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# Detecting Gravitational Waves from Cosmological Phase Transitions with LISA: an Update

C. Caprini et al.

for the LISA Cosmology Working Group

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LISA
CosWG-19-04

For the LISA Cosmology Working Group

**Abstract**

PTPlot

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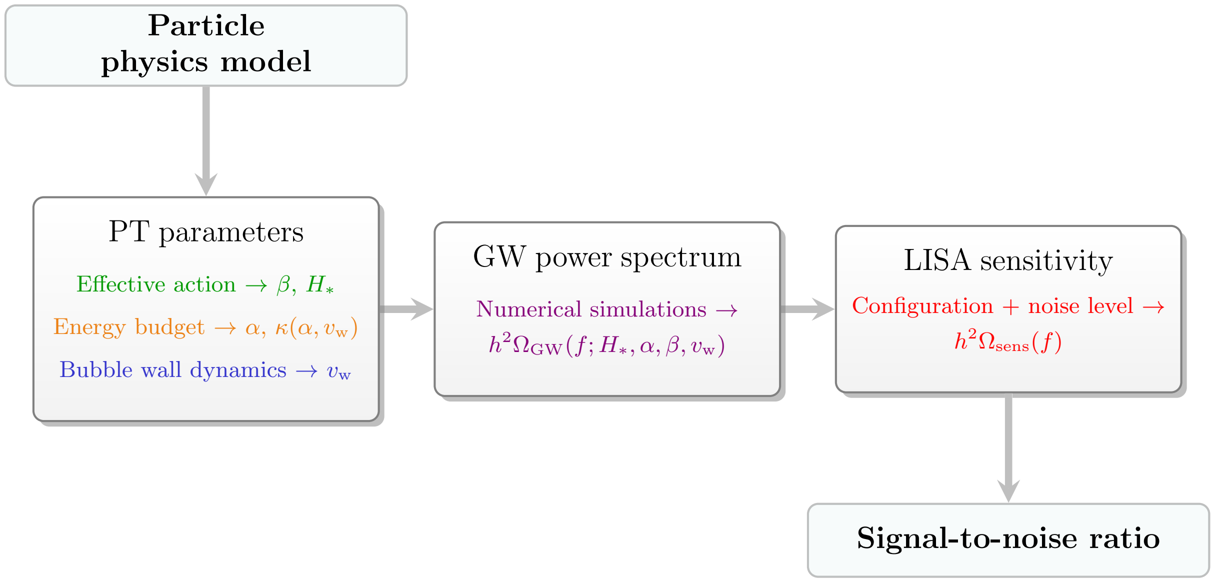

Particle physics model
PT parameters
Effective action → $\beta$, $H_*$
Energy budget → $\alpha$, $\kappa(\alpha, v_w)$
Bubble wall dynamics → $v_w$
GW power spectrum
Numerical simulations →
$h^2\Omega_{GW}(f; H_*, \alpha, \beta, v_w)$
LISA sensitivity
Configuration + noise level →
$h^2\Omega_{sens}(f)$
Signal-to-noise ratio


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ptplot.org Python Django

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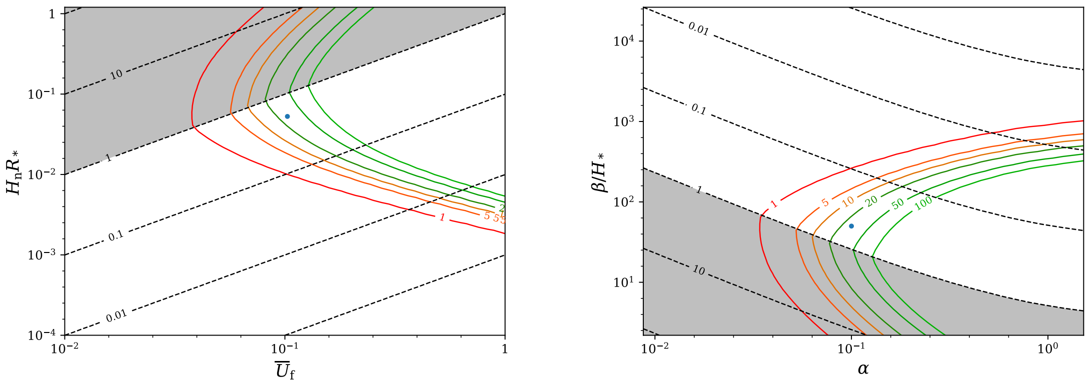


