INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

Probing Particle Physics with Gravitational Wave Detectors

--

A couple of examples

J. Jaeckel[*]

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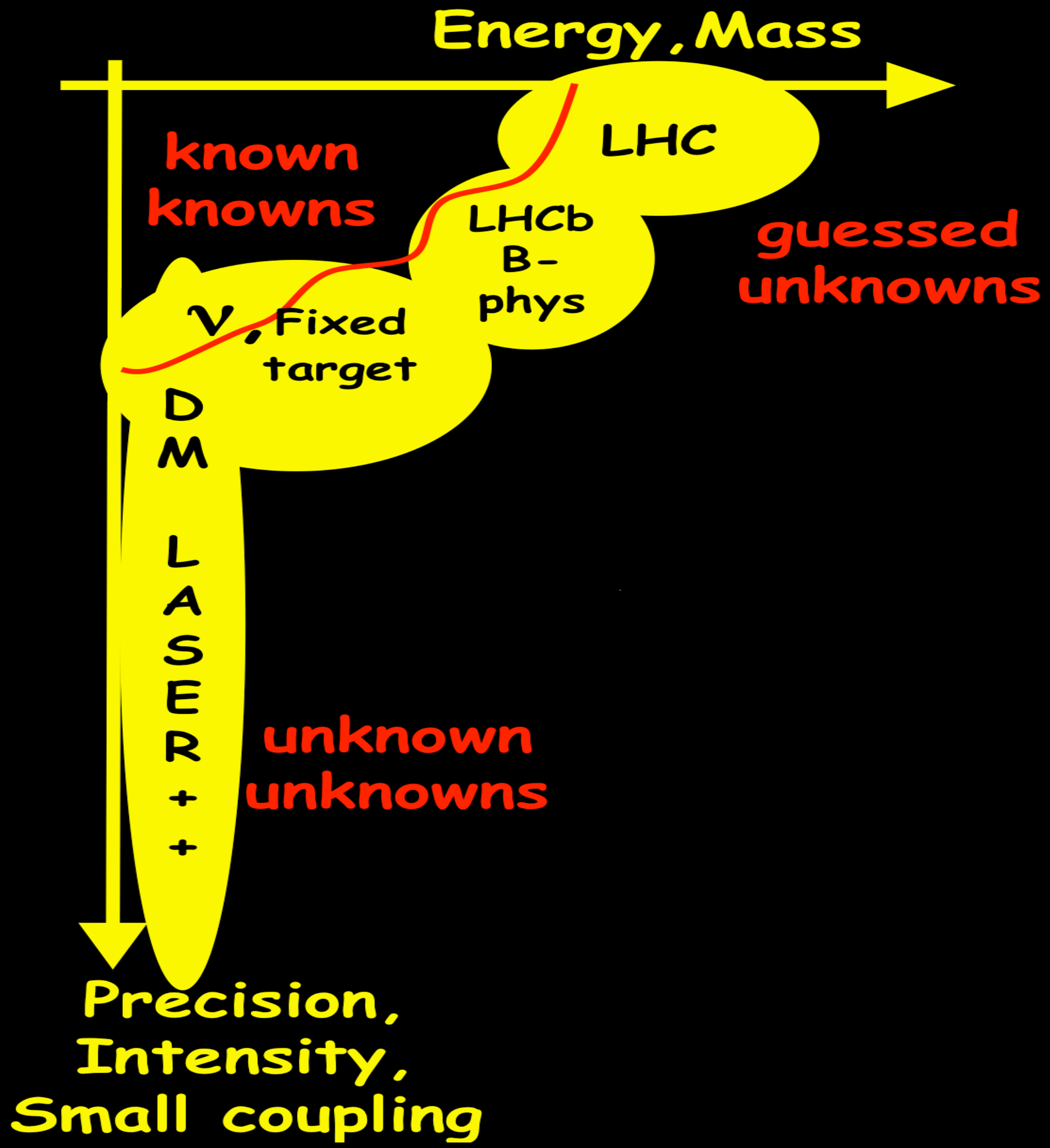
The last weasel that doubted that there is Physics Beyond the Standard Model

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

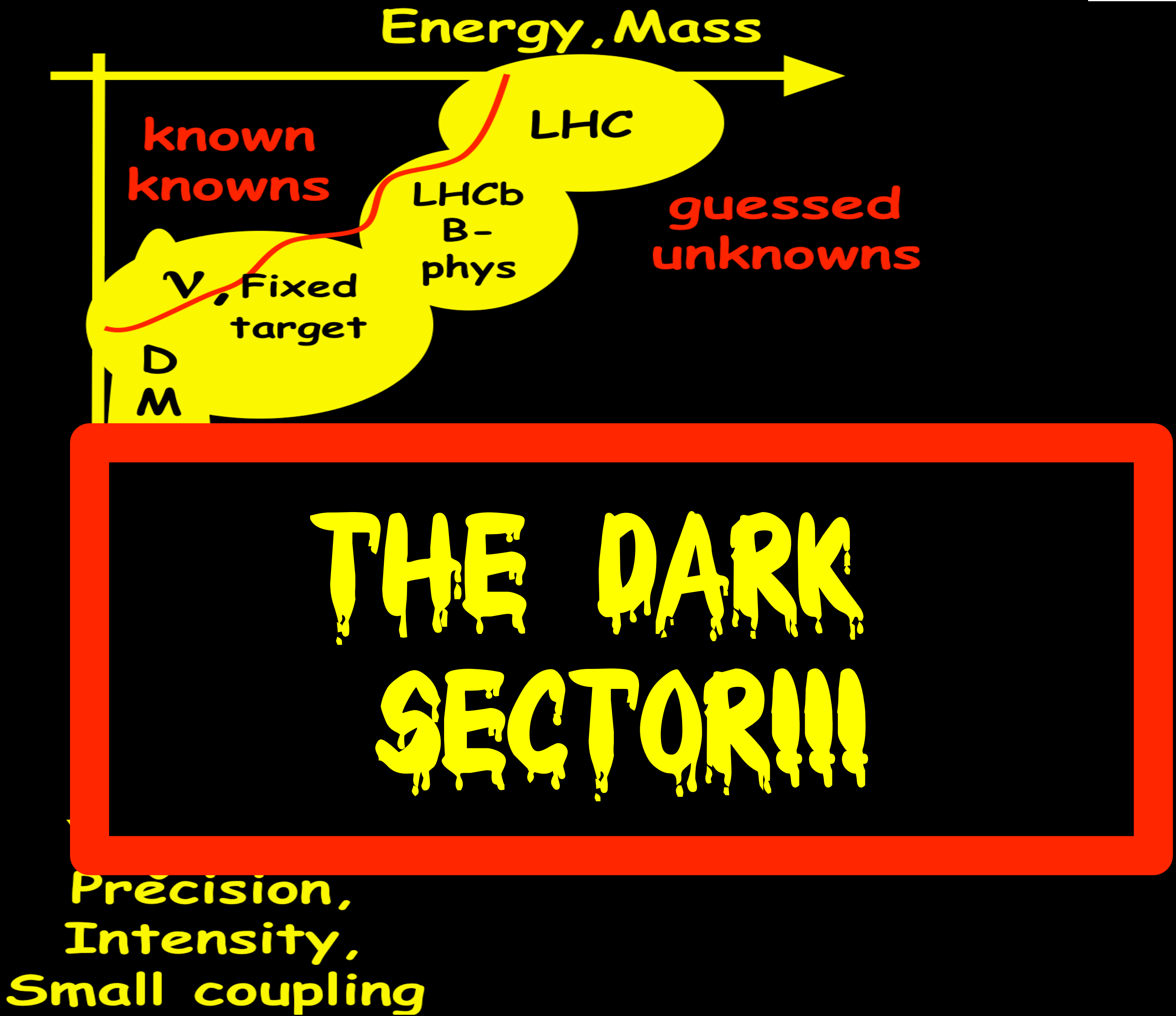
From The Guardian website

Where is the New Physics?

Exploring is (at least) 2 dimensional

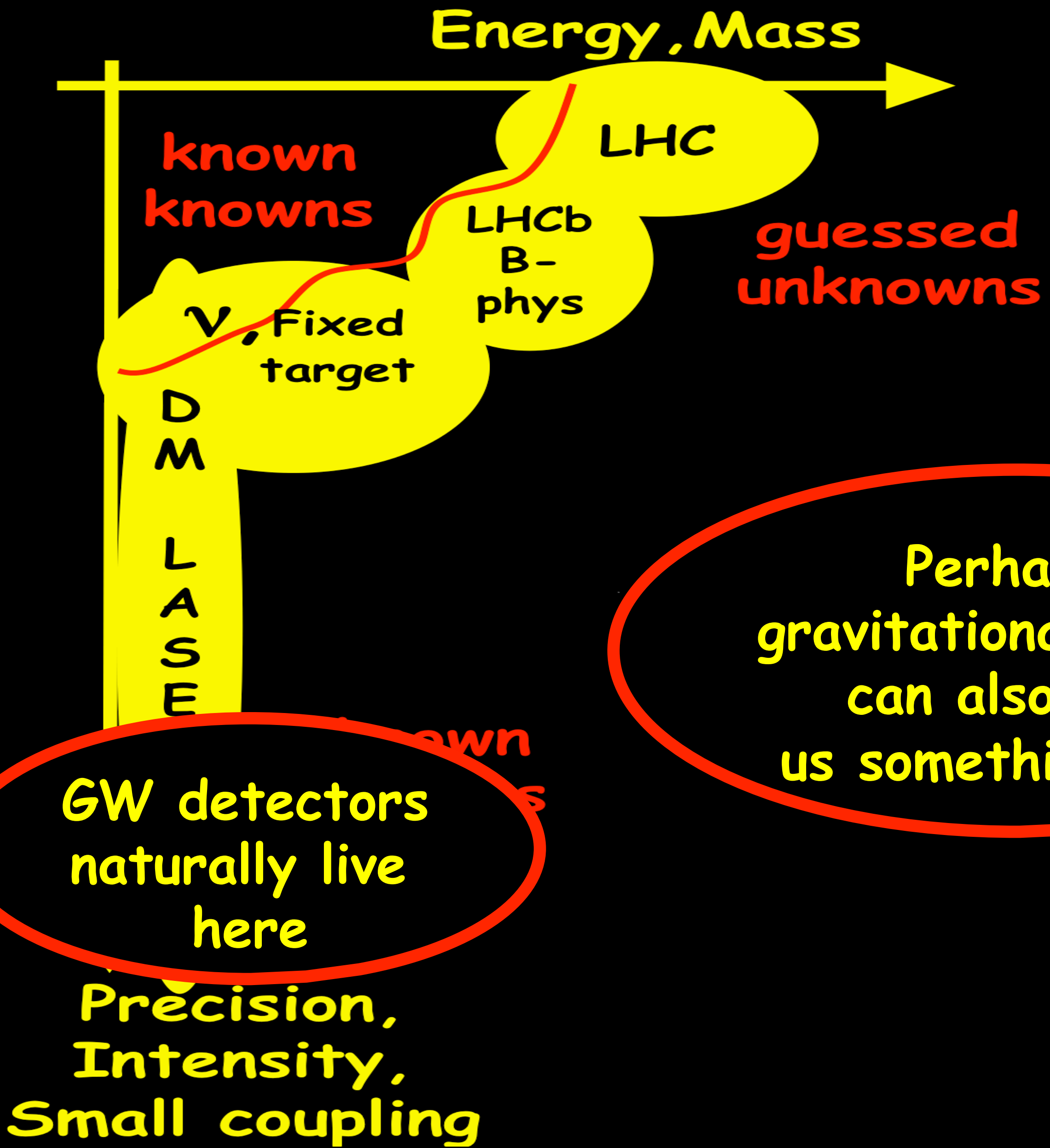


Exploring is (at least) 2 dimensional



THE DARK SECTOR!!!

