R^2(t, t_n) \epsilon(t)$$

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$\bar{R}$ and E_{kin}: key parameters to deduce the GW spectrum

Some assumptions

Entire dynamics specified by $\Gamma(t)$, $\epsilon(t)$, κ_ν, $v(t)$ and $a(t)$.

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Very strong PT:

- large amount of vacuum energy released
- $\Rightarrow \kappa_\nu \sim 1$ [A. Kobakhidze et al, arXiv:1607.00883]
- $\Rightarrow v \sim 1$ (runaway bubbles) [C. Caprini et al., JCAP 1604 (2016) no.04 001]

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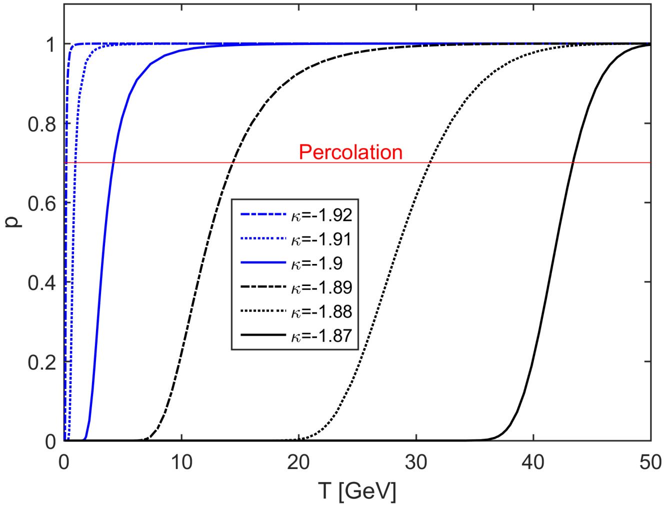
Consider a radiation-dominated Universe:

- $a(t) \propto t^{1/2}$
- $t = \left(\frac{45M_p^2}{16\pi^3 g_\star}\right)^{1/2} \frac{1}{T^2}$
- need to confirm this assumption at low temperature (see below)

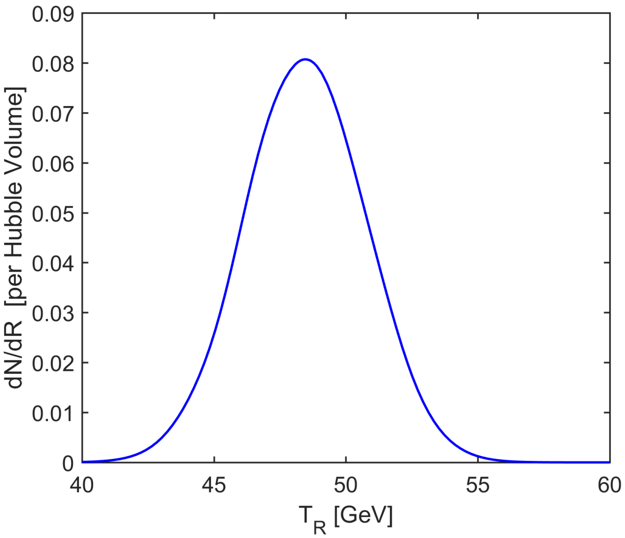
Numerical results

Probability $p(T)$:



Numerical results

Number density distribution for $|\bar{\kappa}| = 1.9$: $\Rightarrow T_n \sim 49$ GeV



Numerical results

$\kappa\ [m_h^2/\lvert v\rvert]$	$T_\star$ GeV	T_n GeV	T_p GeV	$(\bar{R}H_p)^{-1}$	$\rho_{\mathsf{kin}}/\rho_{\mathsf{rad}}$
-1.87	85.9	48.9	43.4	8.79	0.57
-1.88	85.5	48.9	31.2	2.76	1.88
-1.89	84.5	49.0	14.4	1.41	37.8
-1.9	84.1	48.7	4.21	1.09	$5.09 \cdot 10^3$
-1.91	83.9	48.6	0.977	1.02	$1.73 \cdot 10^6$
-1.92	83.3	48.5	0.205	1.00	$8.80 \cdot 10^8$

Observations:

- new feature: $T_p \ll T_n$
- Hubble-size bubbles at collision
- $\rho_{\mathsf{rad}} \ll \rho_{\mathsf{kin}}$: confirm very strong scenario