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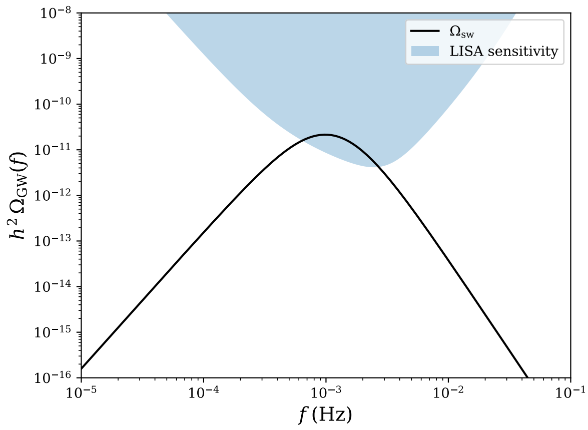


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CosmoTransitions

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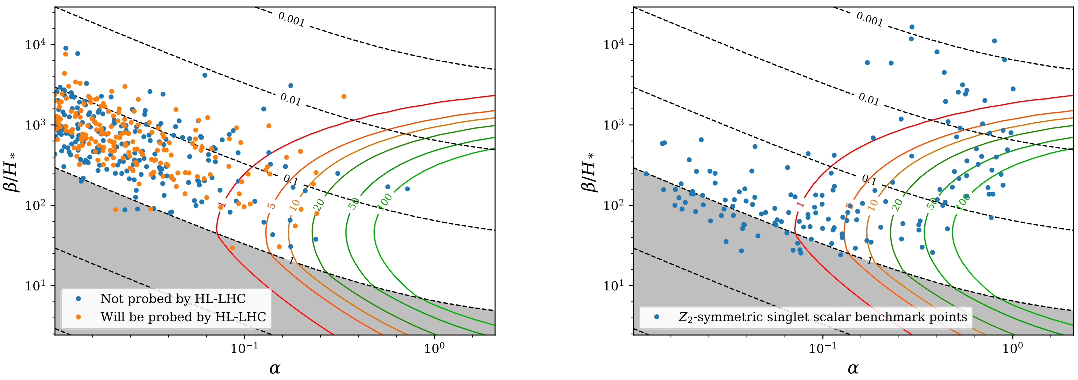

0.001
0.01
0.1
1
5
10
20
50
100
$10^4$
$10^3$
$10^2$
$10^1$
$\beta/H_*$
$10^{-1}$
$10^0$
$\alpha$
Not probed by HL-LHC
Will be probed by HL-LHC
$Z_2$-symmetric singlet scalar benchmark points


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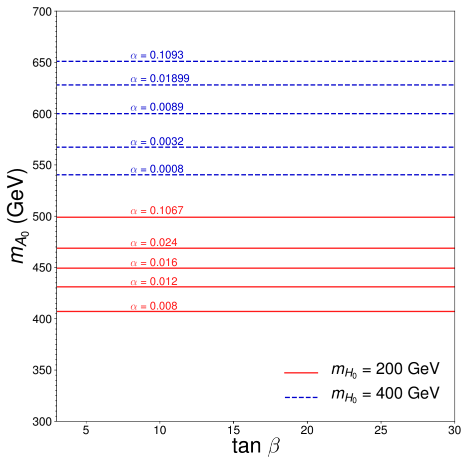