Using gravitational wave detectors



GW detectors naturally live here

Perhaps gravitational waves can also tell us something here

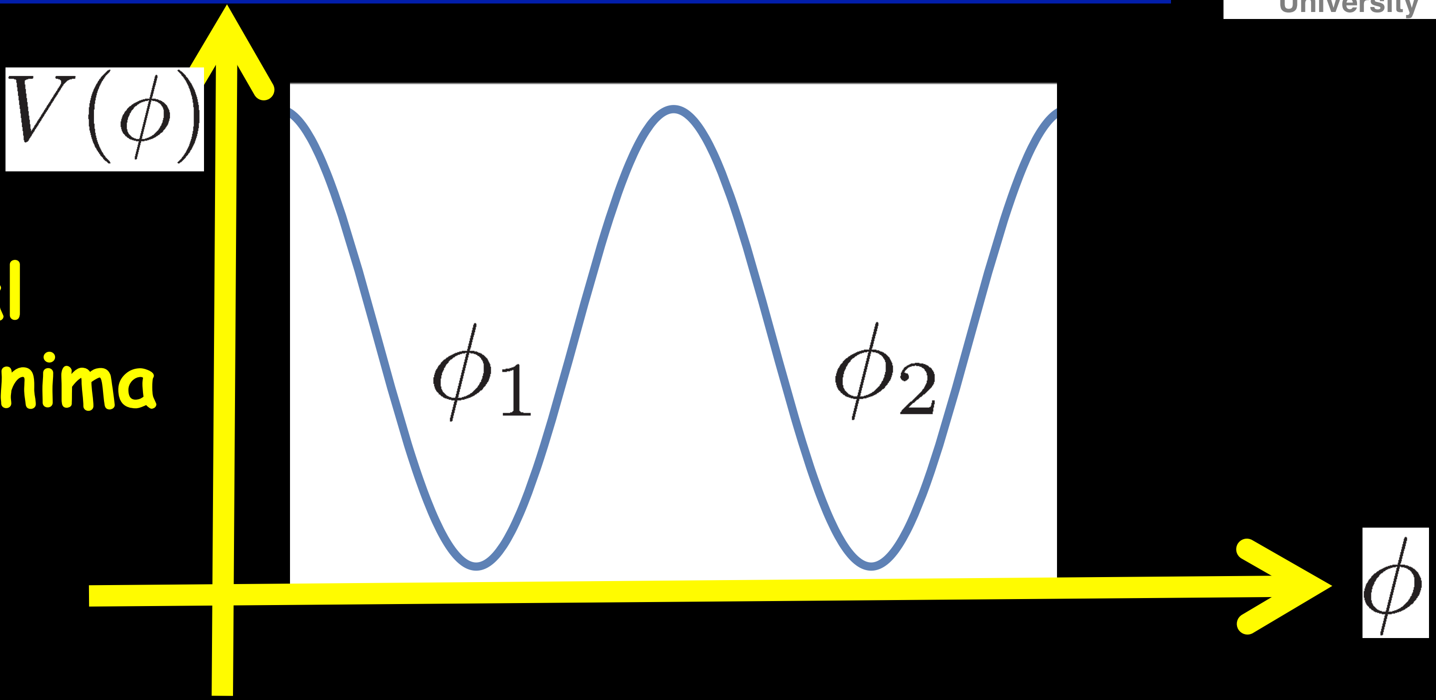
Running through walls

(searching for WISPy domain walls)

