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Probing Particle Physics with Gravitational Wave Detectors -- A couple of examples

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The last weasel that doubted that there is Physics Beyond the Standard Model

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The Cern stone marten, secured for inclusion in the Rotterdam Natural History Museum's Dead Animal Tales exhibition. Photograph: Kees Moeliker

From The Guardian website

Where is the New Physics?

Exploring is (at least) 2 dimensional

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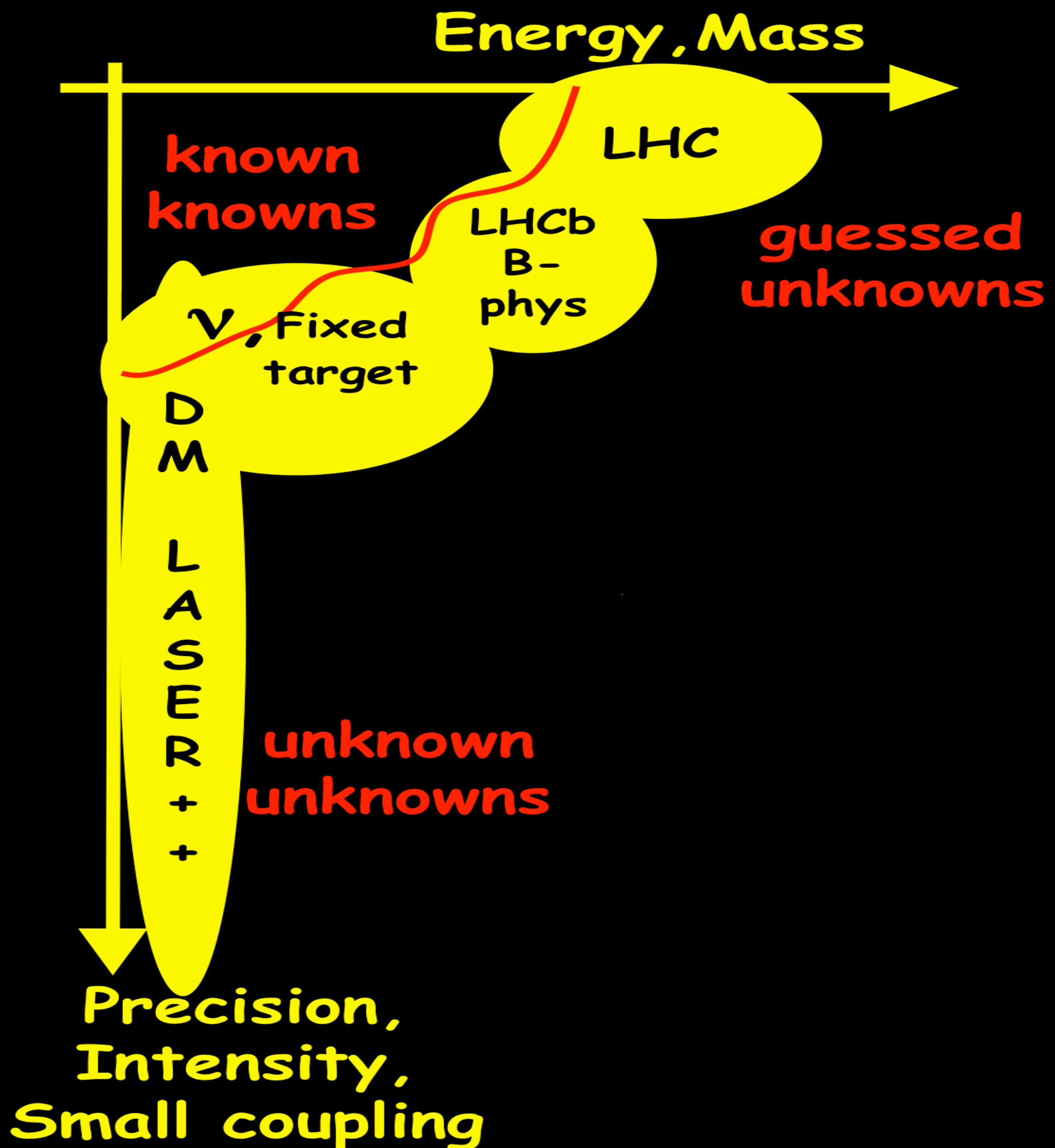

Exploring is (at least) 2 dimensional

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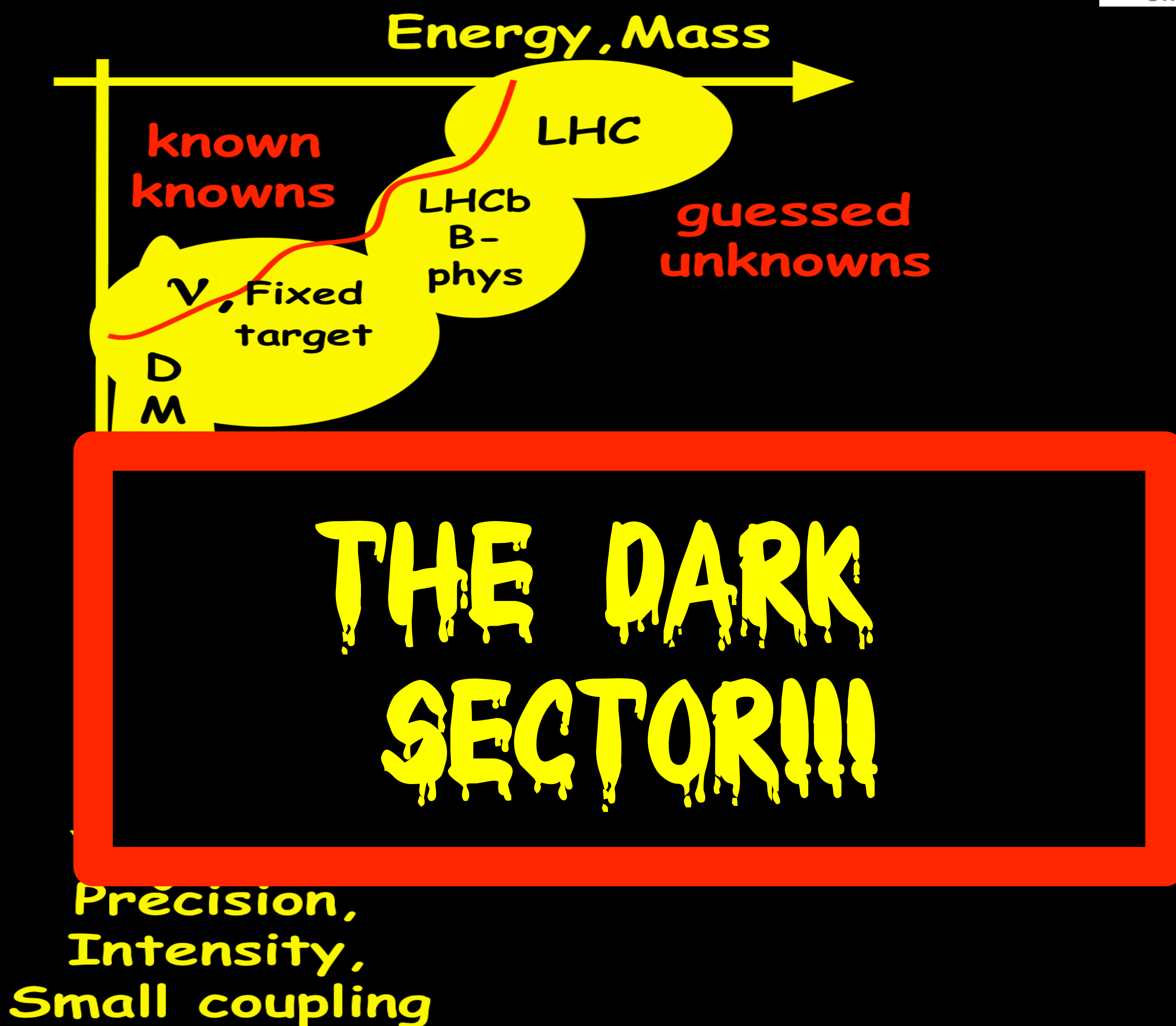

Using gravitational wave detectors

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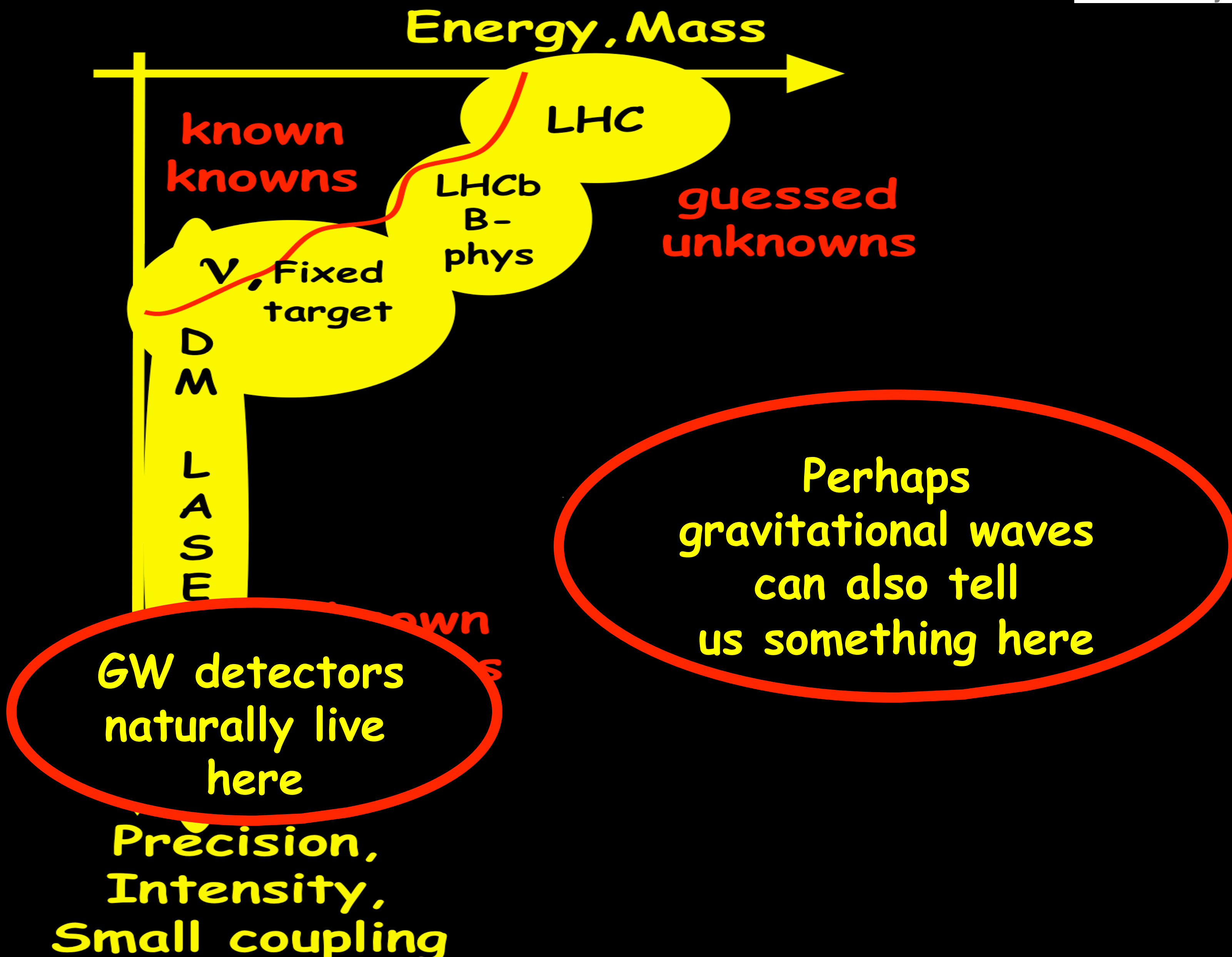