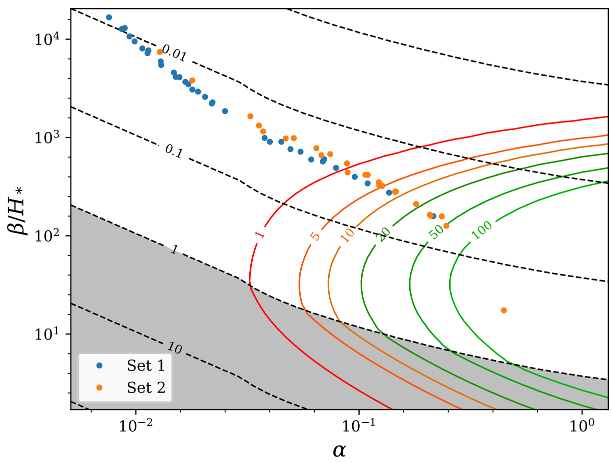


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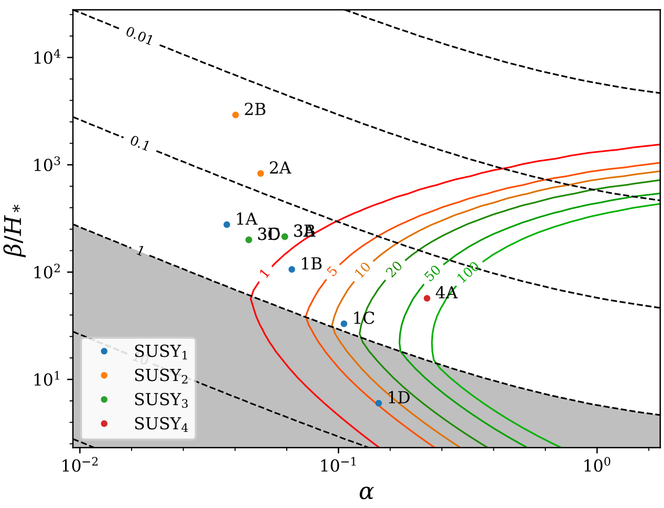

0.01
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1
2B
2A
1A
3D
3B
1B
1C
1D
4A
1
5
10
20
50
100
SUSY$_1$
SUSY$_2$
SUSY$_3$
SUSY$_4$
$10^4$
$10^3$
$10^2$
$10^1$
$\beta/H_*$
$10^{-2}$
$10^{-1}$
$10^0$
$\alpha$


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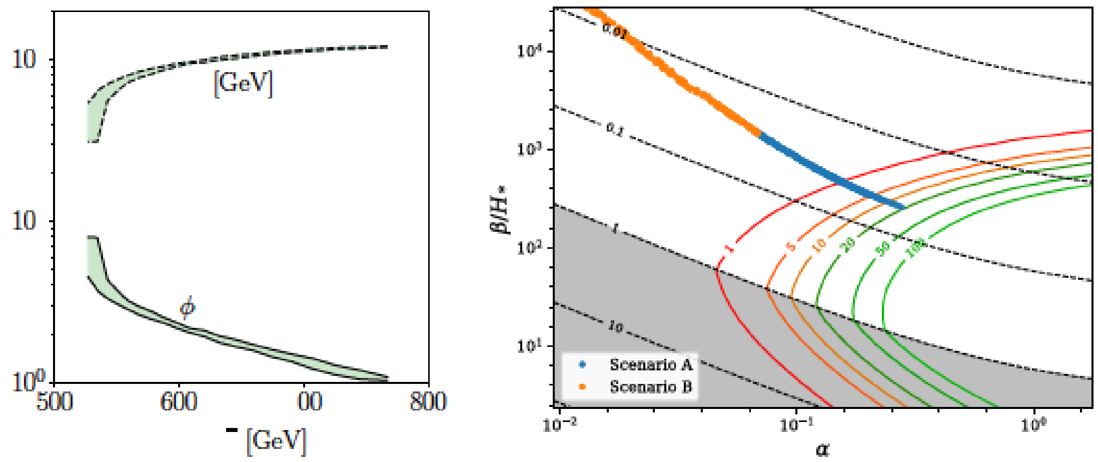