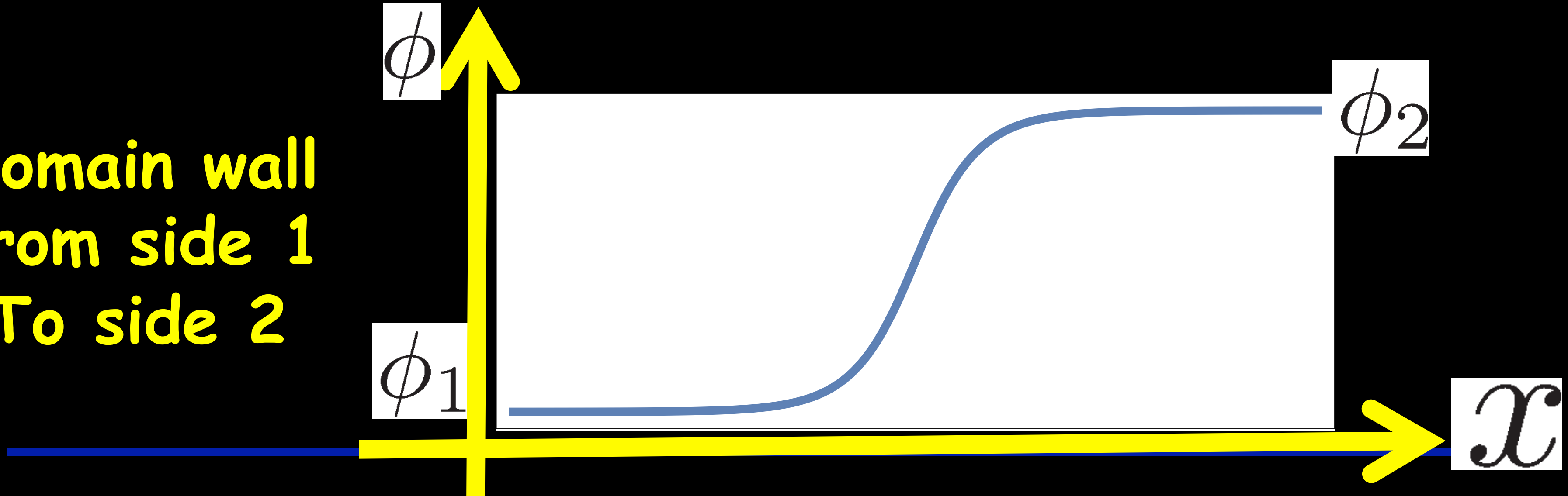
Weakly interacting sub-eV particley

A Domain Wall

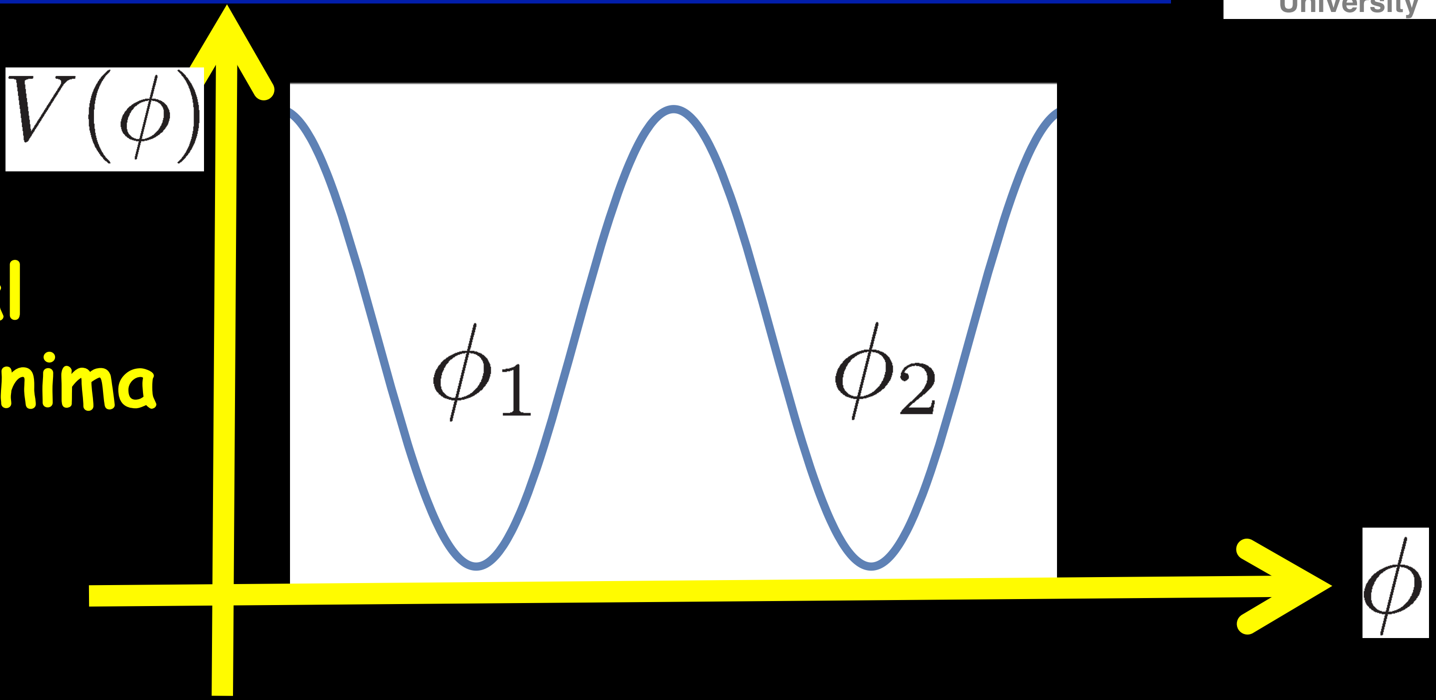
Potential
with two minima



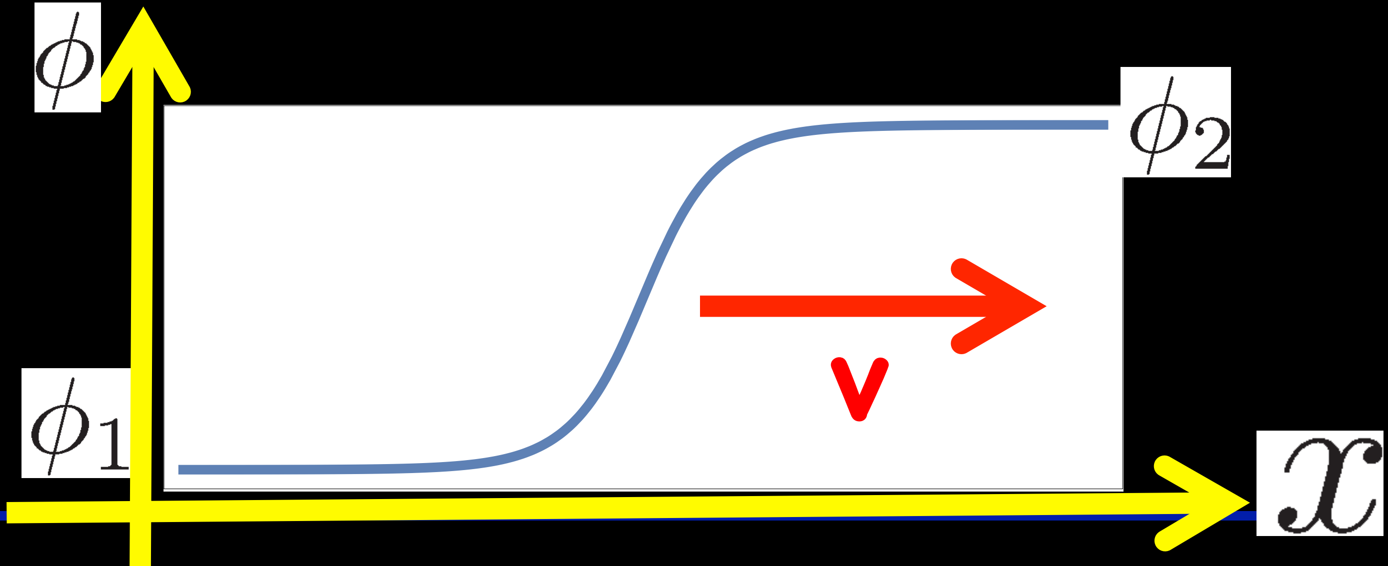
Domain wall
from side 1
To side 2



A Domain Wall



Potential
with two minima



Domain wall
from side 1
To side 2

Adventureous assumption

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

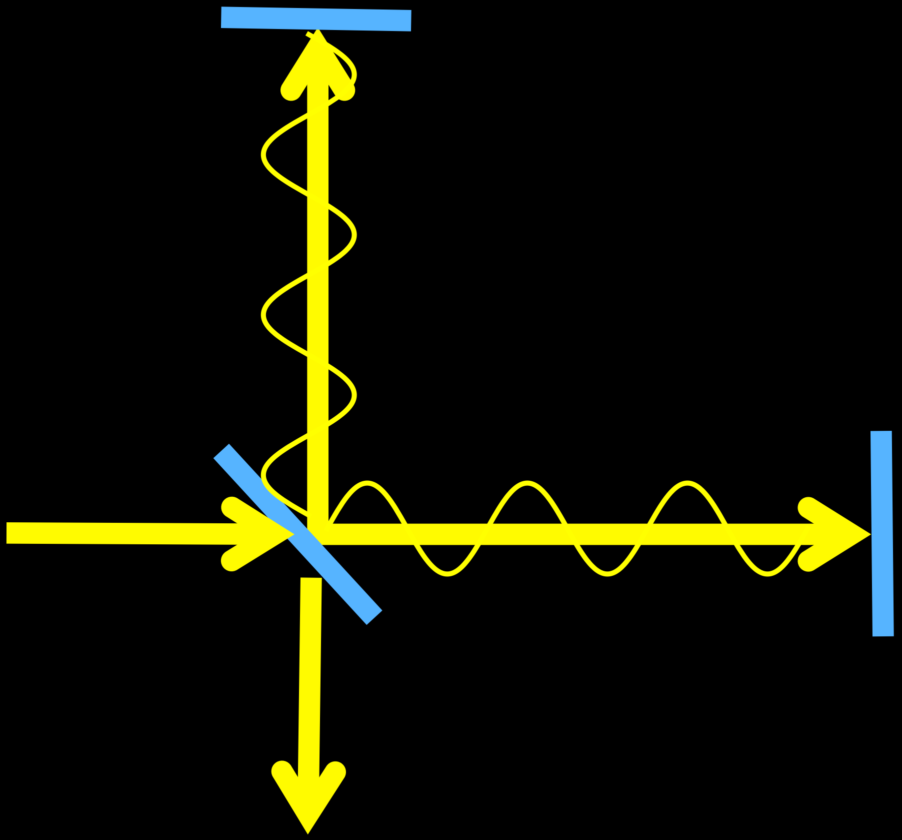
$$\frac{f}{N_\phi} \lesssim \mathrm{TeV} \times \left(\frac{L}{10^{-2}\mathrm{Ly}}\right)^{1/2} \left(\frac{\mathrm{neV}}{m}\right)^{1/2} \left(\frac{\rho_{\mathrm{DW}}}{\rho_{DM}}\right)^{1/2}$$

➔ 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

- 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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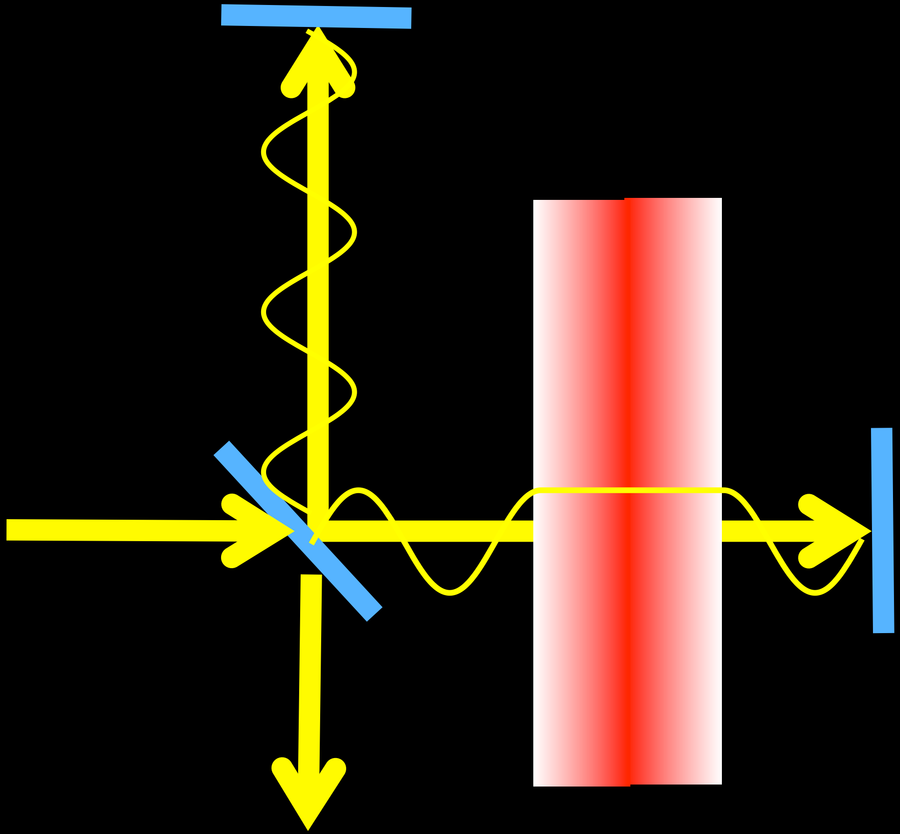


Interference pattern changed

Signal shapes

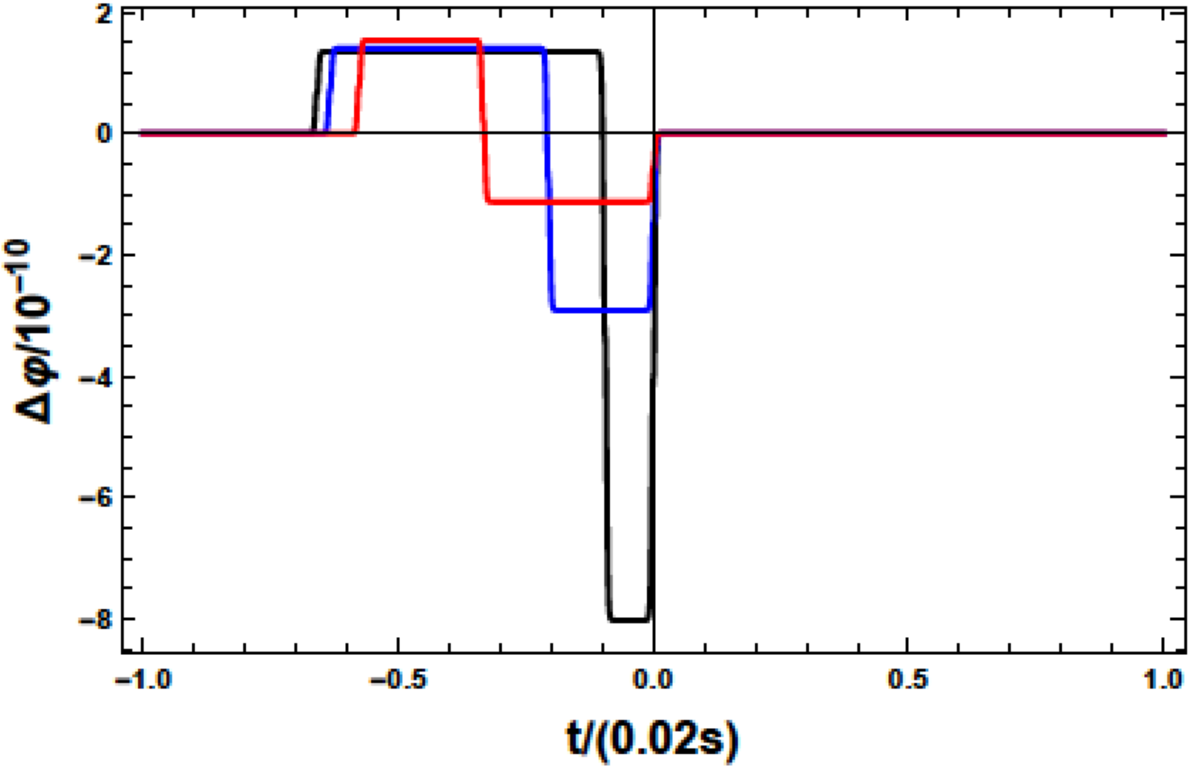


FIG. 6: $L = 4000\,\mathrm{m}$, $\omega \approx 1\,\mathrm{eV}$, $m = 10\,\mathrm{neV}$, $m_{\gamma,0} = 1\,\mathrm{neV}$, $N_A/N_\phi = 1$, $\alpha = \pi/2.2, \pi/2.5, \pi/3$ (black, blue, red), v chosen such that signal has roughly a length of $0.02\mathrm{s} \sim 1/(50\,\mathrm{Hz})$ this corresponds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

Signal shapes

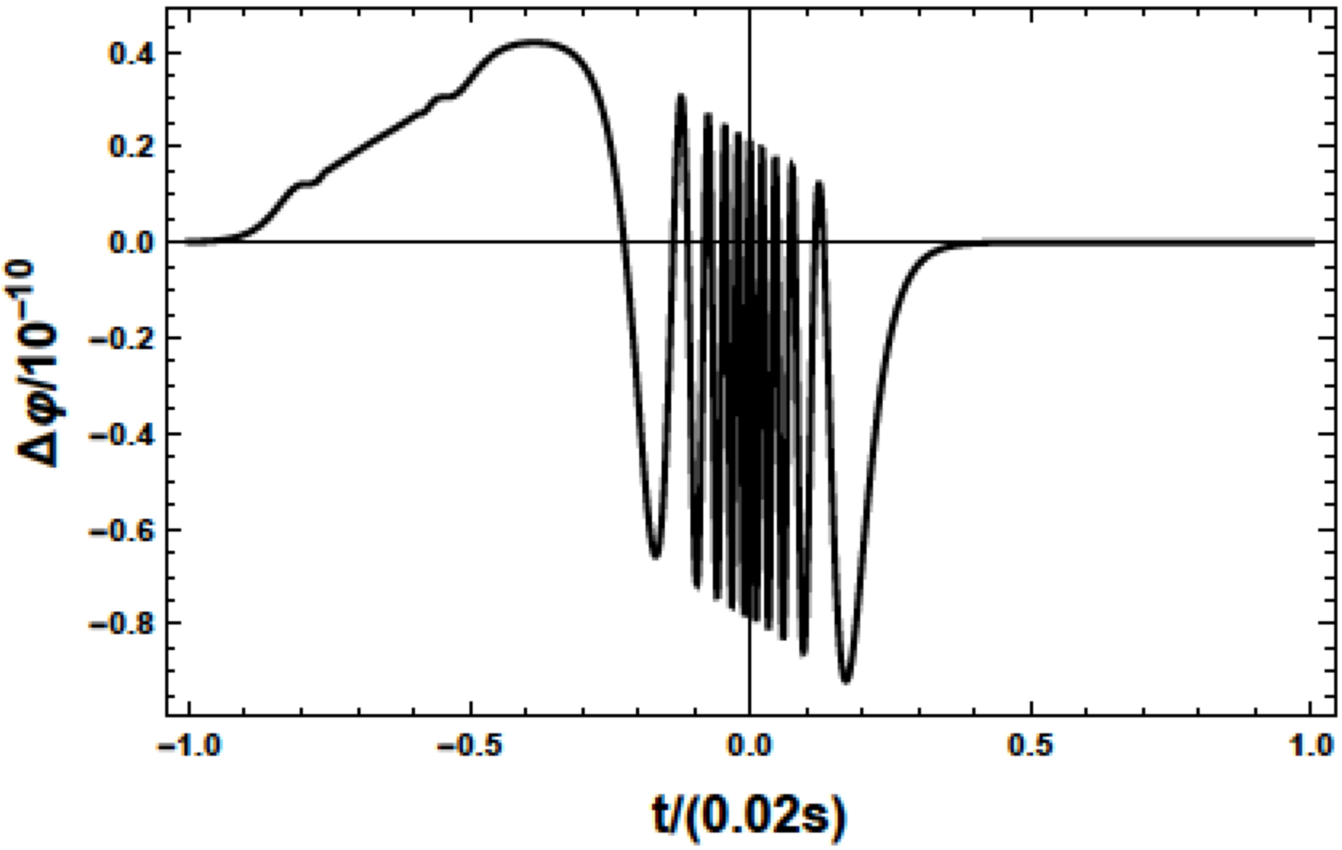


FIG. 8: As in Fig. ?? but $m_{\gamma,0} = 0.1\,\mathrm{neV}$, $N_A/N_\phi = 5$, $m = 0.5\,\mathrm{neV}$, $\alpha = \pi/2$ and $v = 1 \times 10^{-3}$.