Running through walls

(searching for WISPy domain walls)

Weakly interacting sub-eV particley

A Domain Wall

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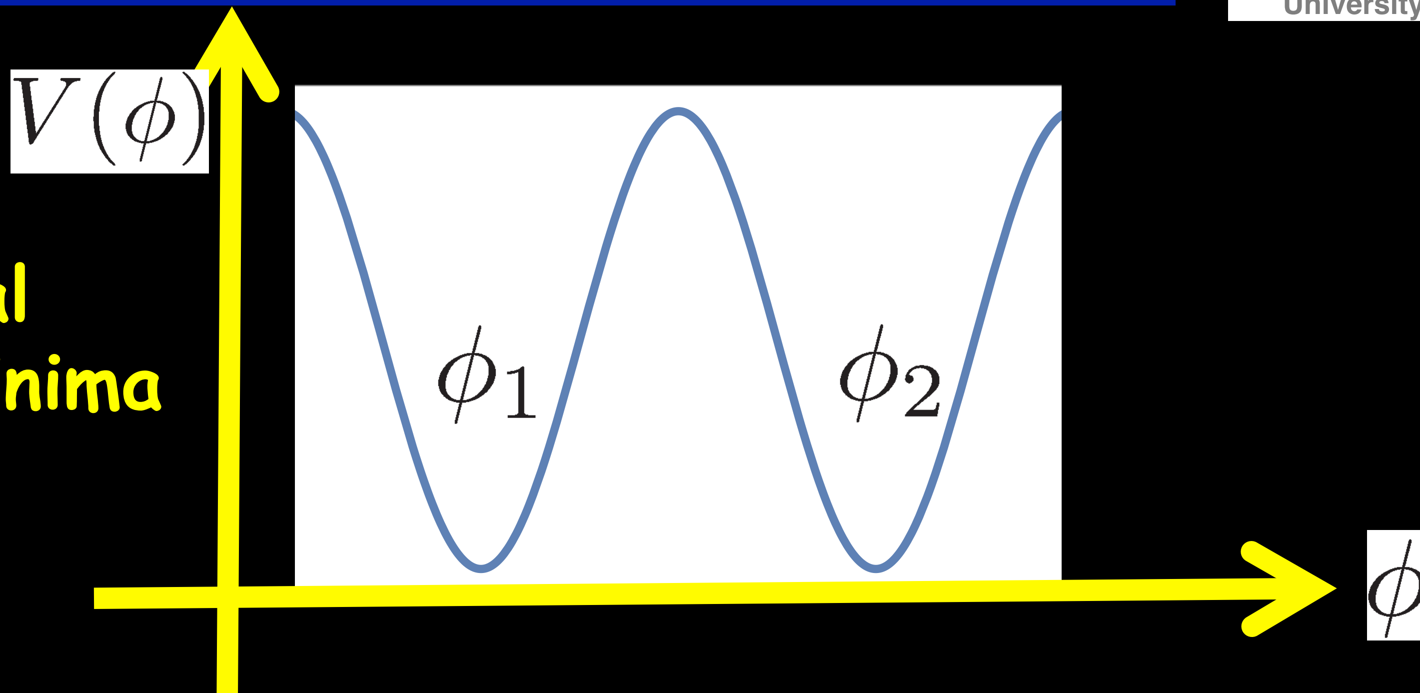
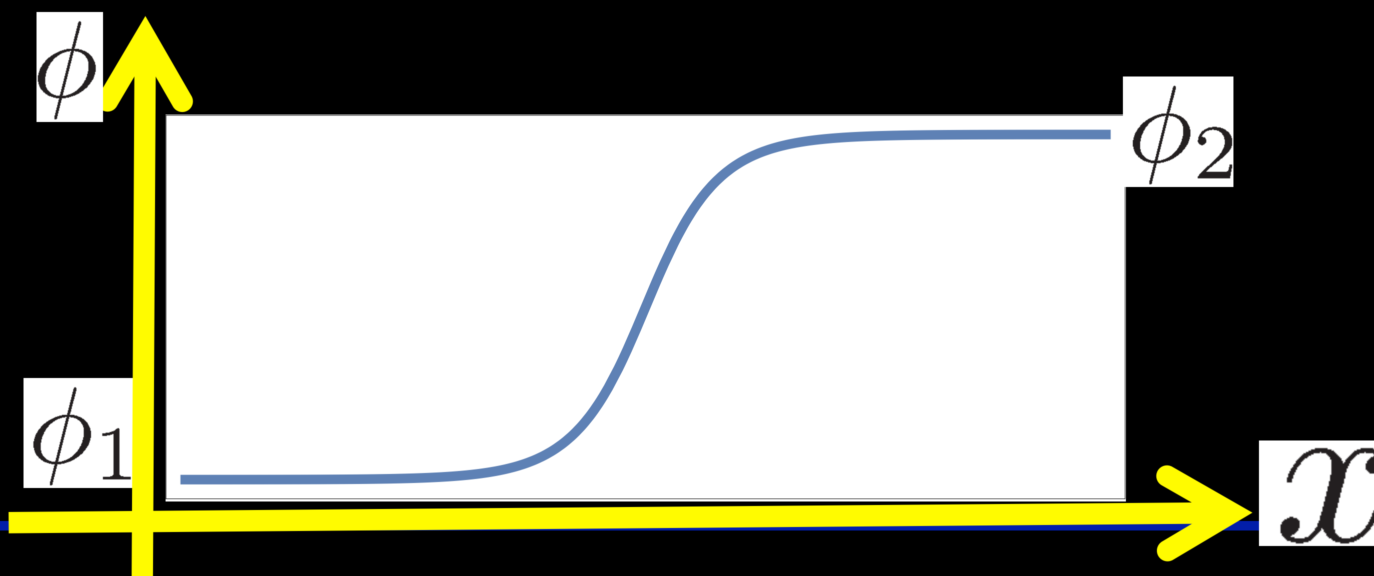
Potential
with two minima



Domain wall
from side 1
To side 2



A Domain Wall

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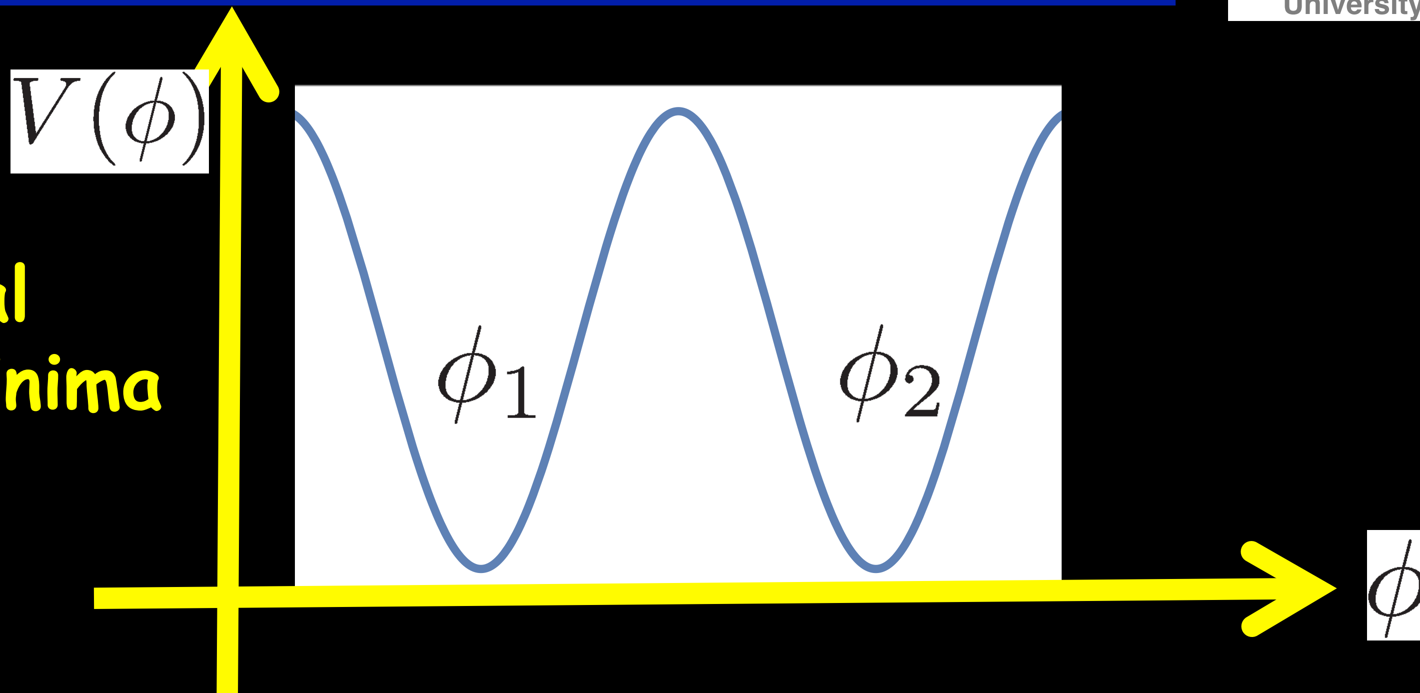
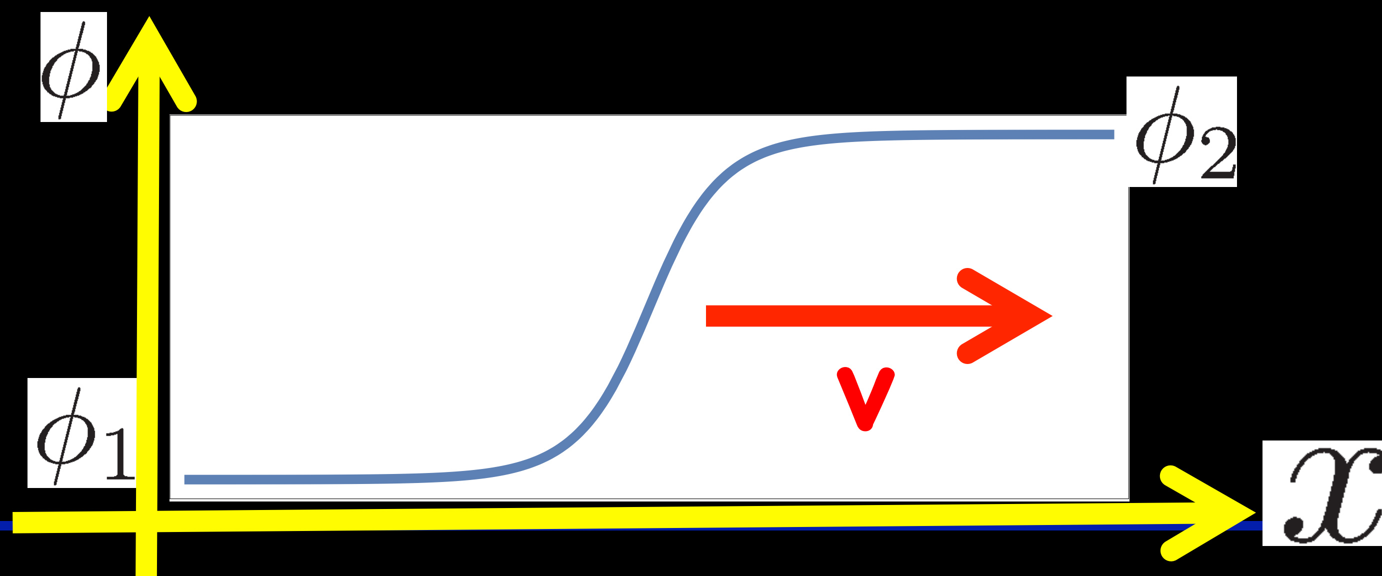
Potential with two minima