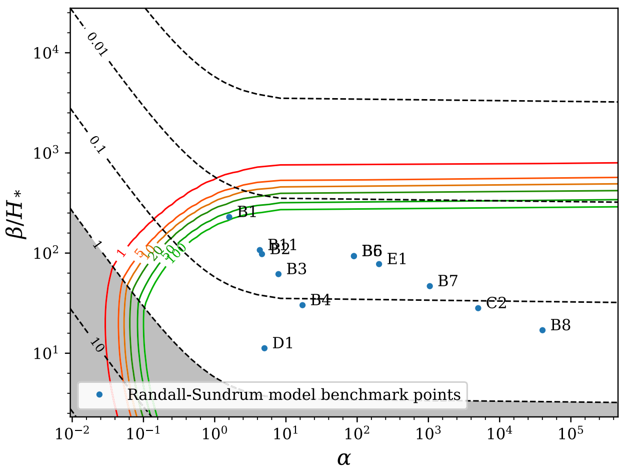

Figure 7: LEFT: Values of $T_*$ and $\phi_*/T_*$ as a function of the effective scale $f/\sqrt{c}$ (note that the parameter $f$ appearing here should not be confused with the GW frequency). RIGHT: Scatter plot on the plane of $\alpha$ and $\beta/H$. The blue (orange) dots, labelled "Scenario A" ("Scenario B"), correspond to scenarios with $T_* \sim 50$ GeV ($T_* \sim 100$ GeV). The wall velocity is taken to be $v_{\rm w} = 0.95$.

future 100 TeV hadron collider, such as the FCC-hh [165]. All in all, LISA will provide the first actual test of the scalar potential of the SMEFT.

### 6.5 Models with warped extra dimensions

The scenarios discussed thus far all rely on weakly-coupled new physics and polynomial scalar potentials which typically predict $\alpha$ significantly smaller than 1. However, there exist compelling and well-motivated frameworks that can generically give rise to large signals at LISA featuring strong dynamics and non-polynomial potentials which are the subject of the next two subsections. We start with models involving warped extra dimensions.

Five-dimensional warped models have attracted much attention in the literature as they provide a natural and well-motivated framework for a very strong first-order PT [28–36, 39]. In the effective 4D language, this PT involves the radion scalar field whose potential stabilizes the interbrane distance determining the size of the slice of Anti-de Sitter space in Randall–Sundrum models. The VEV of the radion field describes the position of the IR (i.e. TeV) brane emerging from infinity. This class of models has been among the most popular solutions to the hierarchy problem. As the Higgs emerges together with the IR brane, the EW scale naturally emerges as the Planck scale suppressed by a geometric (warped) factor. The masses of the Kaluza–Klein resonances are around the TeV for solving the hierarchy problem. As a result, $T_*$ is thus the TeV scale suppressed by some additional parametric factors. For $T_*$ below the EW scale, the radion PT triggers EW symmetry breaking, with intriguing implications for EW baryogenesis and LISA.



$\beta/H_*$
$\alpha$
$10^4$
$10^3$
$10^2$
$10^1$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
0.01
0.1
1
10
1
5
20
100
B1
B11
B2
B3
B4
B5
B6
E1
B7
C2
B8
D1
Randall-Sundrum model benchmark points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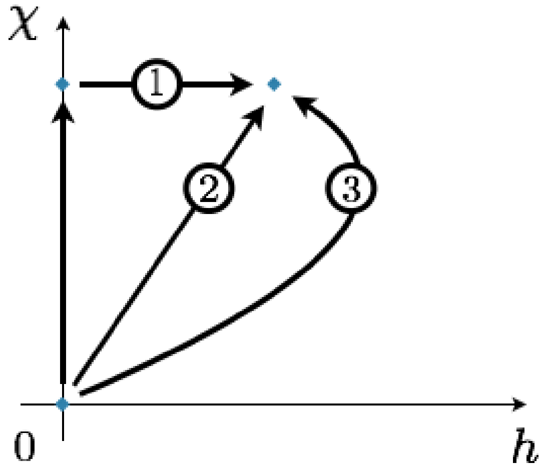
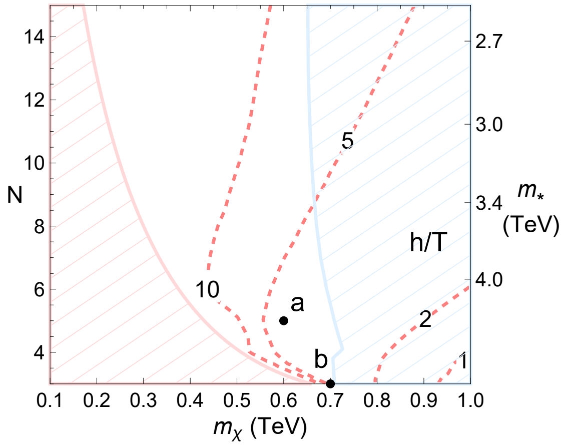