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:

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

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

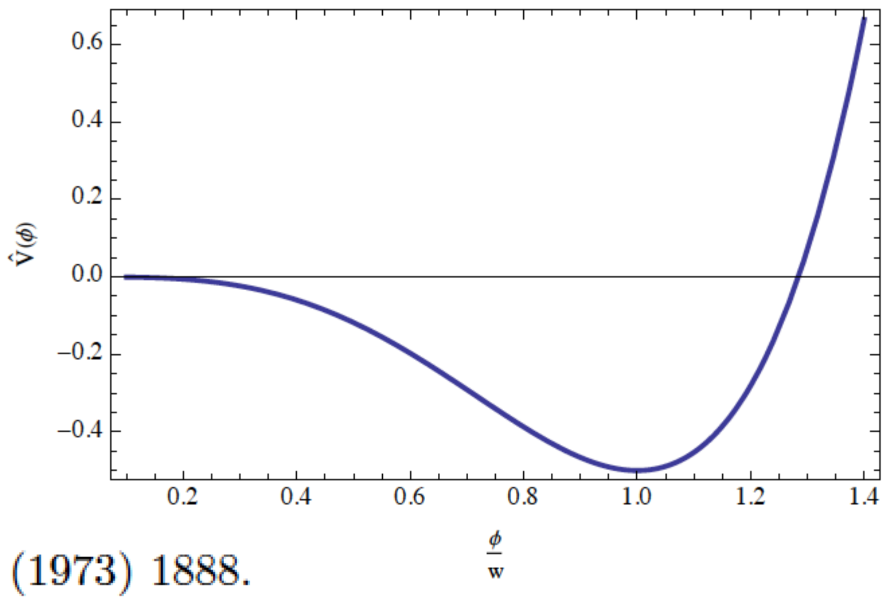
- Scale invariance

➔ No explicit mass scales in the Lagrangian

- EW symmetry breaking?

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

Works
at 1-loop level!



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

Need dark=hidden sector

- 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

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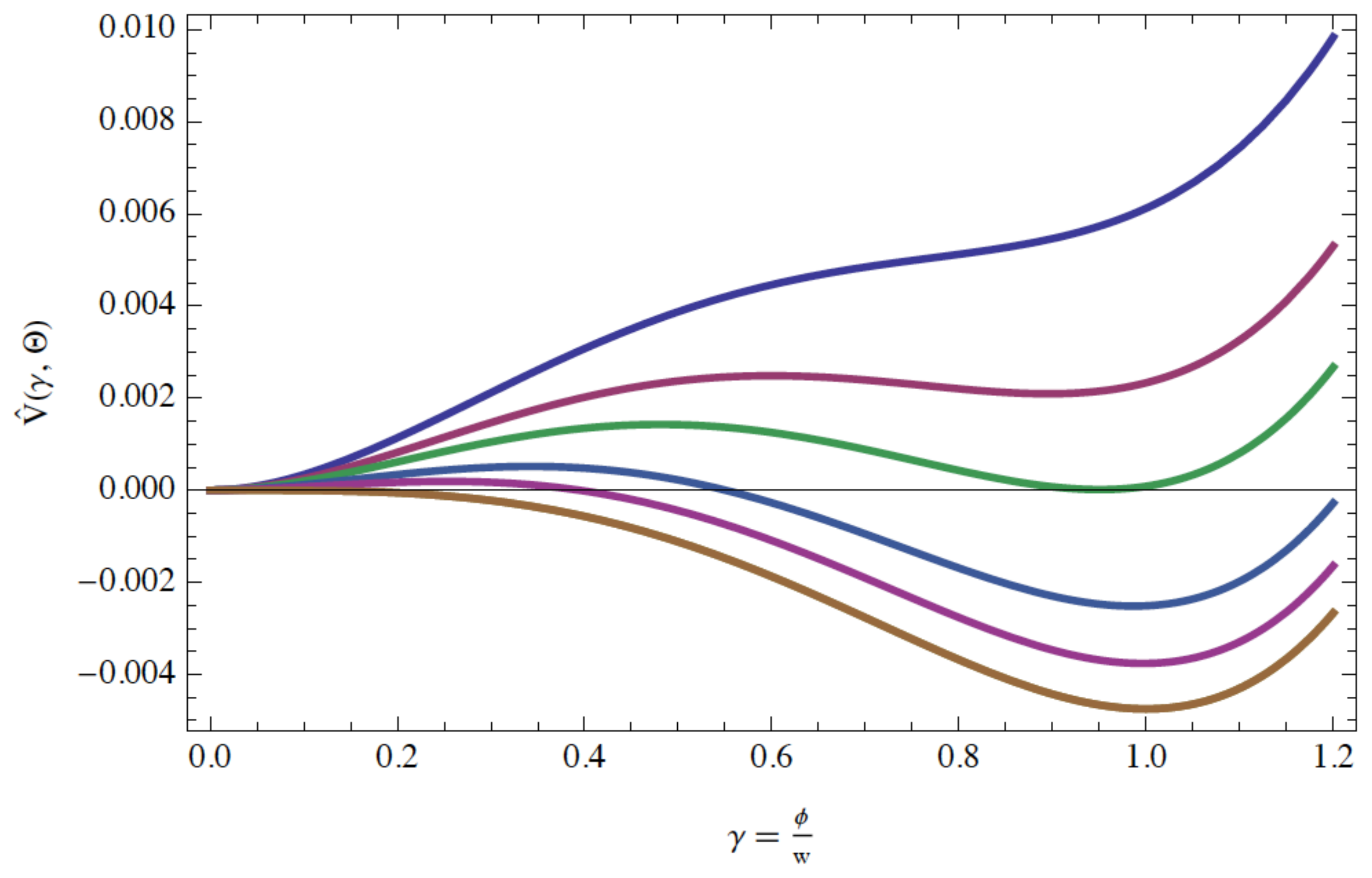

→ First order phase transition

→Bubble formation

→Gravitational waves

Detectable gravitational waves

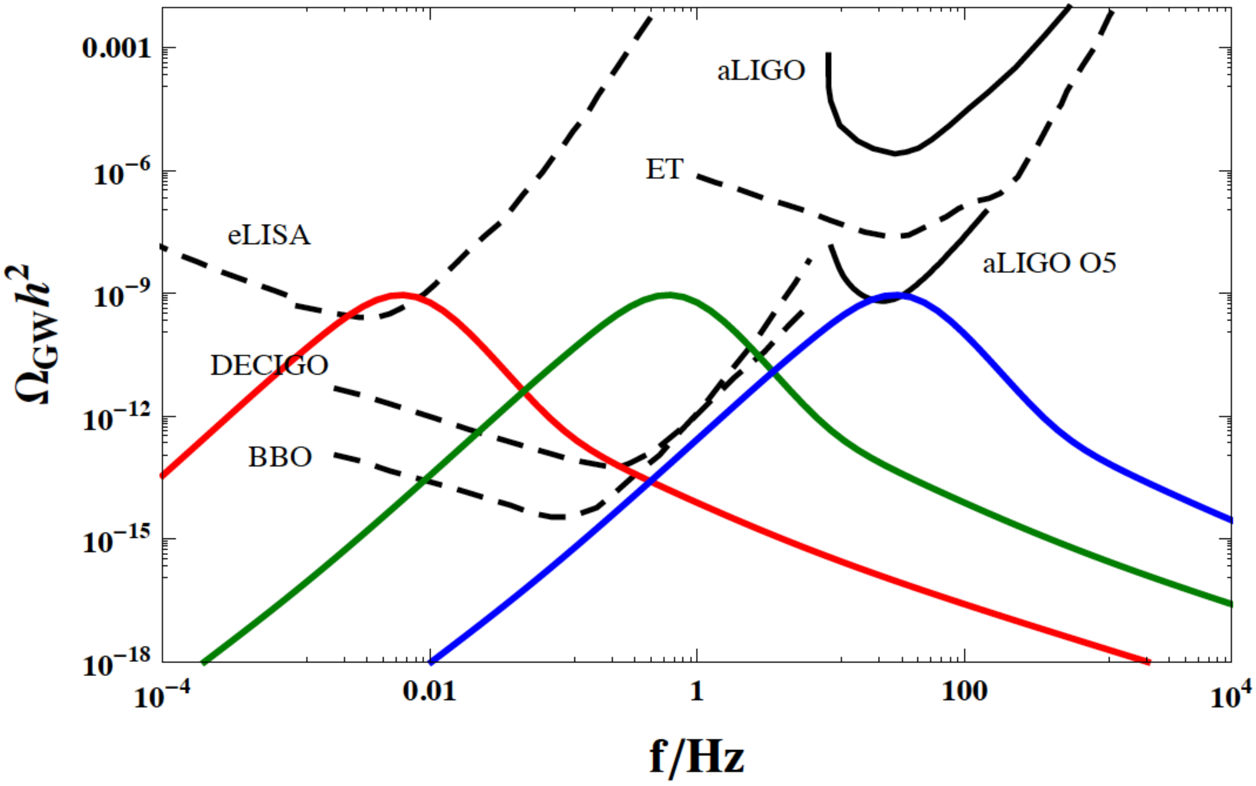

FIG. 6: Reach of gravitational wave detectors: We show aLIGO together with the fifth phase of aLIGO (both solid black), and the proposed detectors BBO, DECIGO, ET and eLISA [dashed black] (the sensitivities are taken from the gravitational wave plotter http://rhcole.com/apps/GWplotter/ [29]). For the 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