Domain wall from side 1 To side 2



Adventureous assumption

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- Domain walls (significantly) contribute to DM in galaxy
- This requires some pushing…

$$\frac{f}{N_\phi} \lesssim \mathrm{TeV} \times \left(\frac{L}{10^{-2}\mathrm{Ly}}\right)^{1/2} \left(\frac{\mathrm{neV}}{m}\right)^{1/2} \left(\frac{\rho_{\mathrm{DW}}}{\rho_{DM}}\right)^{1/2}$$

➔ Event rate

$$\text{Event Rate} \sim \frac{1}{10\ \text{years}} \left(\frac{10^{-2}\,\mathrm{Ly}}{L}\right) \left(\frac{v}{10^{-3}}\right)$$

aLIGO

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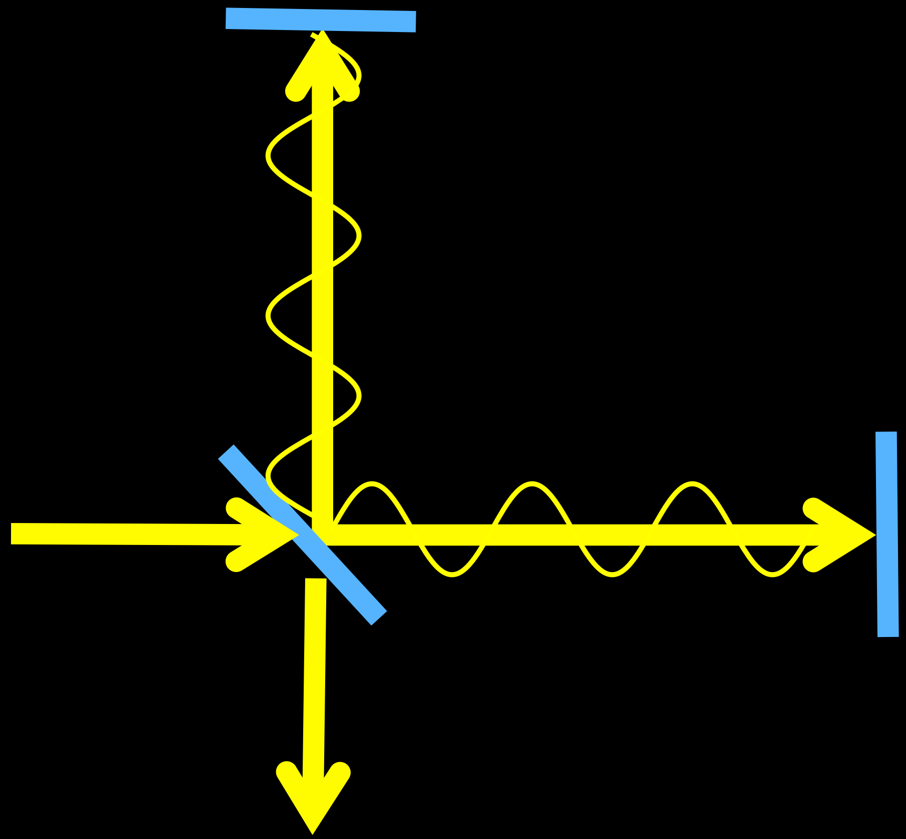
- Has detected gravitational waves!!
- Is an Interferometer



Interference pattern

Causing a phase shift

- Interaction inside wall creates photon mass

$$\mathcal{L}_A = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} m_{0,\gamma}^2 \sin^2\left(\frac{N_A \phi}{f}\right) A^\mu A_\mu$$

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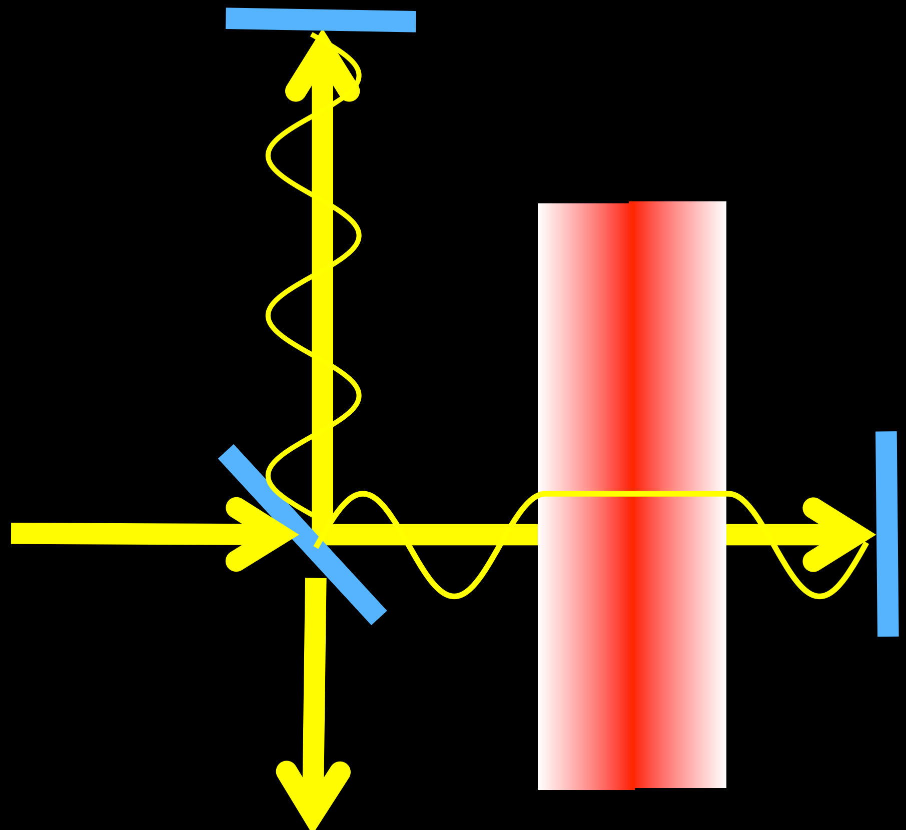

Interference pattern changed

Signal shapes

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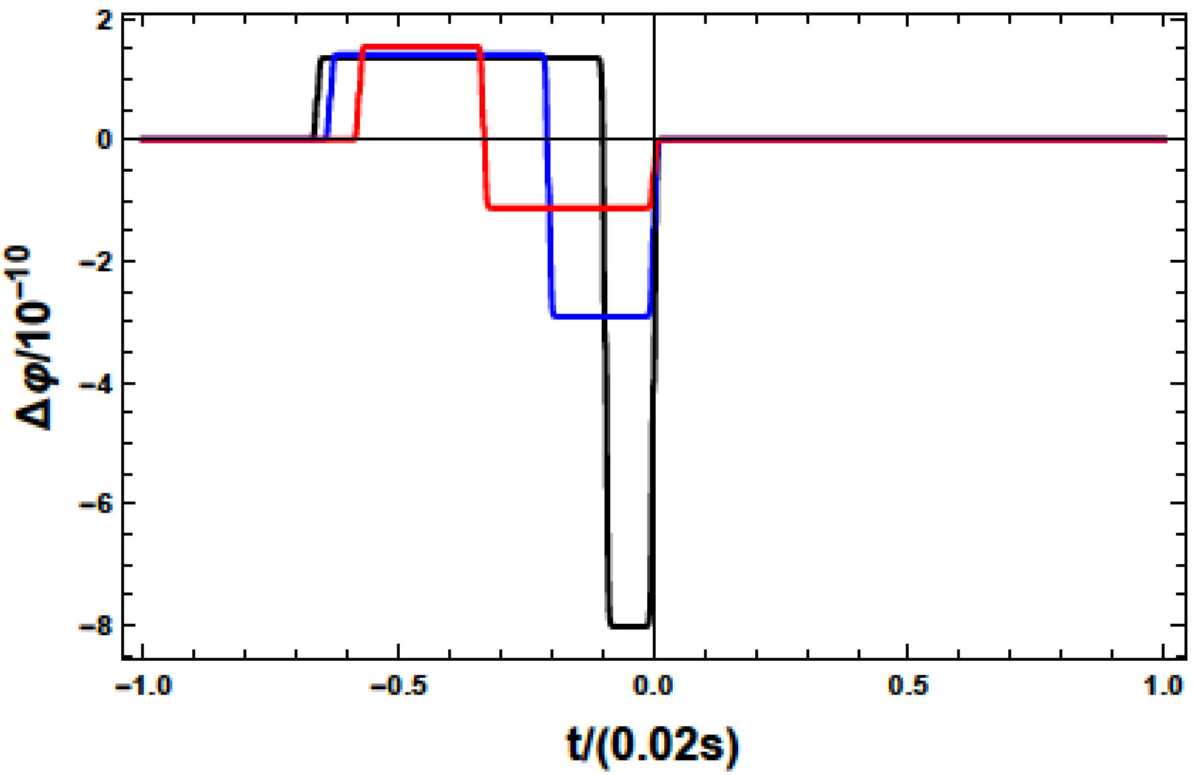

FIG. 6: $L = 4000\,\mathrm{m}$, $\omega \approx 1\,\mathrm{eV}$, $m = 10\,\mathrm{neV}$, $m_{\gamma,0} = 1\,\mathrm{neV}$, $N_A/N_\phi = 1$, $\alpha = \pi/2.2, \pi/2.5, \pi/3$ (black, blue, red), v chosen such that signal has roughly a length of $0.02\mathrm{s} \sim 1/(50\,\mathrm{Hz})$ this corresponds to $v = 1 \times 10^{-3}$.

Signal shapes

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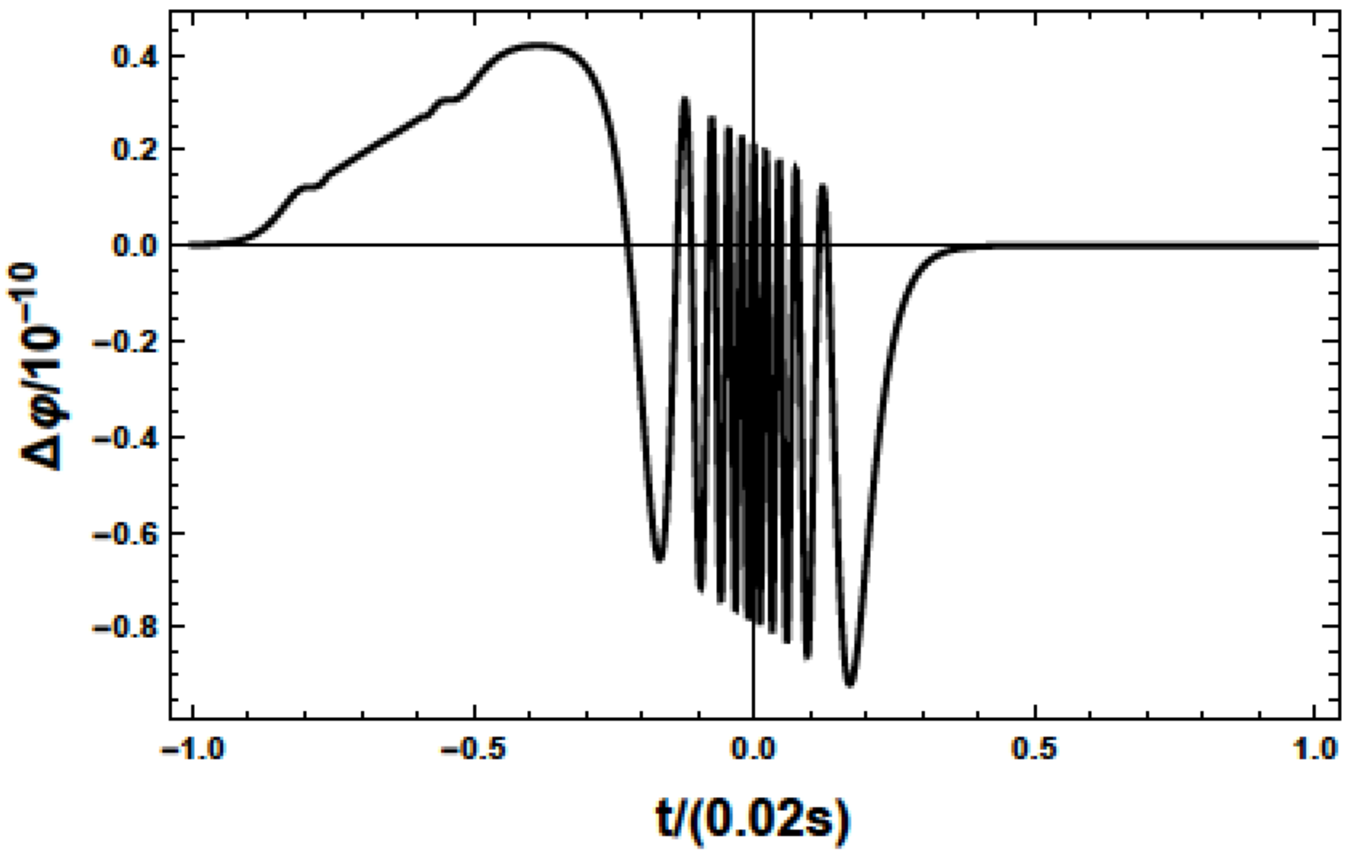