χ
1
2
3
0
h


N
$m_*$
(TeV)
h/T
10
5
2
1
a
b
$m_\chi$ (TeV)
14
12
10
8
6
4
2.7
3.0
3.4
4.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

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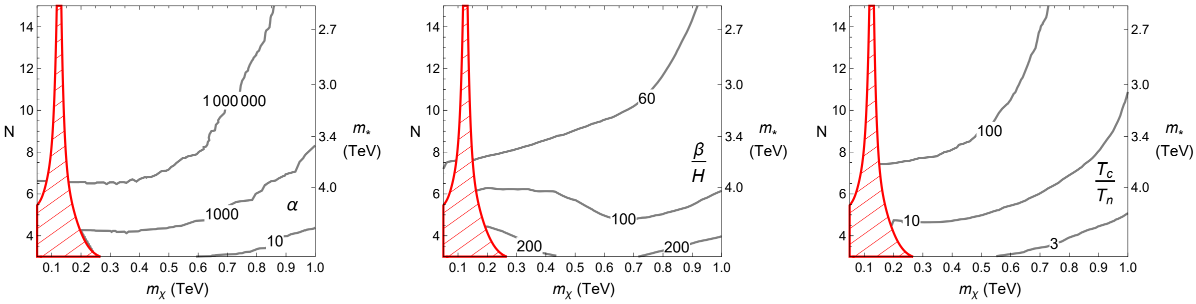
N
14
12
10
8
6
4
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
$m_X$ (TeV)
1 000 000
1000
10
α
2.7
3.0
3.4
4.0
$m_*$ (TeV)
60
100
200
200
β/H
100
10
3
$T_c$/$T_n$

”

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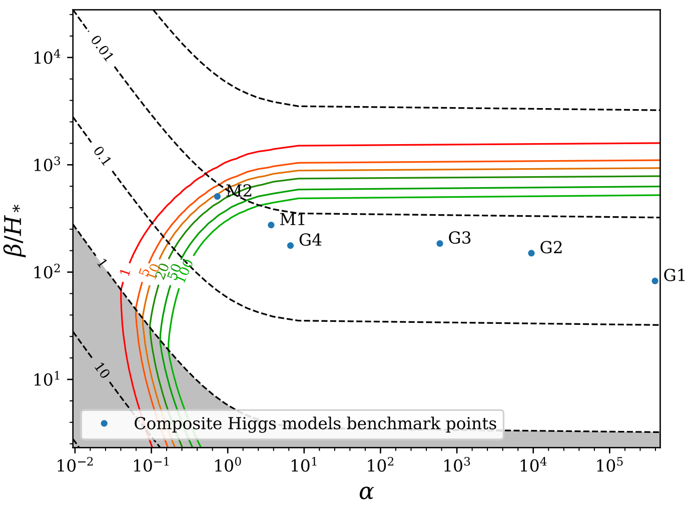
Composite Higgs models benchmark points
M2
M1
G4
G3
G2
G1
0.01
0.1
1
10
1
5
10
20
50
100
$\beta/H_*$
$\alpha$
$10^4$
$10^3$
$10^2$
$10^1$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$