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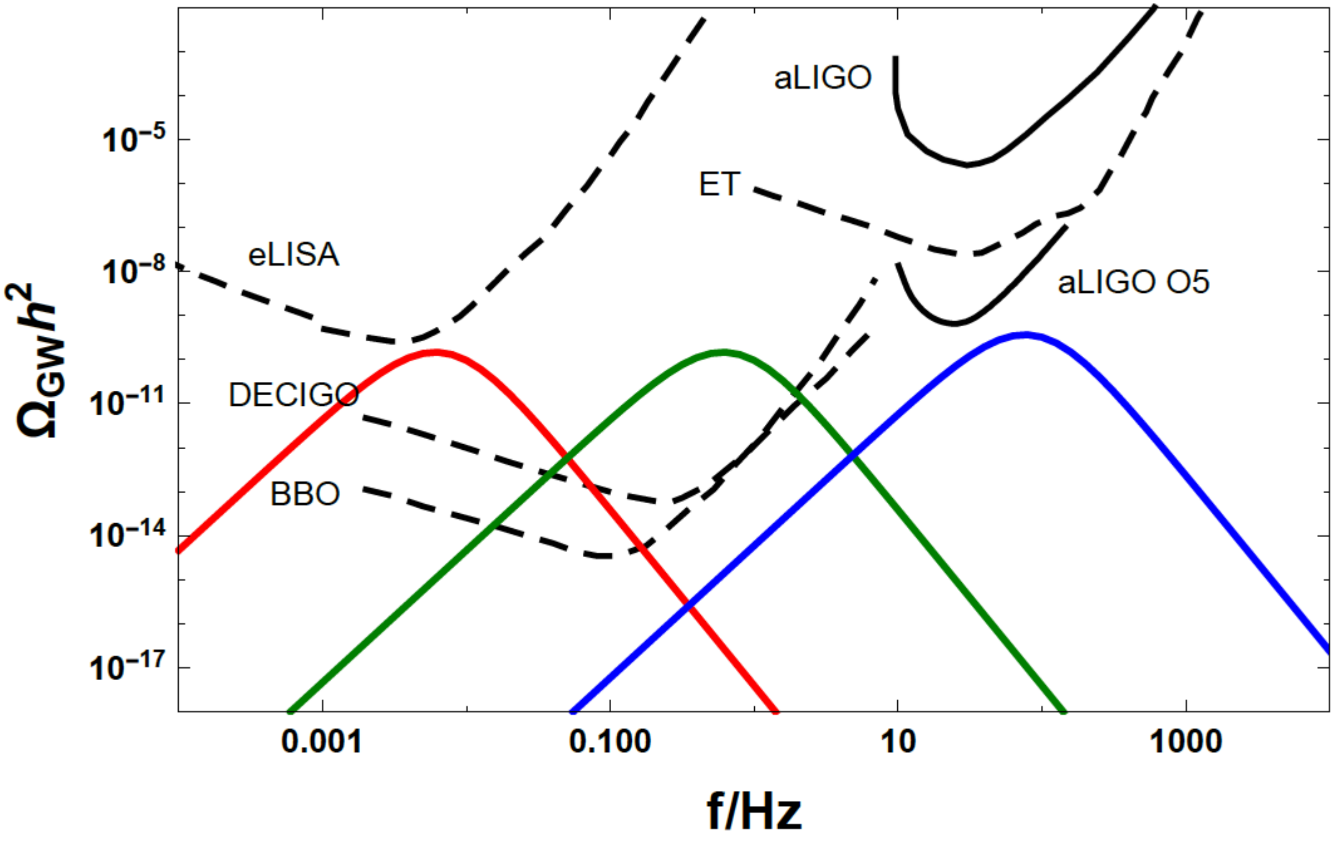
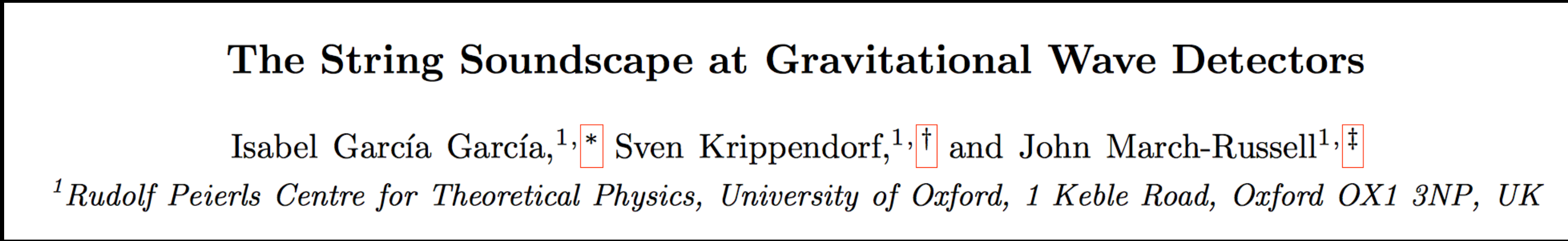


FIG. 7: Reach of gravitational wave detectors for a more conservative scenario $\kappa_{sw} = 0.4$ (all other parameters as in Fig. 6).

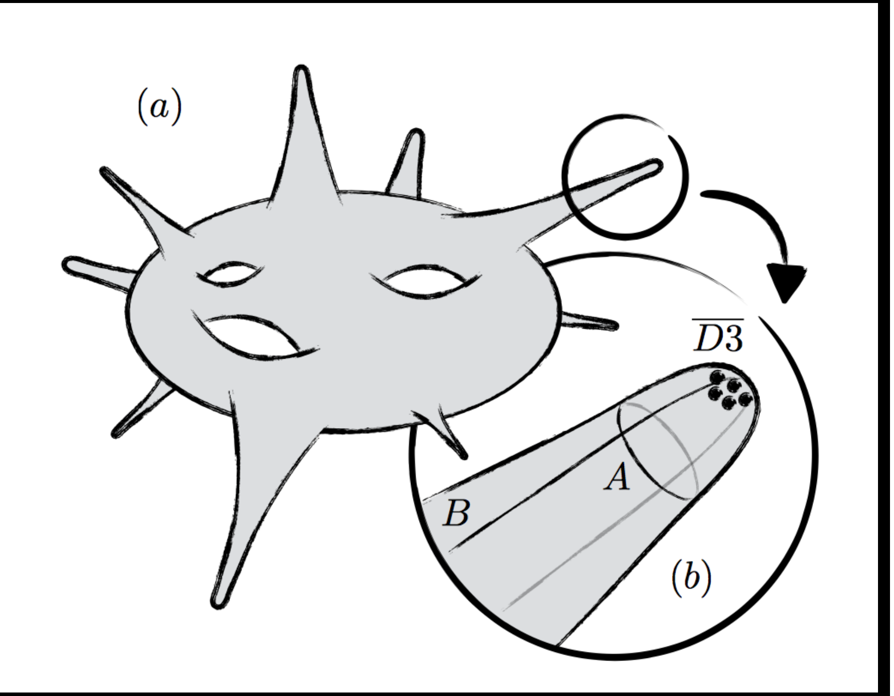
Example I b:
Deep Throats

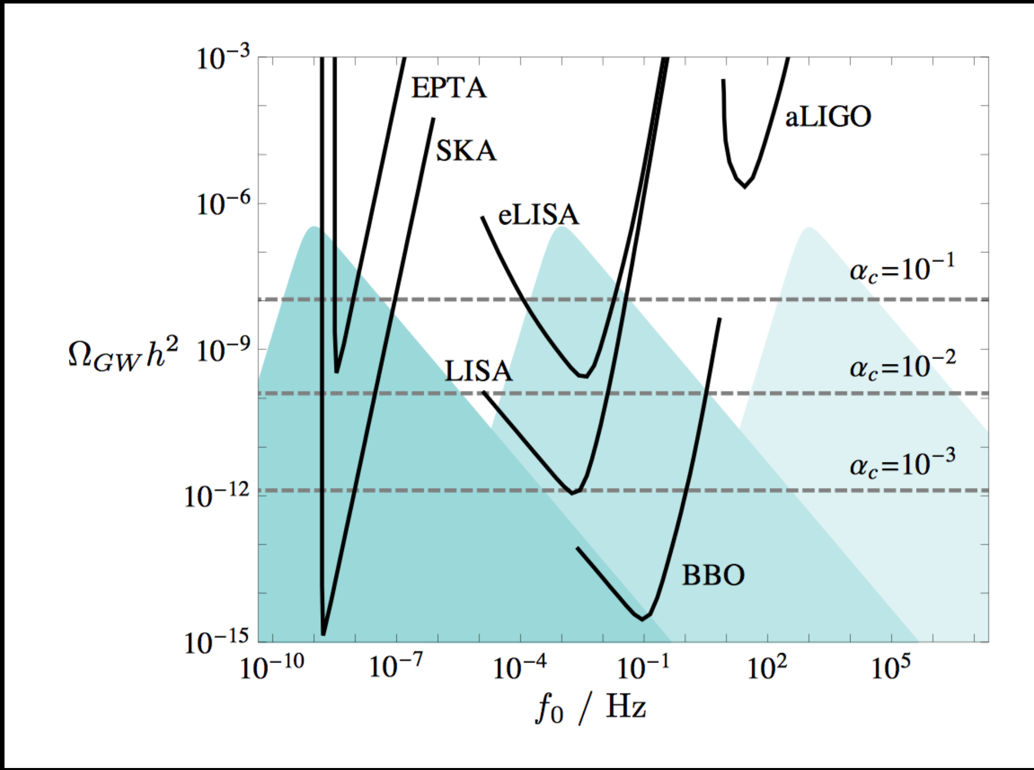


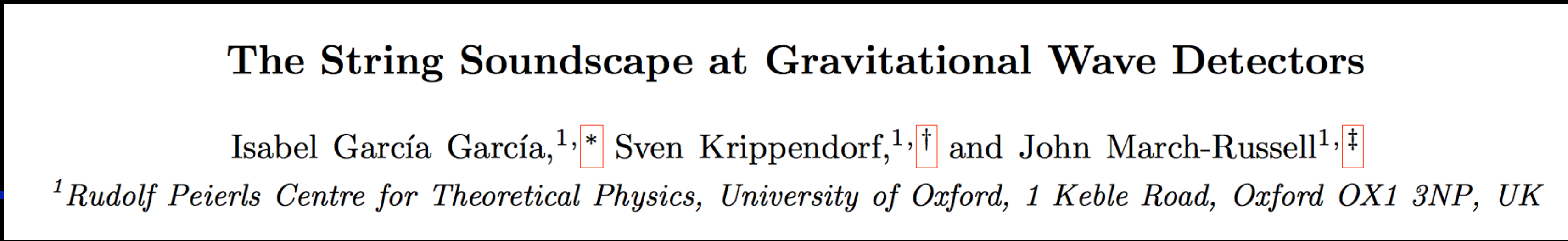
The String Soundscape at Gravitational Wave Detectors

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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Exploring heavier dark sectors with gravitational waves

Example II:
GW Waves from Monodromy Inflation

Monodromy potential

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

Monodromy add-on

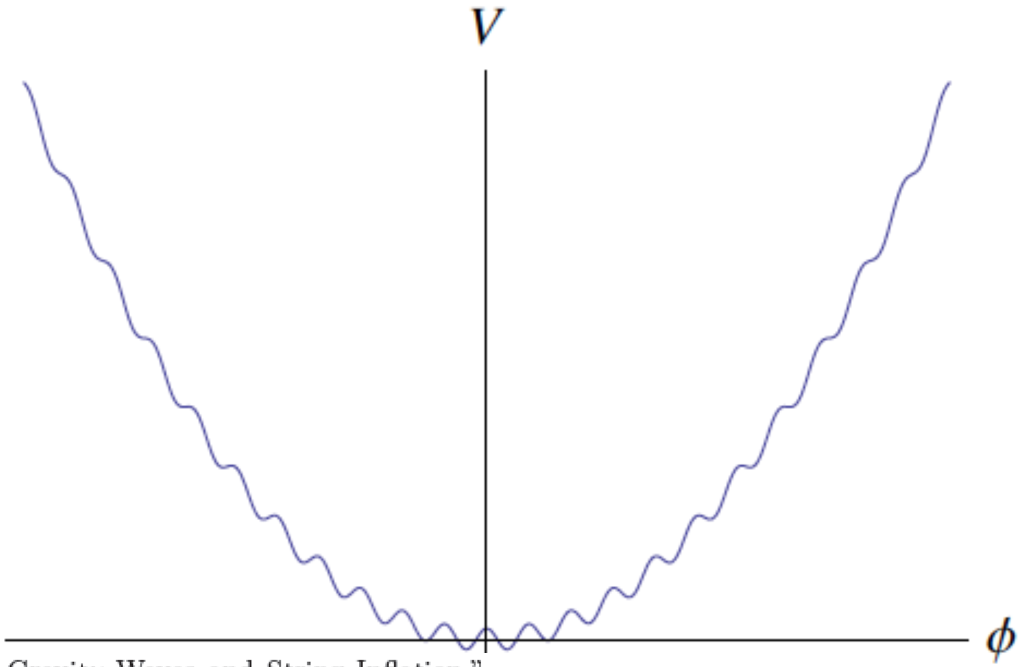
“Axion” potential
(pseudo-Goldstone pot.)