FIG. 8: As in Fig. ?? but $m_{\gamma,0} = 0.1\,\mathrm{neV}$, $N_A/N_\phi = 5$, $m = 0.5\,\mathrm{neV}$, $\alpha = \pi/2$ and $v = 1 \times 10^{-3}$.

How to distiguish from grav waves?

- velocity<<c
- $v \sim 10^{-3}$

➔ Time difference between two sites ~few seconds

➔ Need careful analysis strategies

Promised sensitivity:

$$m_{0,\gamma} \sim \mathrm{neV}\left(\frac{m}{10\,\mathrm{neV}}\right)^{1/2} \quad \text{for } m \gtrsim 0.1\,\mathrm{neV},$$
$$\sim 0.1\,\mathrm{neV} \quad \text{for } m \lesssim 0.1\,\mathrm{neV}.$$

Exploring heavier dark sectors with gravitational waves

Example I:
Scale invariant EW symmetry breaking

Scale invariant EW symmetry breaking

- Scale invariance

➔ No explicit mass scales in the Lagrangian

- EW symmetry breaking?

$$V(\phi) = \frac{1}{4}\phi^4$$

No EW breaking at tree level

Scale invariant EW symmetry breaking

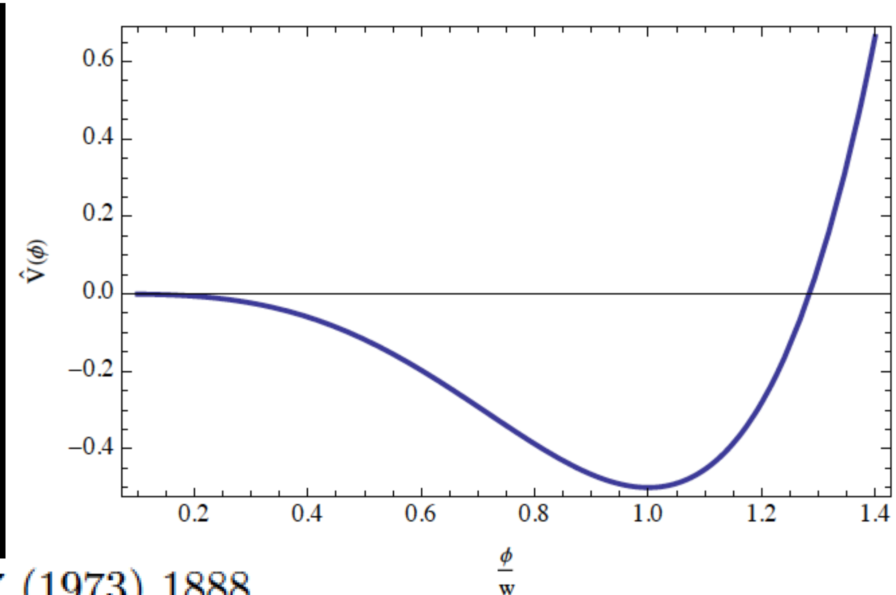
- Scale invariance

  ➔ No explicit mass scales in the Lagrangian

- EW symmetry breaking?

$$V(\phi;\mu) = \frac{\lambda_\phi(\mu)}{4}\phi^4 + \frac{n g_{\mathrm{D}}(\mu)^4}{64\pi^2}\phi^4\left(\log\left(\frac{\phi^2}{\mu^2}\right) - \frac{25}{6}\right)$$

Works at 1-loop level!



S. R. Coleman and E. J. Weinberg, Phys. Rev. D **7** (1973) 1888.

Need dark=hidden sector

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- In the CW-SM Higgs would be too light
- top mass too high → unstable

→Remedy:

Generate mass scale in Dark sector

$$V_0(h,\phi) = \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_H}{4}h^4 - \frac{\lambda_P}{4}h^2\phi^2$$

$<\phi> \neq 0$ generates negative mass for h

→ EW symm breaking

R. Hempfling, Phys. Lett. B **379** (1996) 153.
K. A. Meissner and H. Nicolai, Phys. Lett. B **648** (2007) 312.

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Weak coupling to dark sector