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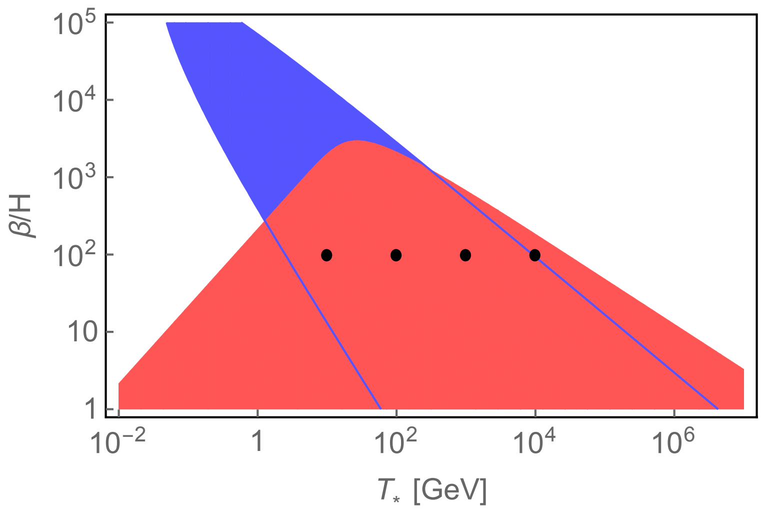
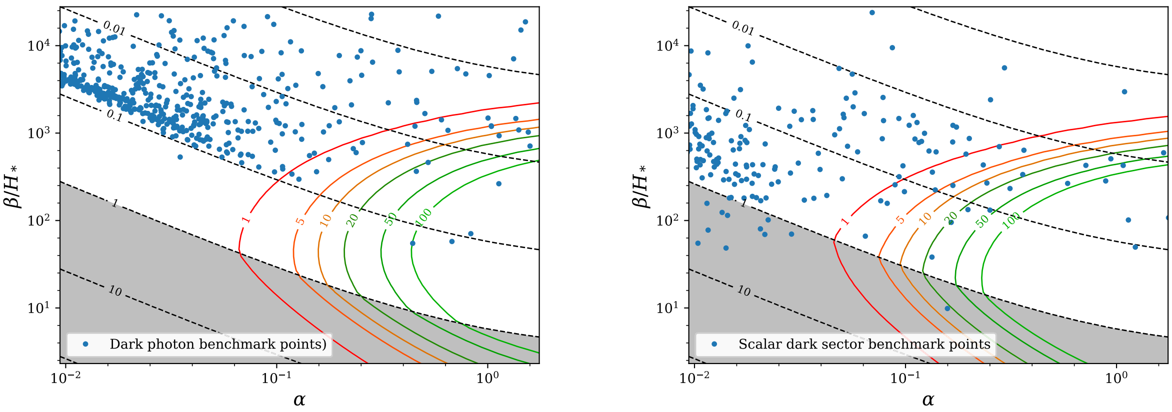


$10^5$
$10^4$
$10^3$
$10^2$
10
1
β/H
$10^{-2}$
1
$10^2$
$10^4$
$10^6$
$T_*$ [GeV]



Dark photon benchmark points)
Scalar dark sector benchmark points
$\beta/H_*$
$\alpha$
0.01
0.1
1
10
5
20
50
100

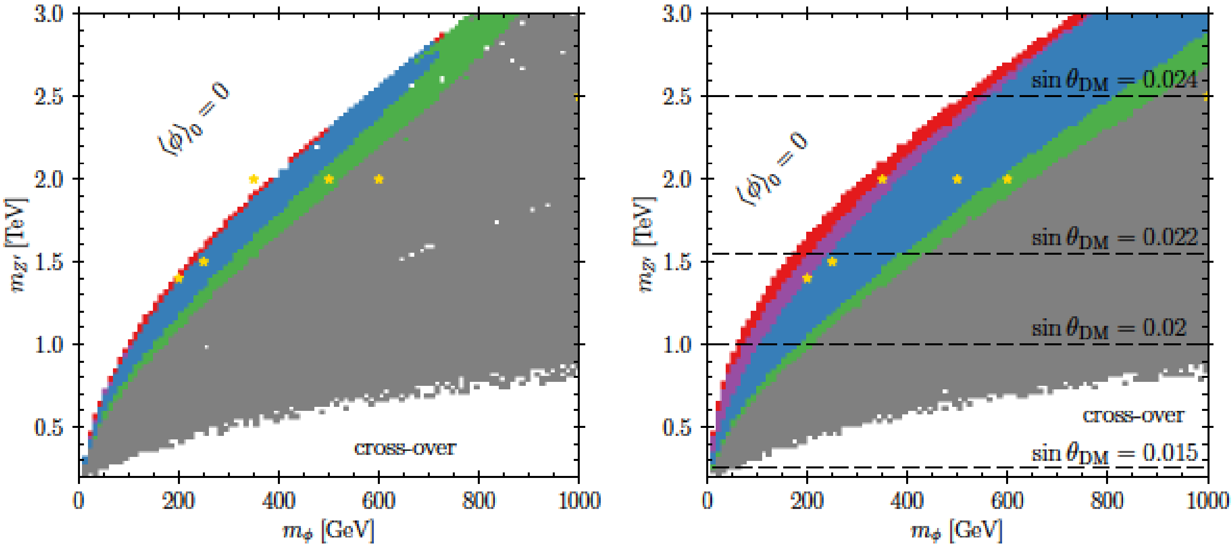
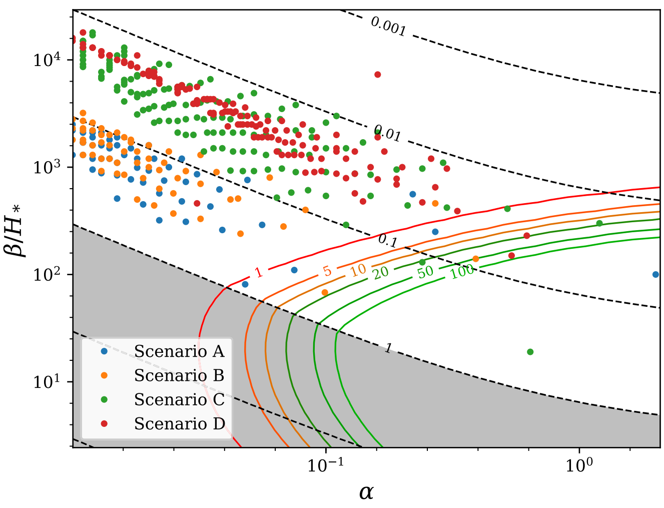