Monodromy potential

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

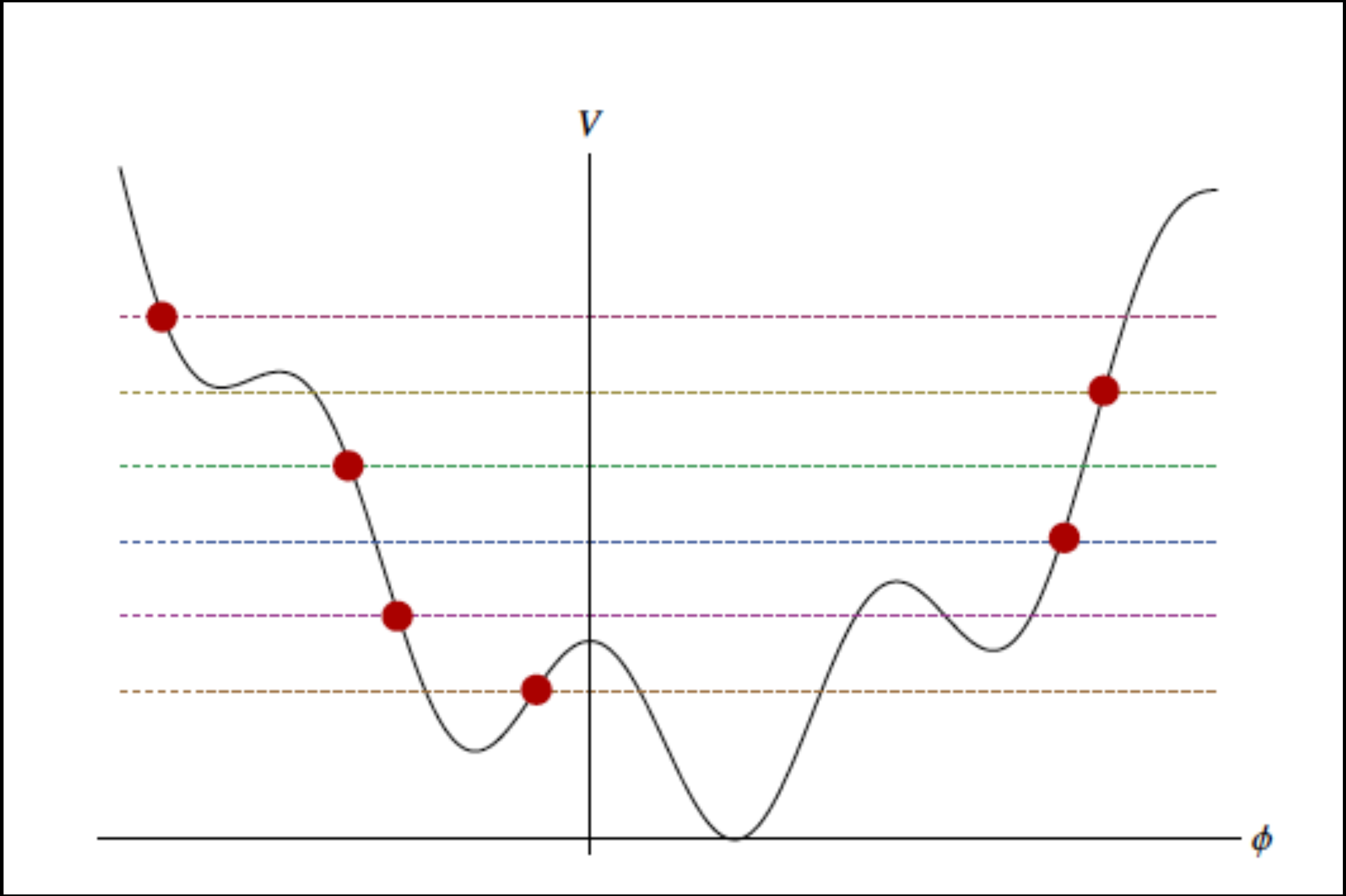
Funny potential

+ enlarged field range

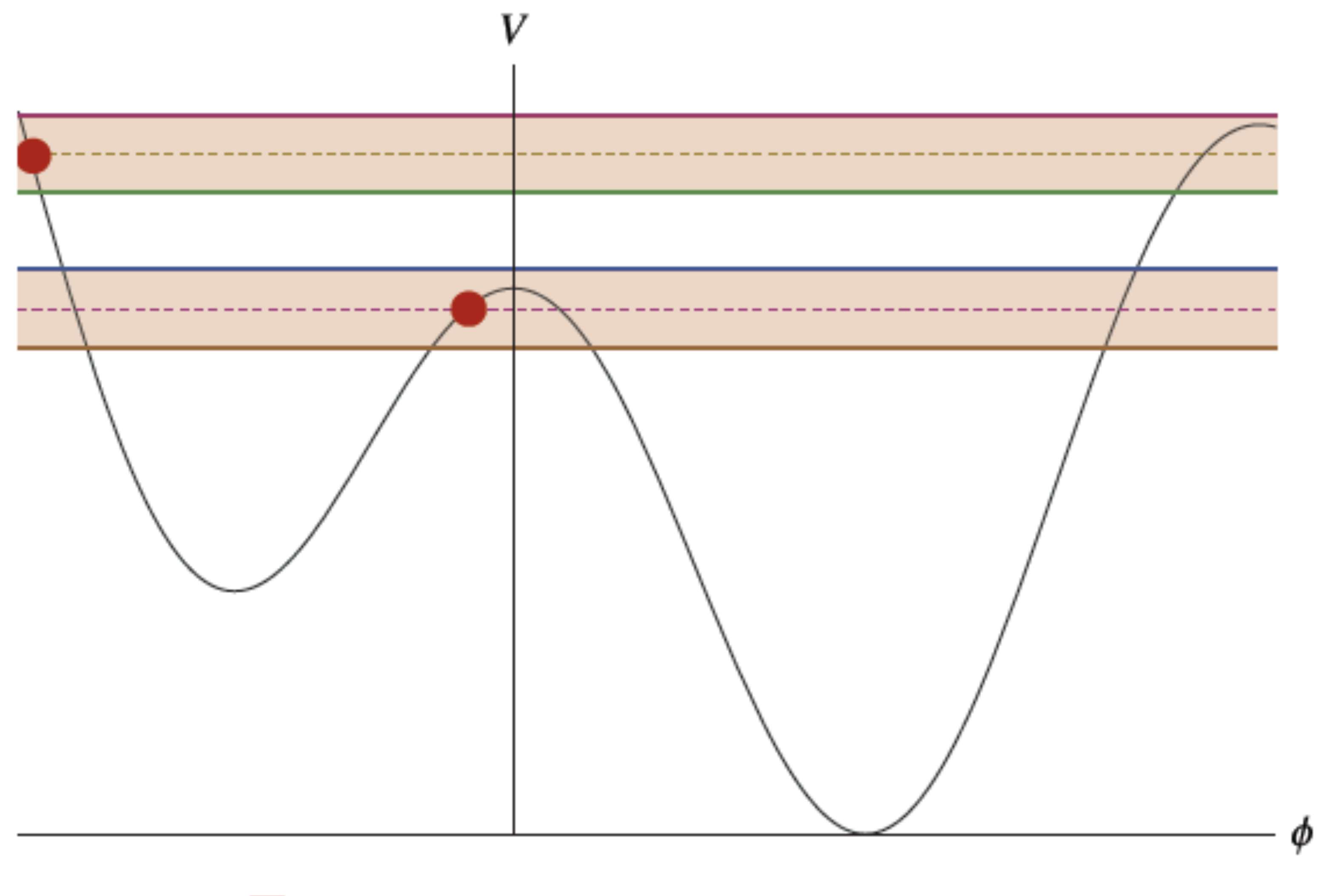


E. Silverstein and A. Westphal, "Monodromy in the CMB: Gravity Waves and String Inflation," Phys. Rev. D **78**, 106003 (2008) doi:10.1103/PhysRevD.78.106003 [arXiv:0803.3085 [hep-th]].