Features

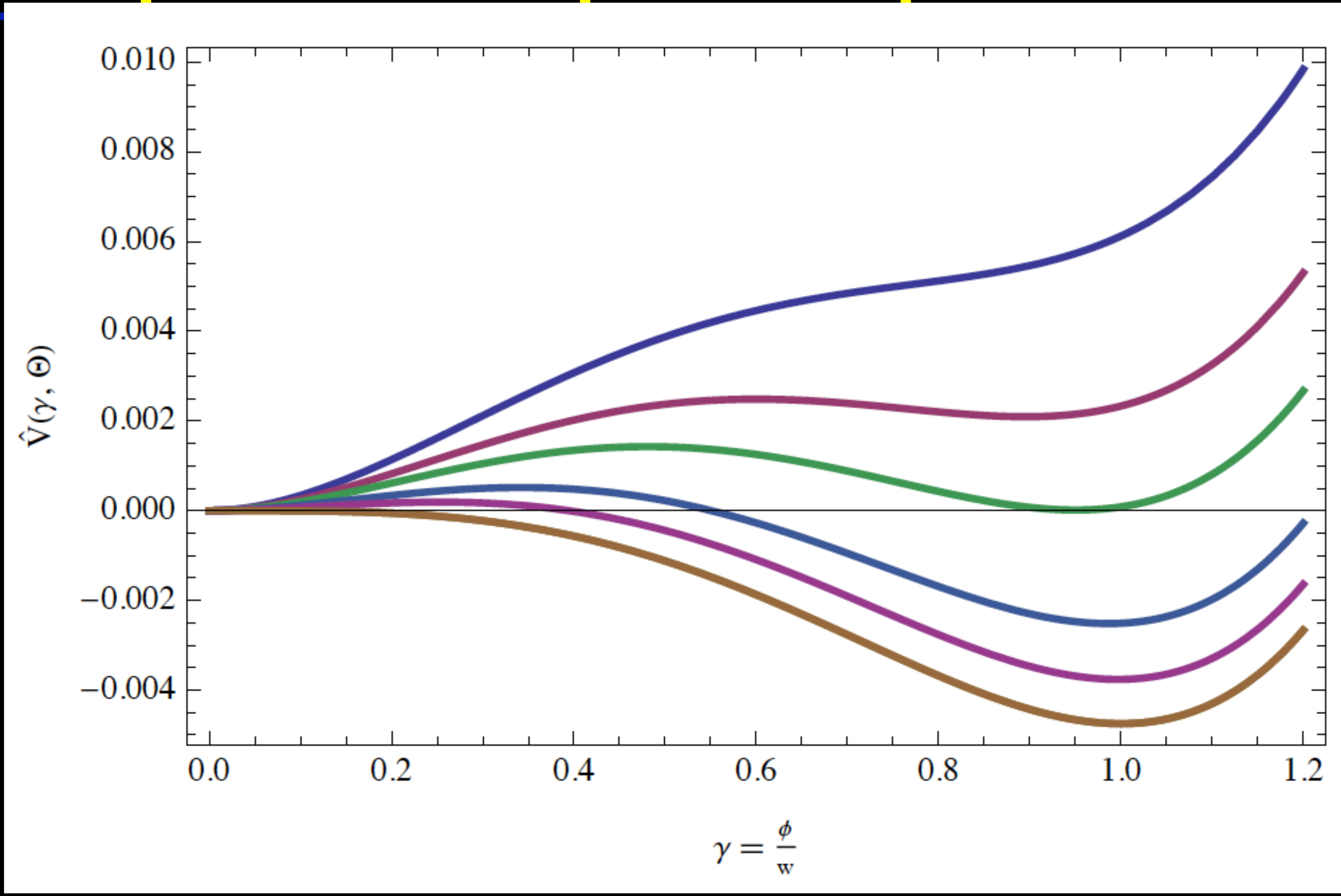
- $\lambda_P \ll 1$

↓

- $\langle\phi\rangle \gg v_{EW}$
- m_ϕ typically sizeable often ~v or bigger

Hard to test weakly coupled and heavy dark sector

Temperature dependent potential



→ First order phase transition

→ Bubble formation

→ Gravitational waves

Detectable gravitational waves

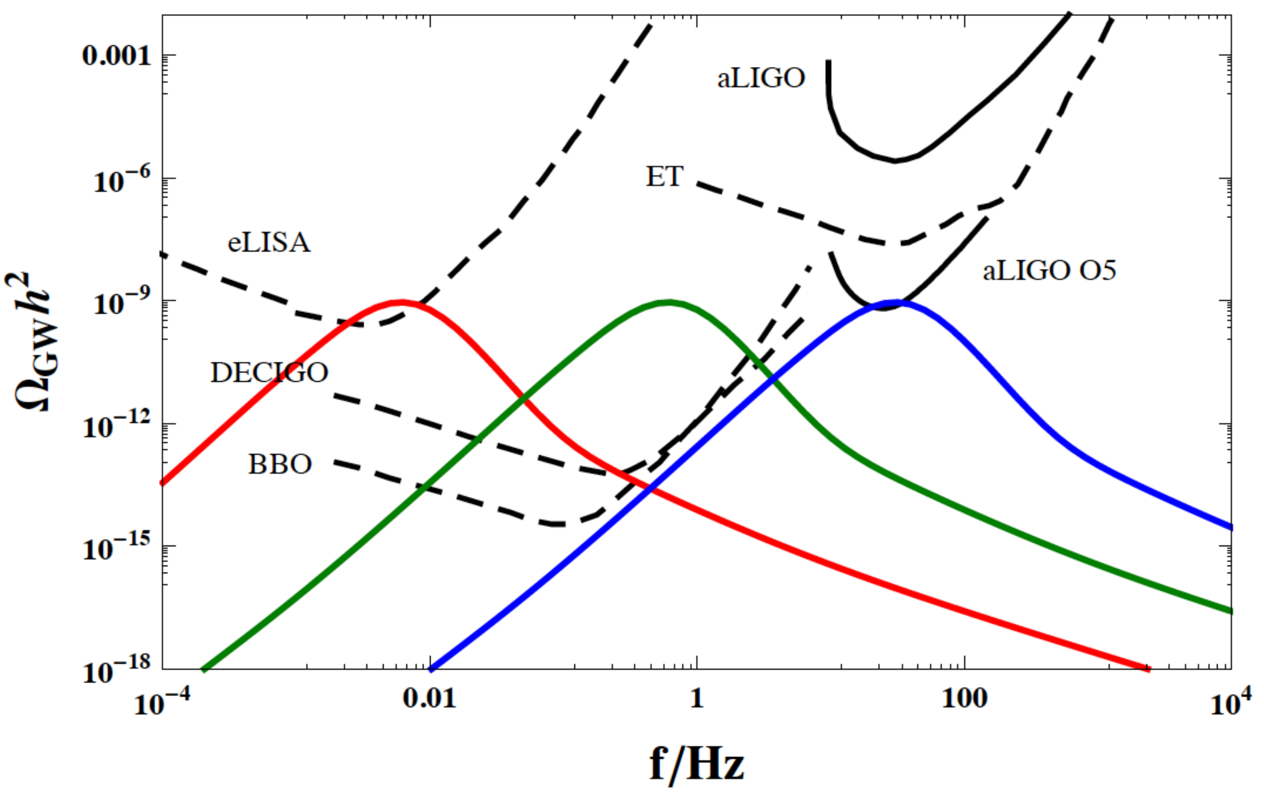


FIG. 6: Reach of gravitational wave detectors: We show aLIGO together with the fifth phase of aLIGO (both solid black), and the proposed detectors BBO, DECIGO, ET and eLISA [dashed black] (the sensitivities are taken from the gravitational wave plotter http://rhcole.com/apps/GWplotter/ [29]). For the curves of the CW phase transition – going from left to right – we choose $v_w = 1$ throughout, and respectively $(\kappa = 1.0, g_D = 0.6, T_* = 100$ GeV) [in red], $(\kappa = 1.0, g_D = 0.6, T_* = 10$ TeV) [green] and $(\kappa = 1.0, g_D = 0.6, T_* = 500$ TeV) [in blue].

Detectable gravitational waves

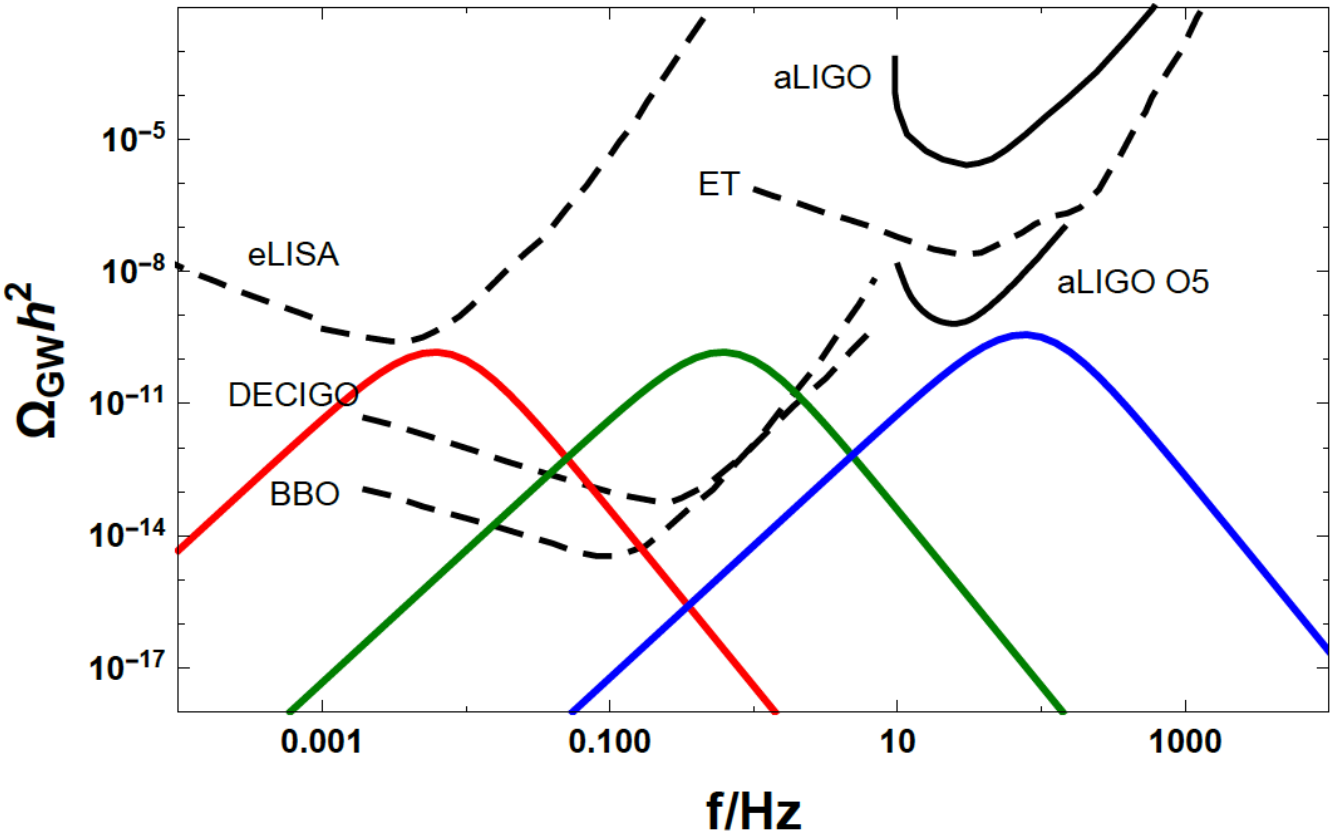


FIG. 7: Reach of gravitational wave detectors for a more conservative scenario $\kappa_{sw} = 0.4$ (all other parameters as in Fig. 6).

Example I b:
Deep Throats

The String Soundscape at Gravitational Wave Detectors

Isabel García García,[1,*] Sven Krippendorf,[1,†] and John March-Russell[1,‡]
[1]*Rudolf Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, UK*

Other models also produce GWs

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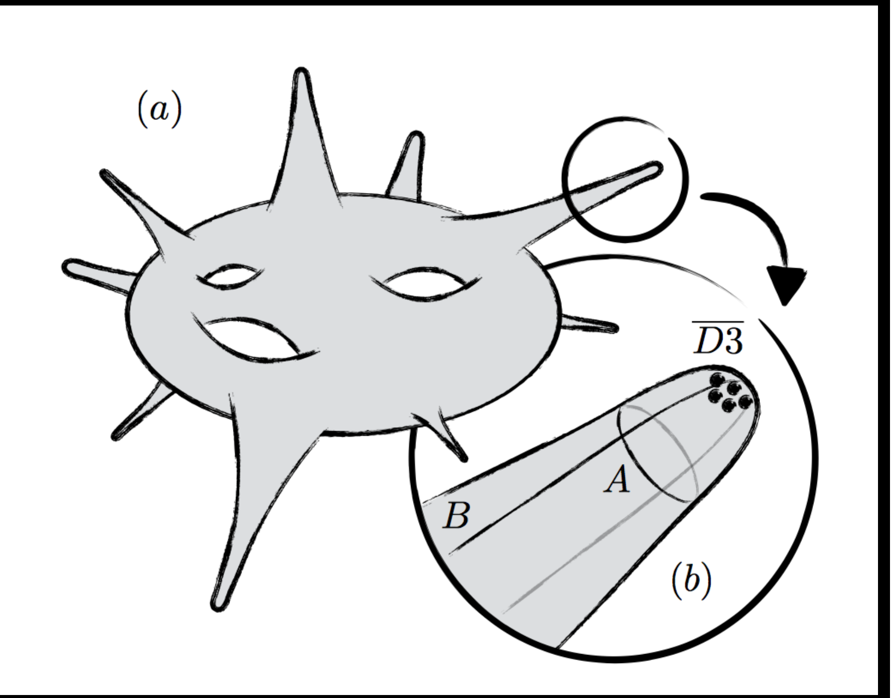

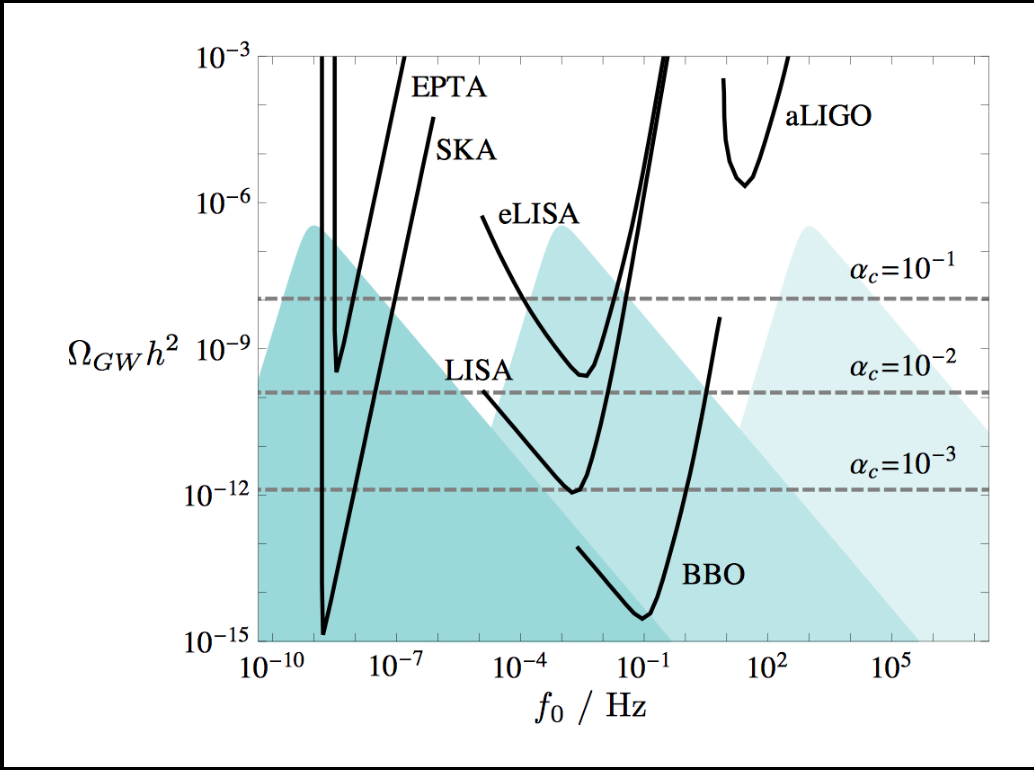

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Exploring heavier dark sectors with gravitational waves

Example II:
GW Waves from Monodromy Inflation

Monodromy potential

$$V(\phi) = \qquad\qquad \Lambda^4 \cos\left(\frac{\phi}{f} + \gamma\right)$$

Monodromy add-on

"Axion" potential
(pseudo-Goldstone pot.)