Figure 15: Reach of LISA for gauged lepton number DM model (red shaded region), from [190]. LEFT: Results for a pure abelian Higgs model with $v_\Phi = 2$ TeV. RIGHT: The Yukawa couplings are chosen such that the correct DM abundance is obtained. The region below the horizontal dashed lines will be probed by Xenon1T, for the indicated value of the DM mixing angle. Notice that in this figure slightly different LISA sensitivities were used. For more details, see [190].

the PT within reach of LISA.

In the simplest case, the effects of the Yukawa couplings of $\Phi$ to the new leptons can be neglected, and the PT depends on only three parameters, which can be taken to be $v_\Phi$ and the masses of the $U(1)_L$ gauge boson $Z_L$ and the real scalar $\phi$. A PT sufficiently strong so as to be detectable by LISA requires a sizeable hierarchy of masses $m_{Z_L}/m_\phi \approx 4 - 10$, with $m_{Z_L}$ typically above a TeV, as can be seen in Fig. 15. Such a heavy leptophilic gauge boson is difficult to detect at the LHC, but is certainly within reach of a high energy lepton collider such as CLIC or a future 100 TeV hadron collider like FCC-hh. Detectability of the scalar depends on its mixing with the SM Higgs, which here is assumed to be small in order to leave the EWPT unaffected.

Including the lepton Yukawa couplings, and in particular setting the DM mass such that it reproduces the correct relic abundance, has an interesting effect on the phenomenological predictions, namely the region in the $m_\phi$–$m_{Z_L}$ plane that can be probed by LISA is increased significantly, as shown in Fig. 15. While searches for leptophilic DM at colliders is notoriously difficult, the whole parameter space is in principle detectable by Xenon1T [198] or other future direct detection experiments. As far as complementarity with LISA is concerned, here the PT is not essential for producing or setting the DM relic abundance, and as such one cannot conclusively probe the model with GWs alone. However., one could for example envision a scenario where $Z_L$ is found at a future collider but the corresponding scalar $\phi$ remains elusive. Observation of a signal in LISA could then point to the correct mass range for the scalar, and thus aid in its discovery. The SNR values for several benchmark scenarios are shown in



$\beta/H_*$
$\alpha$
$10^4$
$10^3$
$10^2$
$10^1$
$10^{-1}$
$10^0$
0.001
0.01
0.1
1
5
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20
50
100
Scenario A
Scenario B
Scenario C
Scenario D


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LIGO SCIENTIFIC, VIRGO *Binary Black Hole Mergers in the first Advanced LIGO Observing Run* Phys. Rev. 1606.04856

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*Phys. Rev. Lett.* hep-ph/9809291

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LISA *Laser Interferometer Space Antenna*
1702.00786

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*JCAP* 0709.2091

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*Phys. Rev.*

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