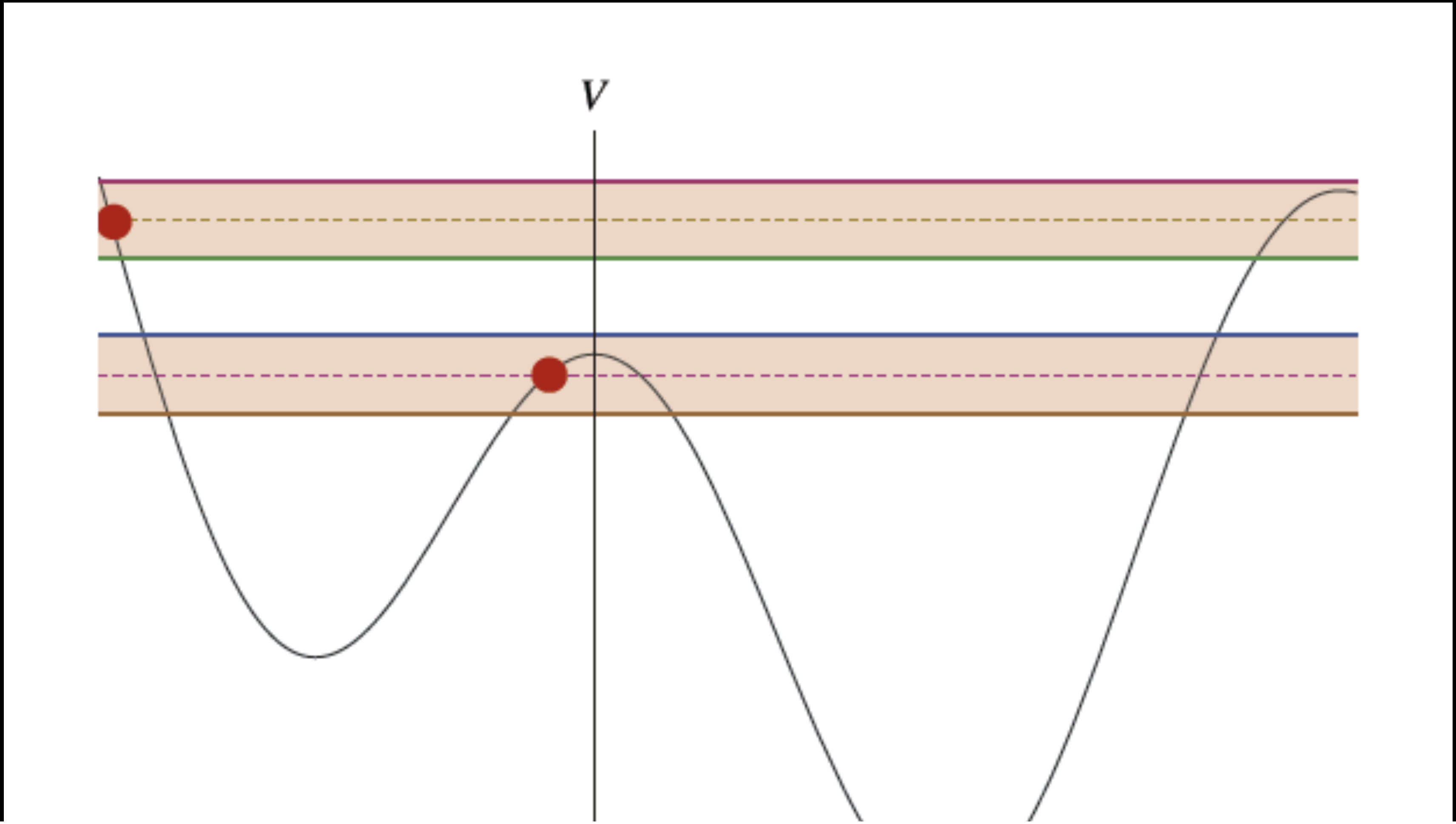
Field oscillations



Including fluctuations



Including fluctuations



Different parts of Universe end in different minima

➔ Bubbles form

➔ GW are produced

Gravitational wave spectra

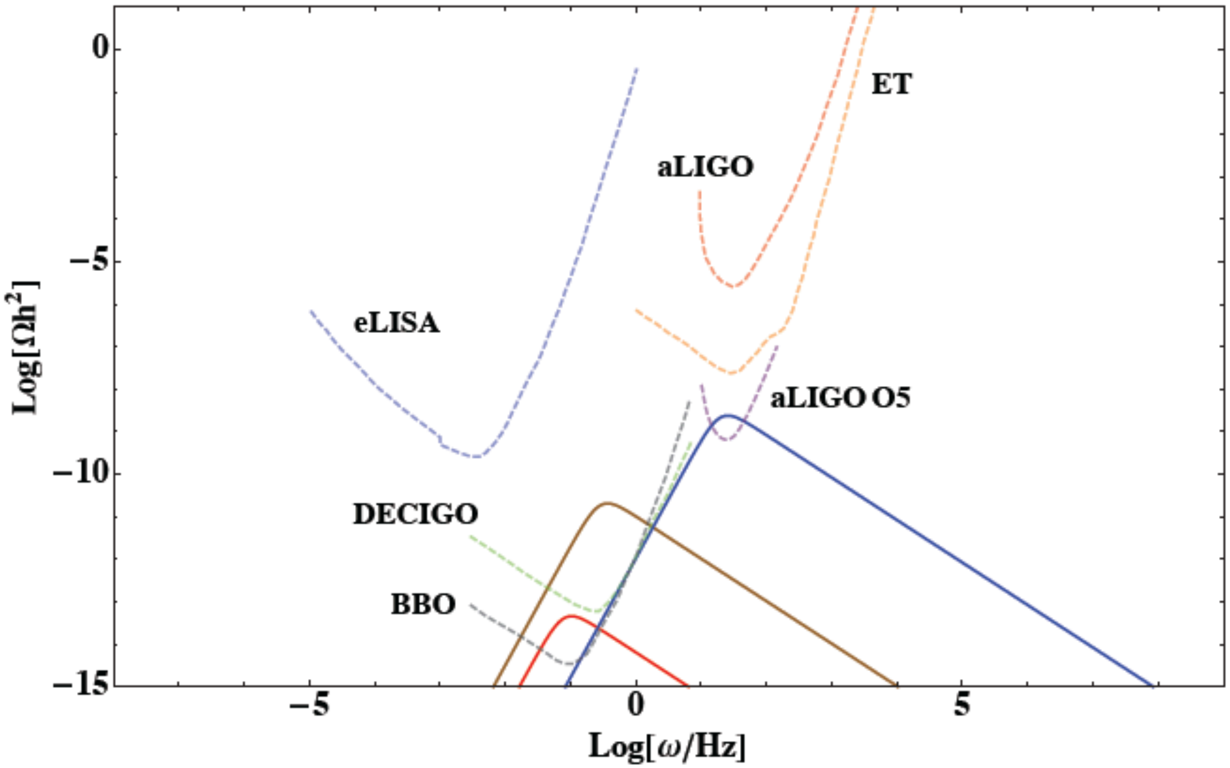
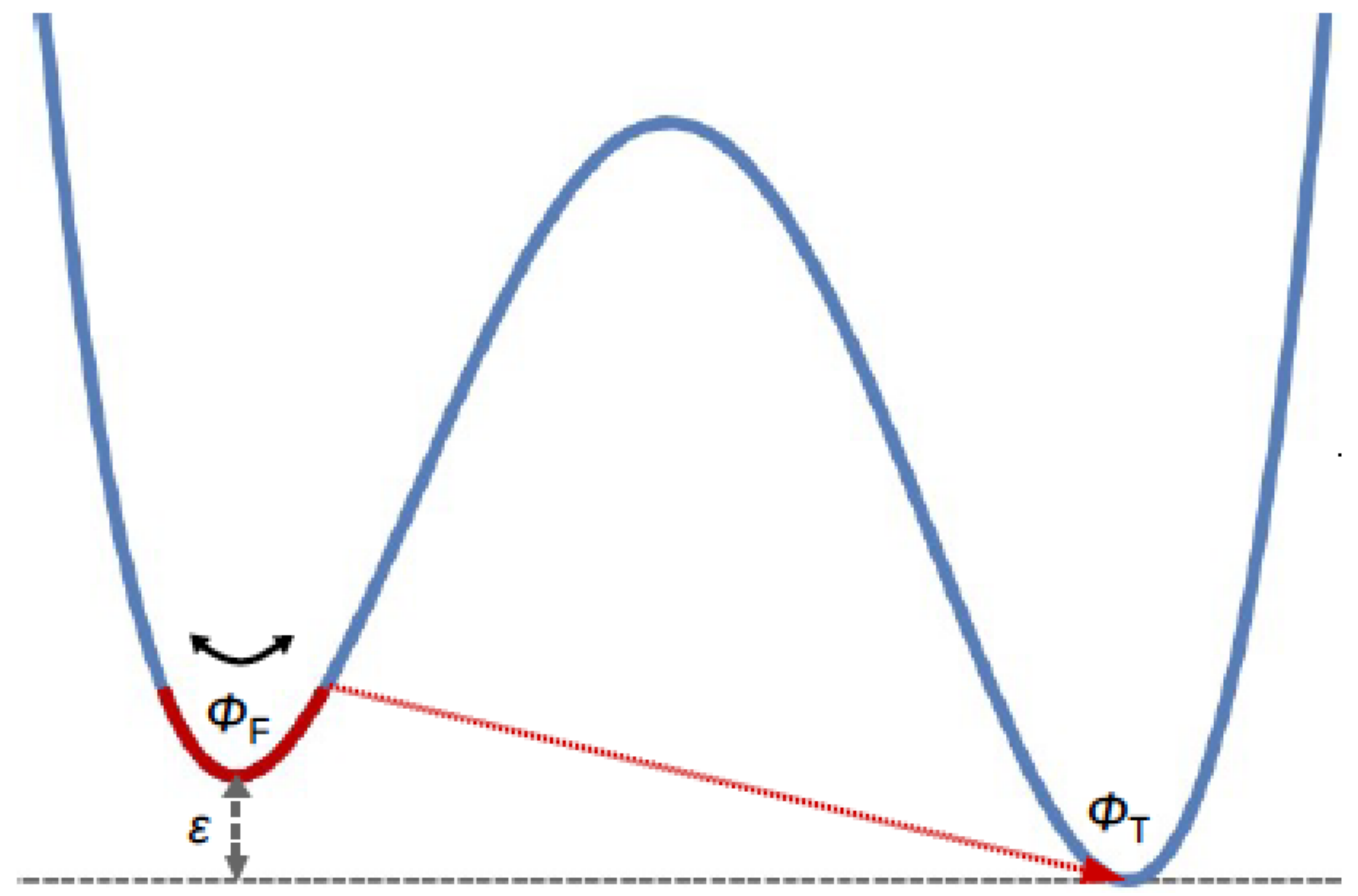


Figure 12: Gravitational wave spectra as in (5.22) with $w = 1/3$. The inflaton mass is fixed to $m \sim 10^{-5} M_p$. Spectra are shown as solid lines for different values of κ, f and T_{RH}: the blue curve is obtained for $\kappa = 5$, $f = 0.1 M_p$, $T_{RH} \sim 10^{12}$ GeV; the brown curve for $\kappa = 10$, $f = 0.01 M_p$, $T_{RH} \sim 10^{11}$ 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

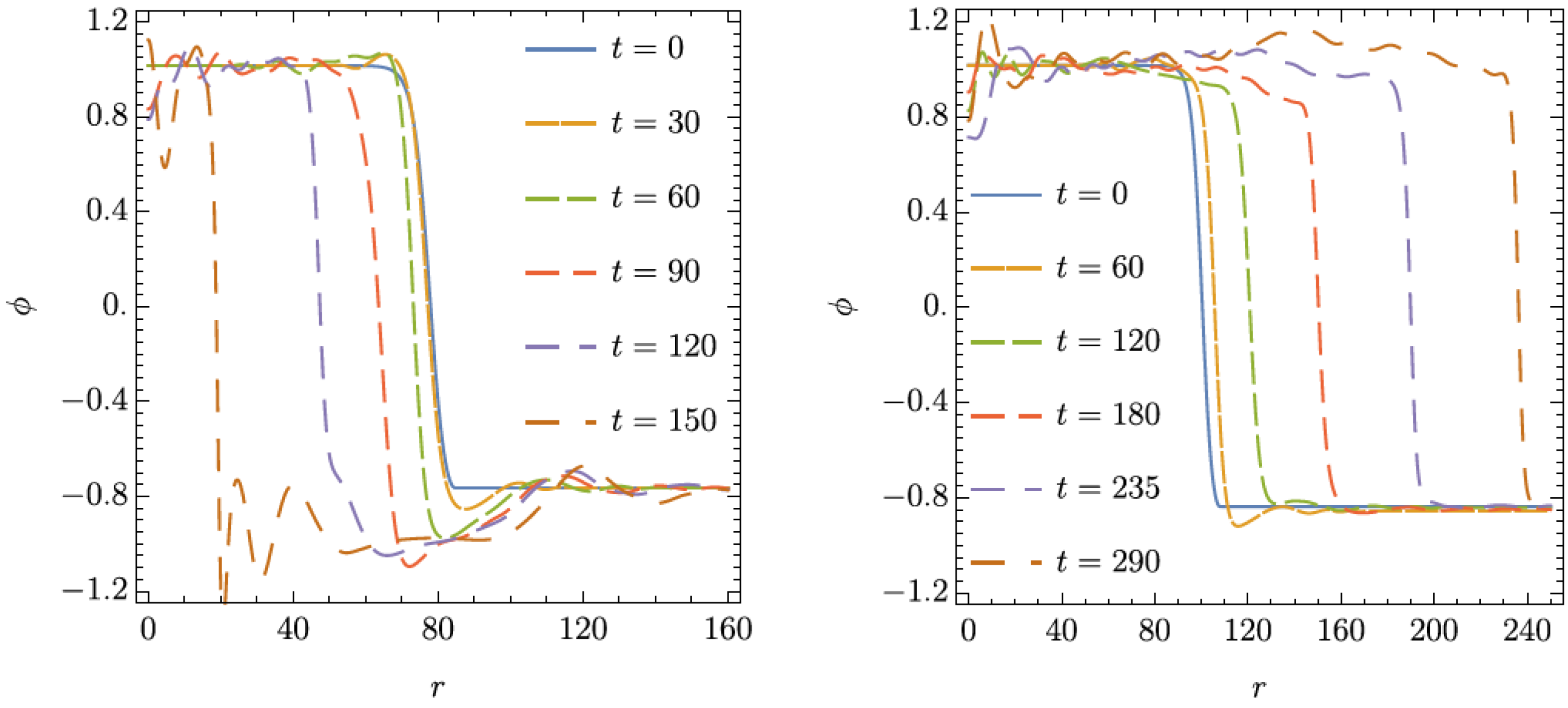
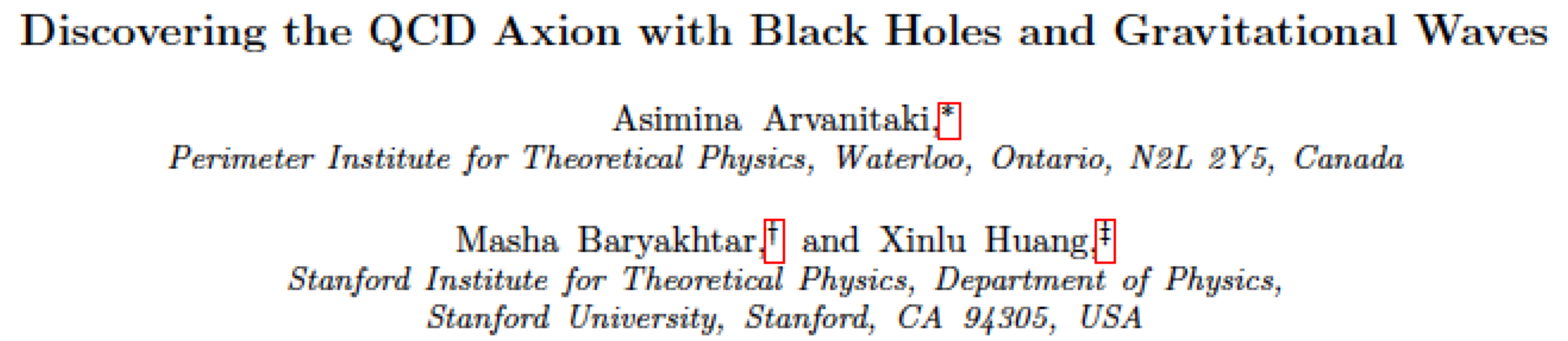


Figure 8: Field profiles showing lattice bubble evolution for oscillation reaching $1.2\sqrt{2\alpha_{\text{tw}}}$ (left panel) and $0.8\sqrt{2\alpha_{\text{tw}}}$ (right panel). The values defining the potential were set to $g = 1/10$, $b = 1/300$ and $c = 1$.