Monodromy potential

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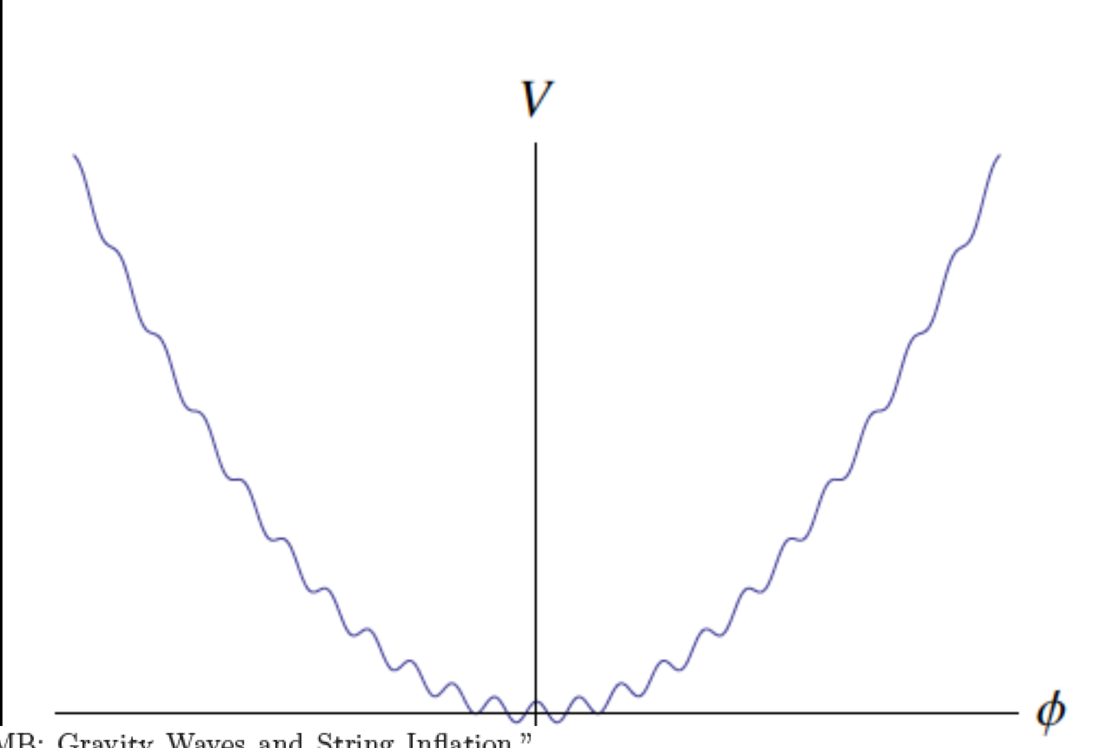
$$V(\phi) = \frac{1}{2}m^2\phi^2 + \Lambda^4 \cos\left(\frac{\phi}{f} + \gamma\right)$$

Funny potential

+ enlarged field range



E. Silverstein and A. Westphal, "Monodromy in the CMB: Gravity Waves and String Inflation," Phys. Rev. D **78**, 106003 (2008) doi:10.1103/PhysRevD.78.106003 [arXiv:0803.3085 [hep-th]].

Field oscillations

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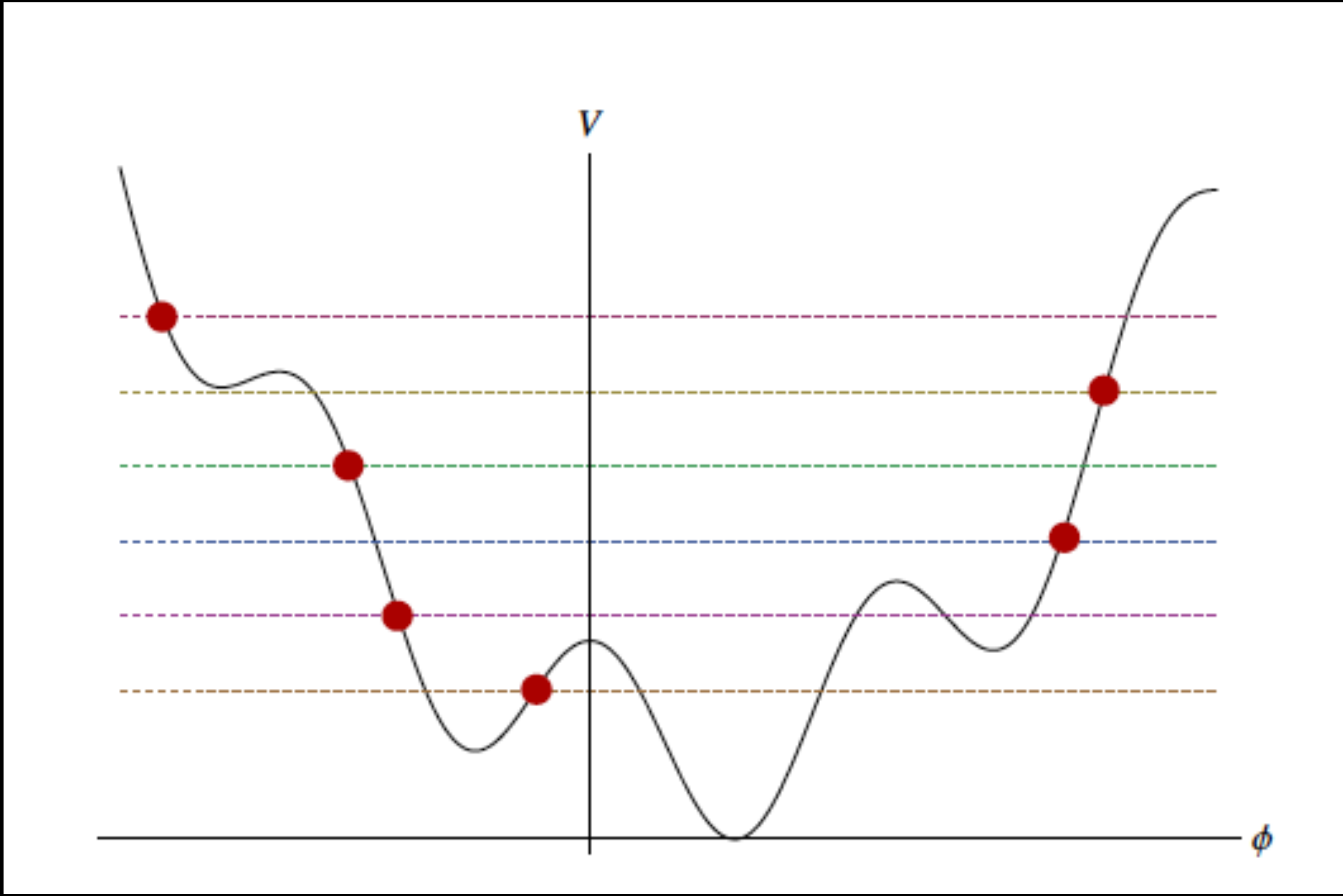
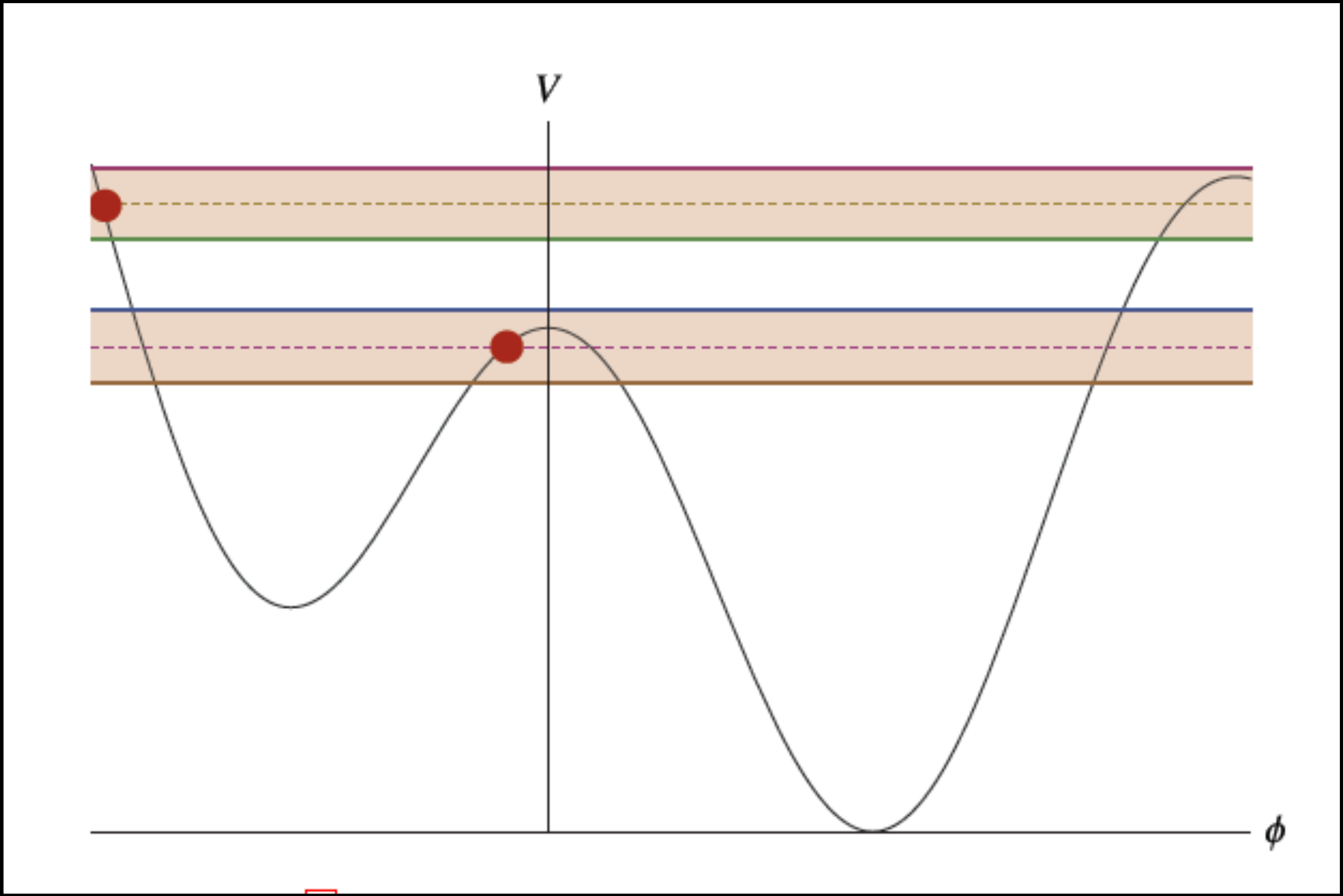