Discussing the equation of state

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Two scenarios:

- $T_p \sim T_n \ll T_{EW}$: inflation indeed occurs [T. Konstandin and G. Servant, JCAP 1112 (2011) 009]
- $T_p \ll T_n \lesssim T_{EW}$: bubbles produced before vacuum-radiation equality

  $\Rightarrow$ vacuum energy transferred to bubble-walls + inhomogeneous Universe

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  [Brandenberger, Int.J.Mod.Phys. D26 (2016) no.01, 1740002]

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For example $|\bar{\kappa}| = 1.9$:

- vacuum-radiation equality at $(T \sim 36$ GeV $) < (T_n \sim 49$ GeV$)$
- inhomogeneity at $T \sim 36$ GeV: 0.47 bubbles per Hubble volume with size 26% of Hubble radius

Gravitational wave signal

GWs from bubble collisions

Stochastic background from three sources [C. Caprini et al., JCAP 1604 (2016) no.04 001]:

$$h^2\Omega_{\mathsf{GW}}(f) \simeq h^2\Omega_{col} + h^2\Omega_{sw} + h^2\Omega_{\mathsf{MHD}}$$

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Dimensional analysis:

- peak frequency from collision: $f_{\mathrm{peak}}(t_p) \sim (\bar{R})^{-1}$
- peak amplitude at collision: $\Omega_{col}(f_p) \sim (\bar{R}H_p)^2 \frac{\rho_{\mathrm{kin}}^2}{(\rho_{\mathrm{kin}}+\rho_{\mathrm{rad}})^2}$

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Then redshift from collision time to today

Bubble-collision simulations

Going beyond dimensional analysis with state-of-the-art numerical simulations (and redshift) [Huber and Konstandin, JCAP 0809 (2008) 022]

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Amplitude:

$$h^2 \Omega_{col}(f) = 1.67 \times 10^{-5} \left(\frac{100}{g_*} \right)^{1/3} \left(\frac{\beta}{H_p} \right)^{-2} \kappa_v^2 \left(\frac{\alpha}{1+\alpha} \right)^2 \left(\frac{0.11 v^3}{0.42 + v^2} \right) S(f)$$

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Peak frequency:

$$f_0 = 1.65 \times 10^{-7} \left(\frac{T_p}{1\ \mathrm{GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6} H_p^{-1} \beta \left(\frac{0.62}{1.8 - 0.1v + v^2}\right) \mathrm{Hz}$$

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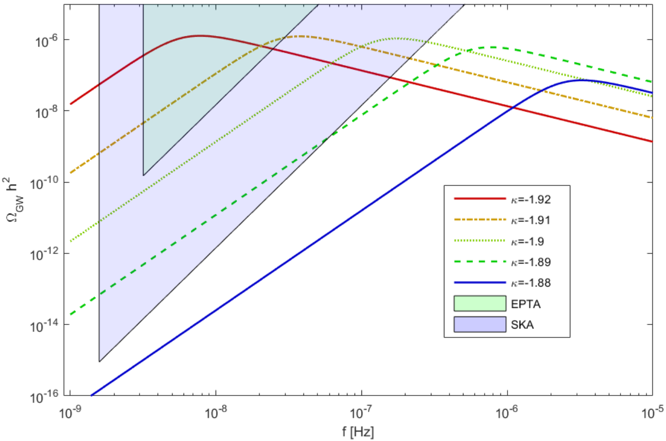
$$f_0 = 1.65 \times 10^{-7} \left(\frac{T_p}{1\ \text{GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6} H_p^{-1}\beta \left(\frac{0.62}{1.8-0.1v+v^2}\right) \text{Hz}$$

To discuss further: applicability of these simulations to large bubbles ($\sim$long-lasting PT)

GW spectra: results



- Current constraints: EPTA, PPTA, NANOGrav
- Possible detection: Square Kilometre Array

[Moore et al., Class. Quant. Grav. 32 (2015) 015014]

Conclusion

- Study of a very strong and prolonged EWPT:

$$T_n \sim 50 \text{ GeV and } T_p \sim [0.2 - 10] \text{ GeV}$$

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- Not limited to the model discussed here (just need a barrier at T=0):

  e.g. singlet extensions of SM or NMSSM