Including fluctuations



Including fluctuations

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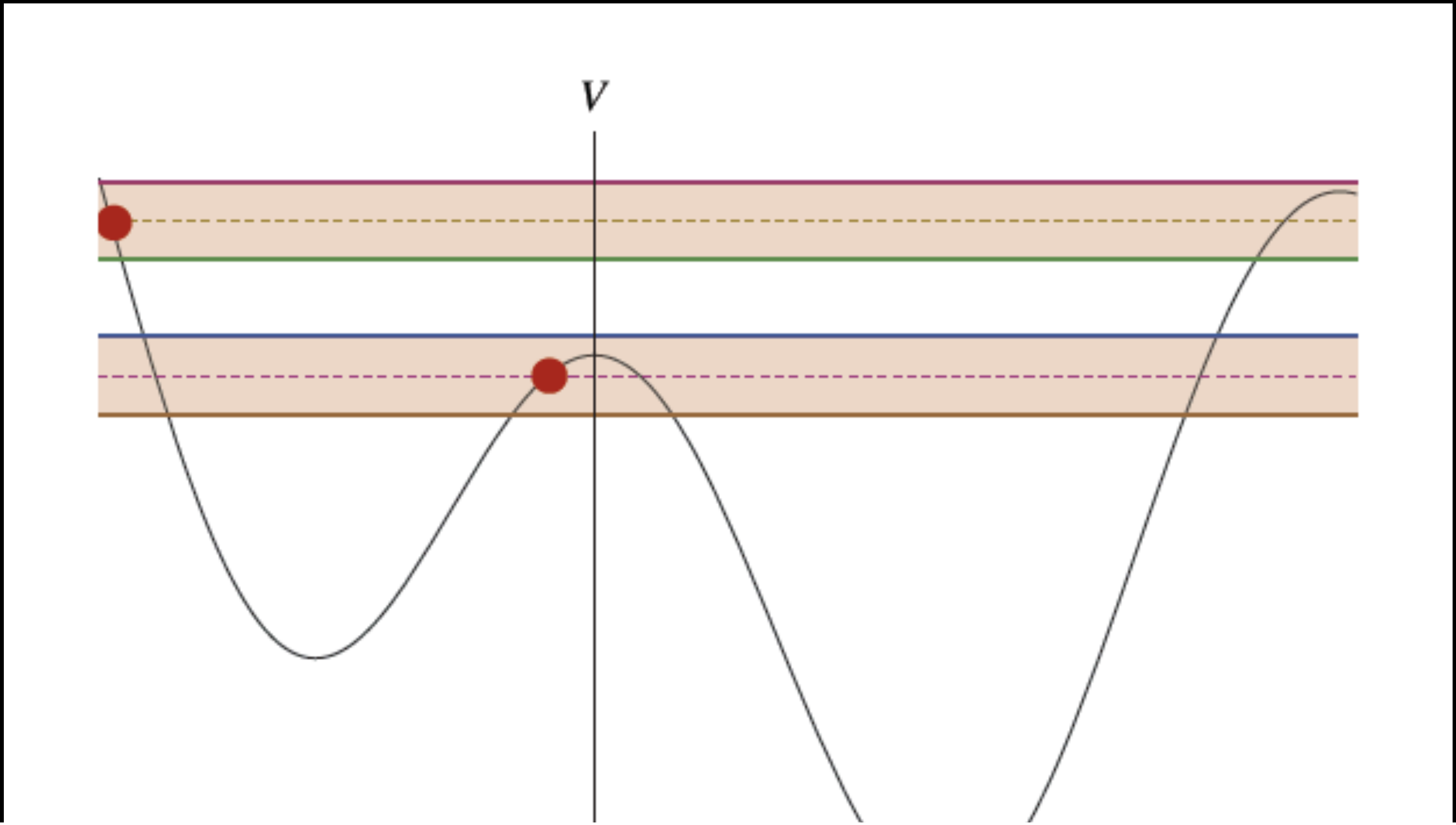

Different parts of Universe end in different minima
➔ Bubbles form
➔ GW are produced

Gravitational wave spectra

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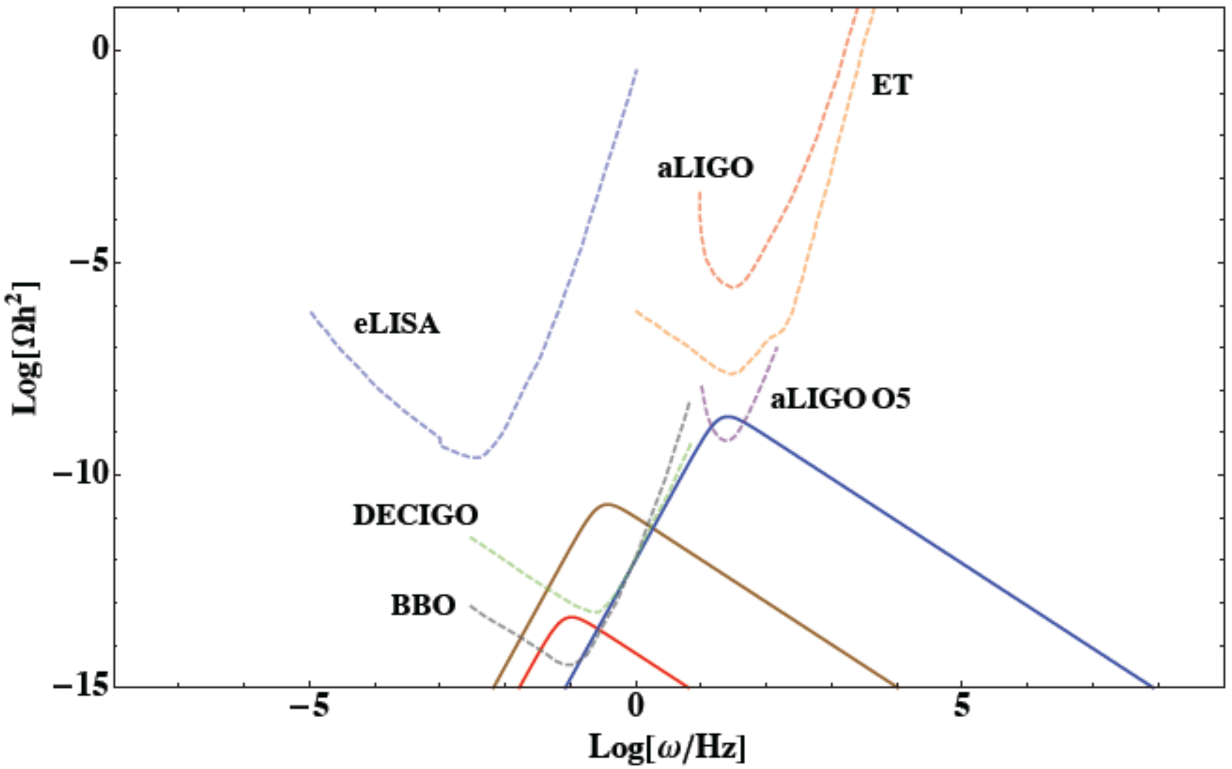
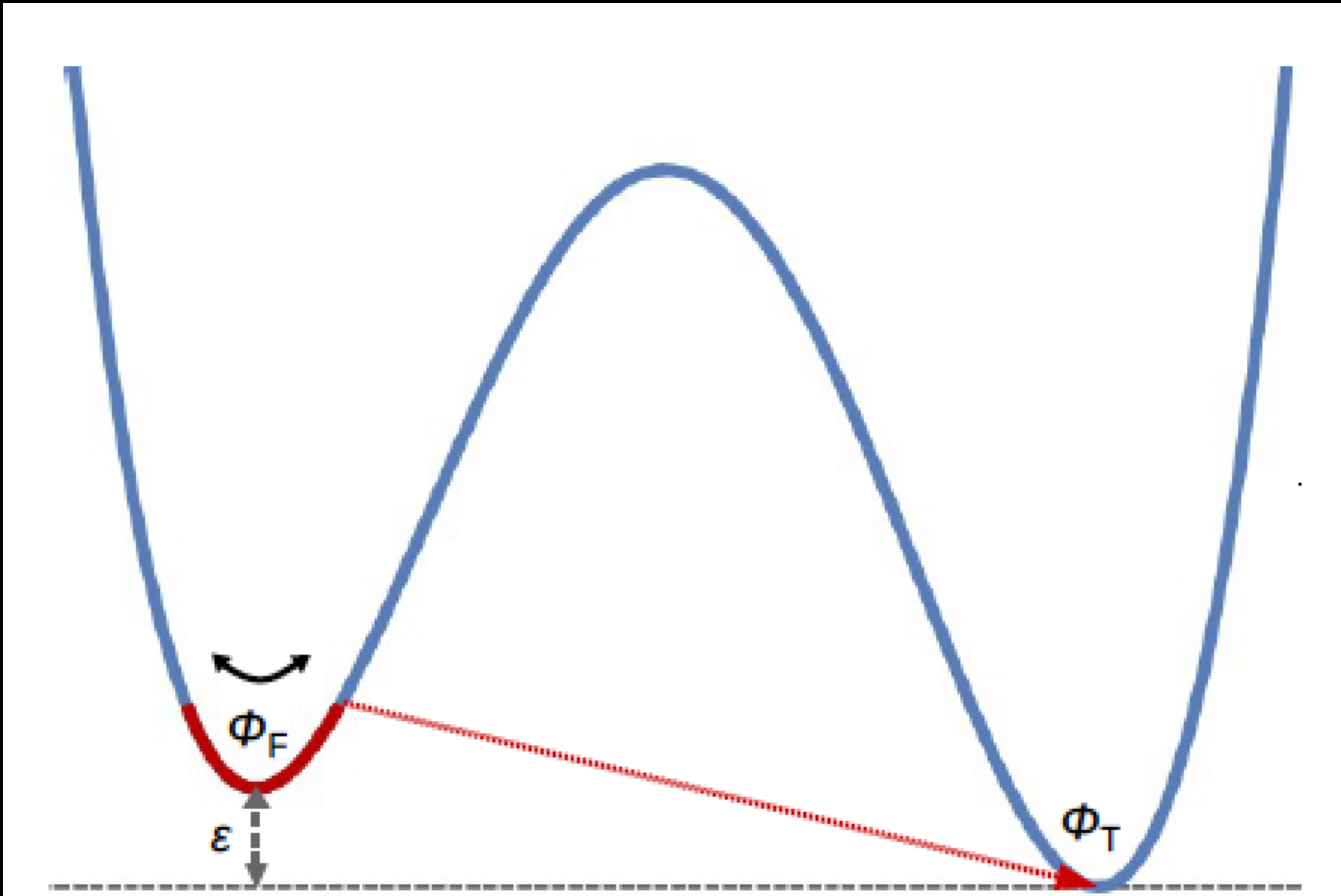


Figure 12: Gravitational wave spectra as in (5.22) with $w = 1/3$. The inflaton mass is fixed to $m \sim 10^{-5} M_p$. Spectra are shown as solid lines for different values of κ, f and T_{RH}: the blue curve is obtained for $\kappa = 5$, $f = 0.1 M_p$, $T_{RH} \sim 10^{12}$ GeV; the brown curve for $\kappa = 10$, $f = 0.01 M_p$, $T_{RH} \sim 10^{11}$ GeV; the red one for $\kappa = 70$, $f = 0.001 M_p$, $T_{RH} \sim 10^{11}$ GeV. We have also taken $w = 1/3, \theta_0 = 10^{-2}, \sigma = 10^{-1}$ in (5.22). For the values of the reheating temperature considered here, we have $g_*(T_{RH}) \sim 10^2$. Sensitivity curves of some ground- and space-based interferometers are shown for comparison as dashed curves (data taken from [74]).

Technical note:

Tunneling from an oscillating vacuum...

Non-trivial initial state



Bubbles can collapse

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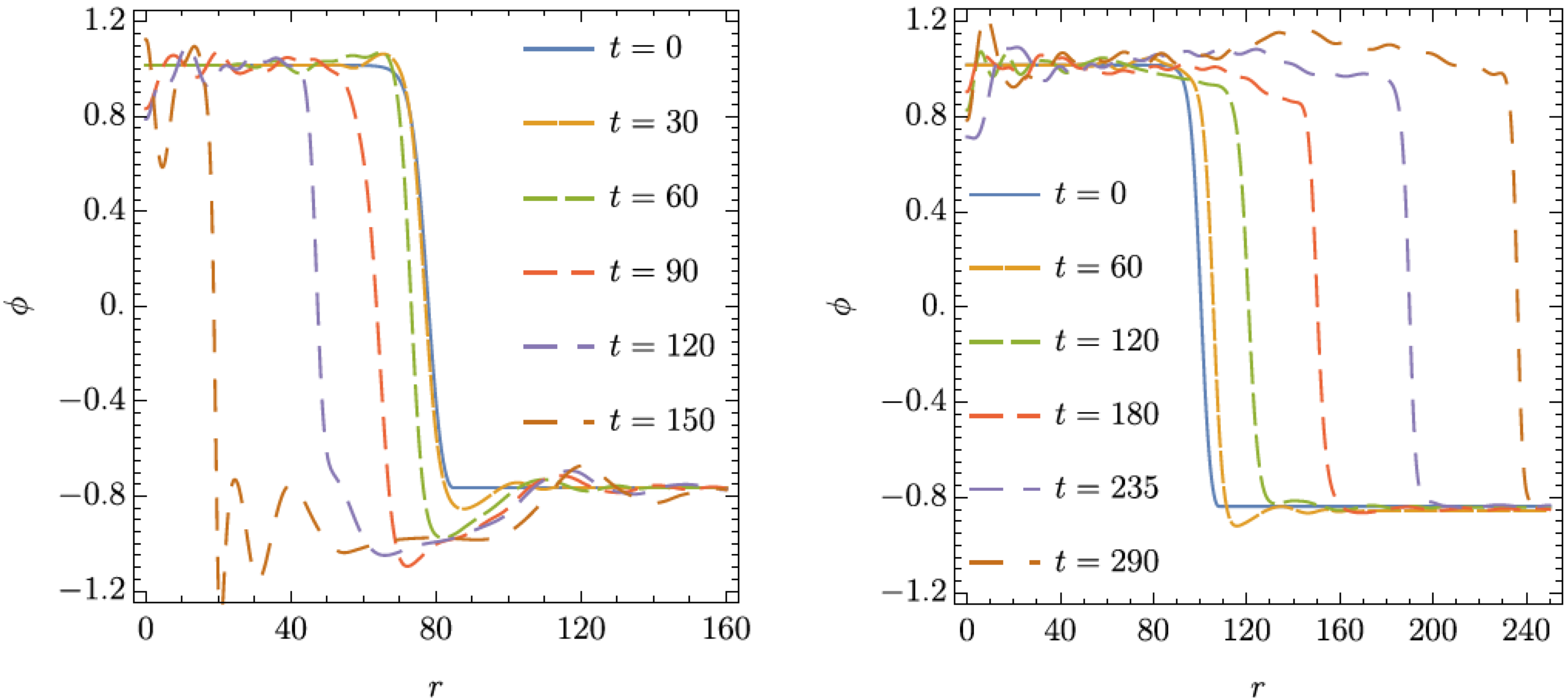

Figure 8: Field profiles showing lattice bubble evolution for oscillation reaching $1.2\sqrt{2\alpha_{\rm tw}}$ (left panel) and $0.8\sqrt{2\alpha_{\rm tw}}$ (right panel). The values defining the potential were set to $g = 1/10$, $b = 1/300$ and $c = 1$.

Another really cool example

Discovering the QCD Axion with Black Holes and Gravitational Waves

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Masha Baryakhtar,[†] and Xinlu Huang,[‡]
Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305, USA

Black Hole Mergers and the QCD Axion at Advanced LIGO

Asimina Arvanitaki,[1,*] Masha Baryakhtar,[1,†] Savas Dimopoulos,[2,‡] Sergei Dubovsky,[3,§] and Robert Lasenby[1,¶]
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[3]*Center for Cosmology and Particle Physics, New York University New York, NY, 10003, USA*

GWs probe axion detectors

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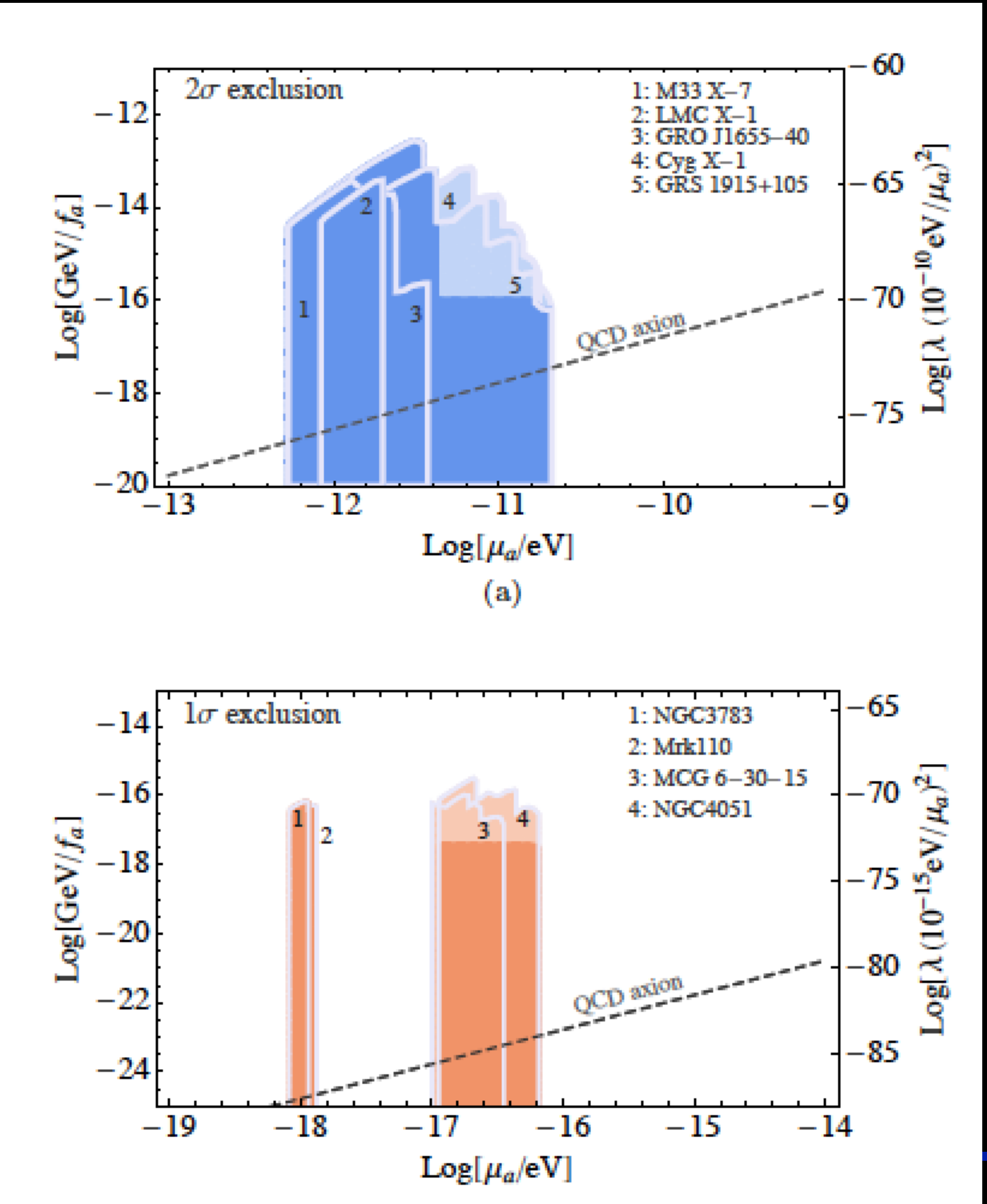
If light bosons

- ➔ superradiance for Spinning Black holes
- ➔ efficient if $R_{BH} \sim 1/m_{Boson}$

- ➔ spin is quickly "used up" to produce bosons
- ➔ Measure spin of black holes (aLIGO, LISA)

Sensitivity to “zero” couplings



Do statistics with aLIGO

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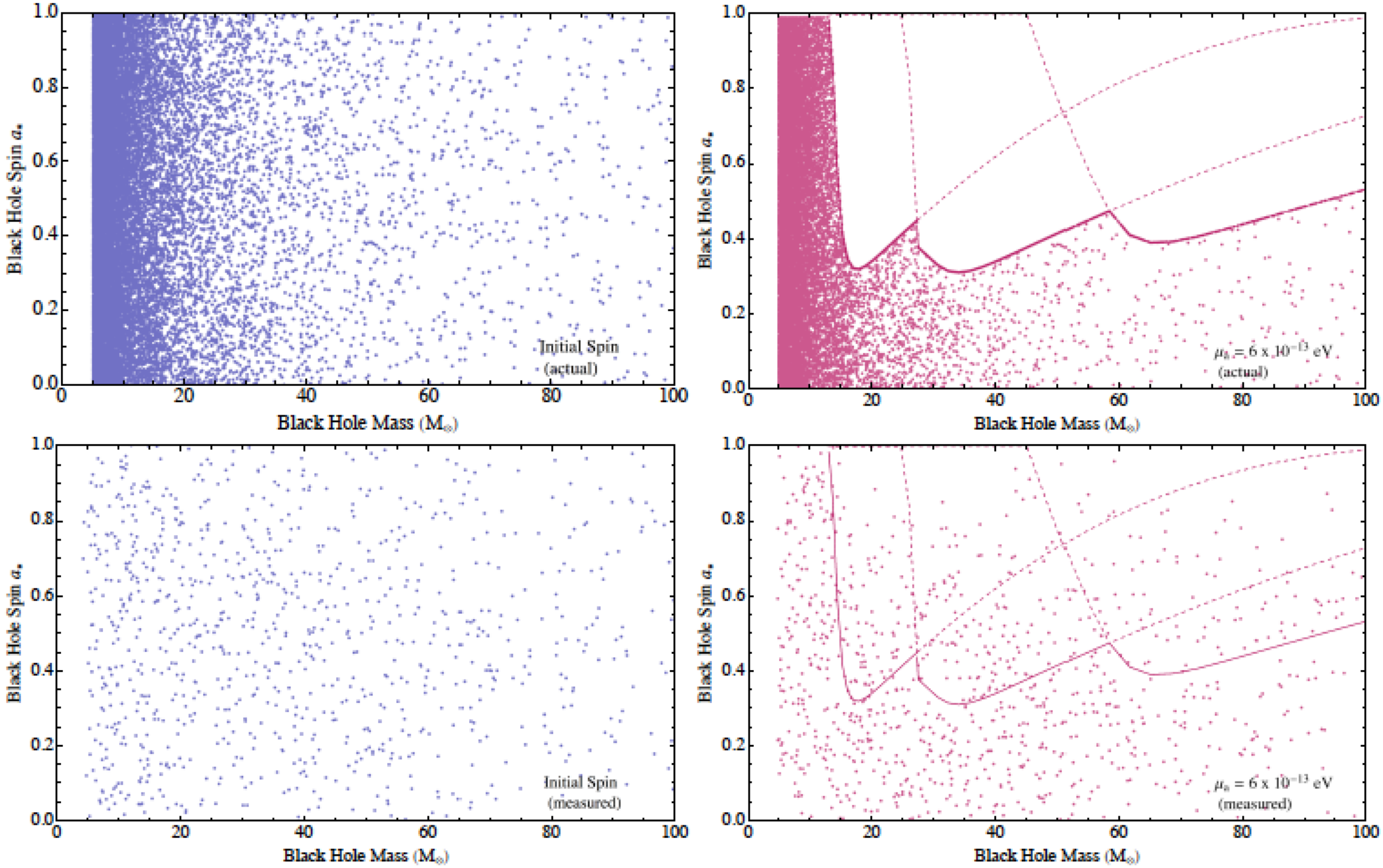

FIG. 2. Expected distribution of intrinsic (top) and measured (bottom) spins and masses of merging BHs in the absence (left) and the presence (right) of an axion of mass 6×10^{-13} eV, normalized to 1000 events detected at aLIGO. We assume $\sigma_M/M \sim 10\%$ measurement error in the mass and $\sigma_{a_*} \sim 0.25$ error in the spin [30, 31]. We have assumed that all BBHs formed at a distance such that they take 10^{10} years to merge. The theoretical curves shown are boundaries of the regions where SR had at most 10^{10} years to spin down the BHs, and the effect of the companion BH does not significantly affect the SR rate.

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More signals…

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Bose enhanced level transitions

➔ Monofrequency signals

Annihilation of bosons into gravitons

➔ Monofrequency signal $\omega=2m_a$

Conclusions

Conclusions

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- Gravitational wave detectors are amazing tools

  → use to learn about dark sectors

- Use to directly search for new particles (Example WISPy domain walls and ultralight bosons such as axions)

- Use gravitational wave signatures to probe dark sectors populated by heavier particles that are hard to detect otherwise

  → Challenge: Need to develop specificity to distinguish different scenarios!


Hidden sector