Another really cool example



Discovering the QCD Axion with Black Holes and Gravitational Waves

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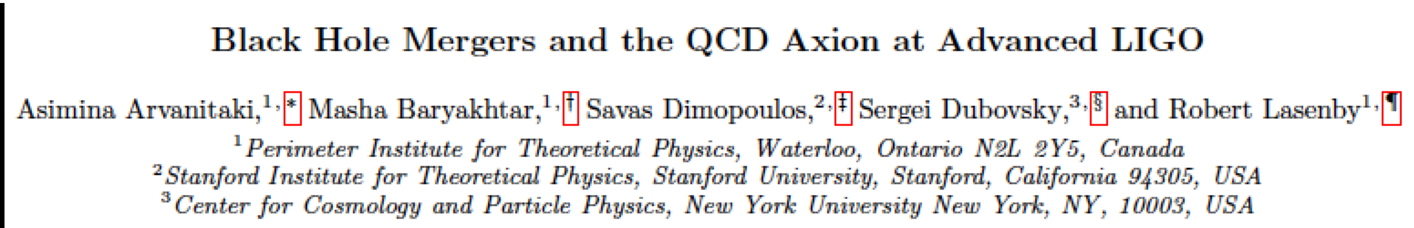
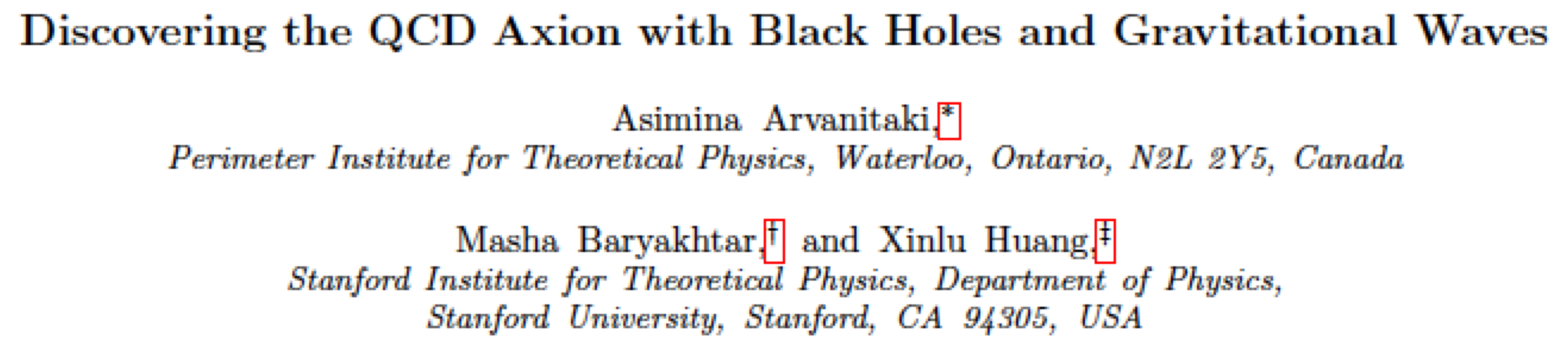
Masha Baryakhtar,[†] and Xinlu Huang,[‡]
Stanford Institute for Theoretical Physics, Department of Physics,
Stanford University, Stanford, CA 94305, USA



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,¶]
[1]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
[2]*Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*
[3]*Center for Cosmology and Particle Physics, New York University New York, NY, 10003, USA*

GWs probe axion detectors



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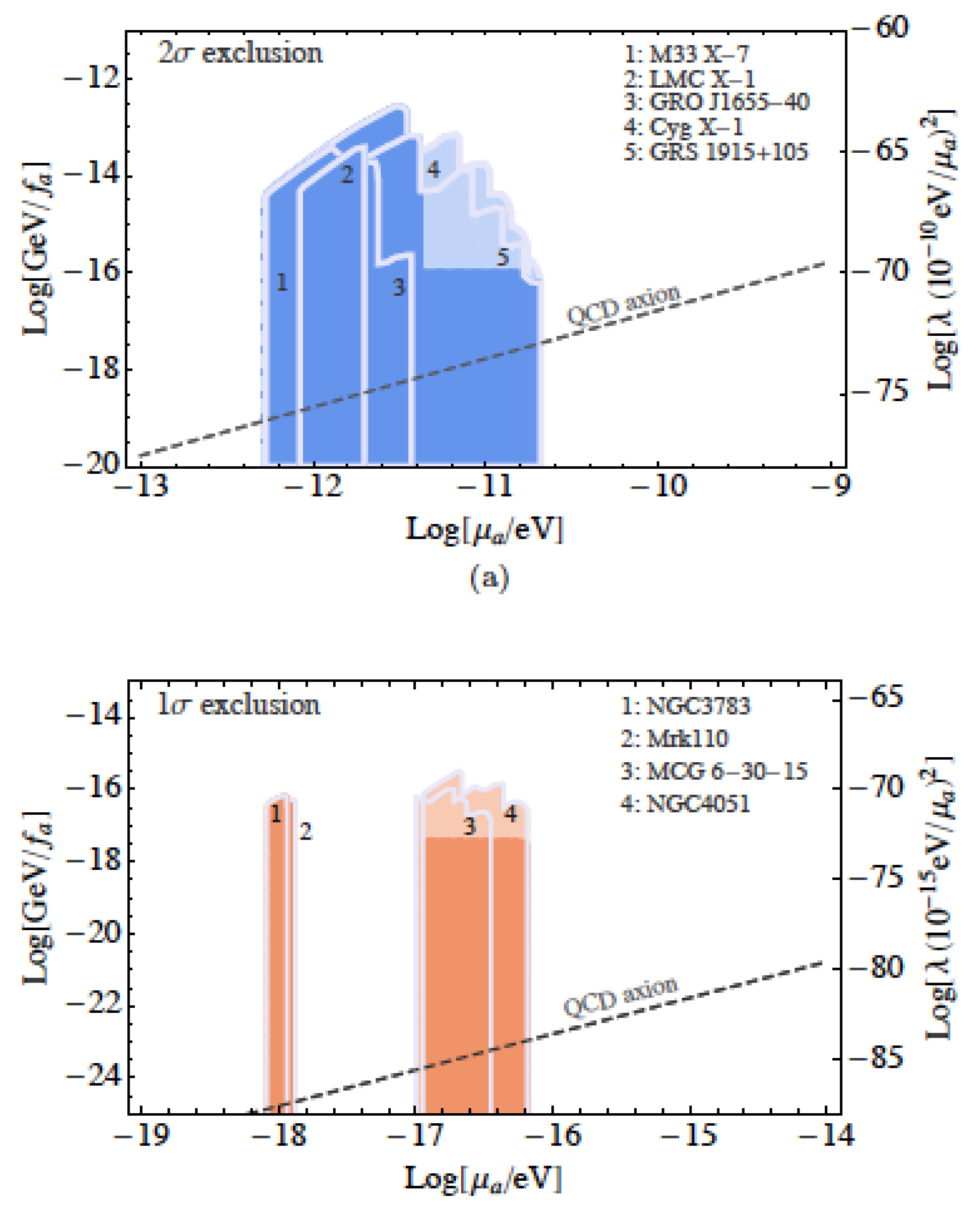
If light bosons

- ➔ 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

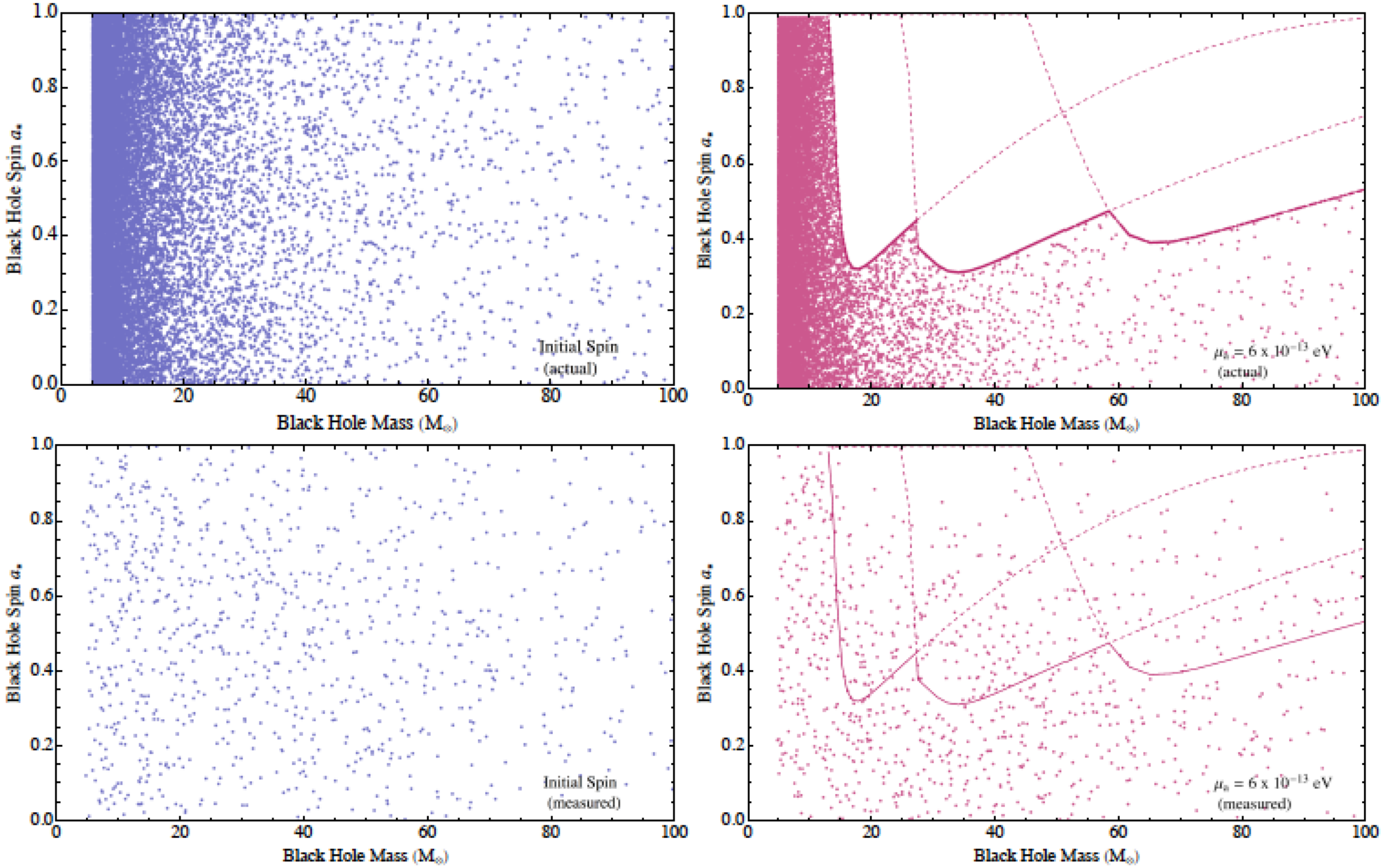


FIG. 2. Expected distribution of intrinsic (top) and measured (bottom) spins and masses of merging BHs in the absence (left) and the presence (right) of an axion of mass 6×10^{-13} eV, normalized to 1000 events detected at aLIGO. We assume $\sigma_M/M \sim 10\%$ measurement error in the mass and $\sigma_{a_*} \sim 0.25$ 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…

Bose enhanced level transitions

➔ Monofrequency signals

Annihilation of bosons into gravitons

➔ Monofrequency signal $\omega=2m_a$

Conclusions

Conclusions

- 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

What is PBC?

Study group mandated by CERN management to prepare for the next European HEP strategy update

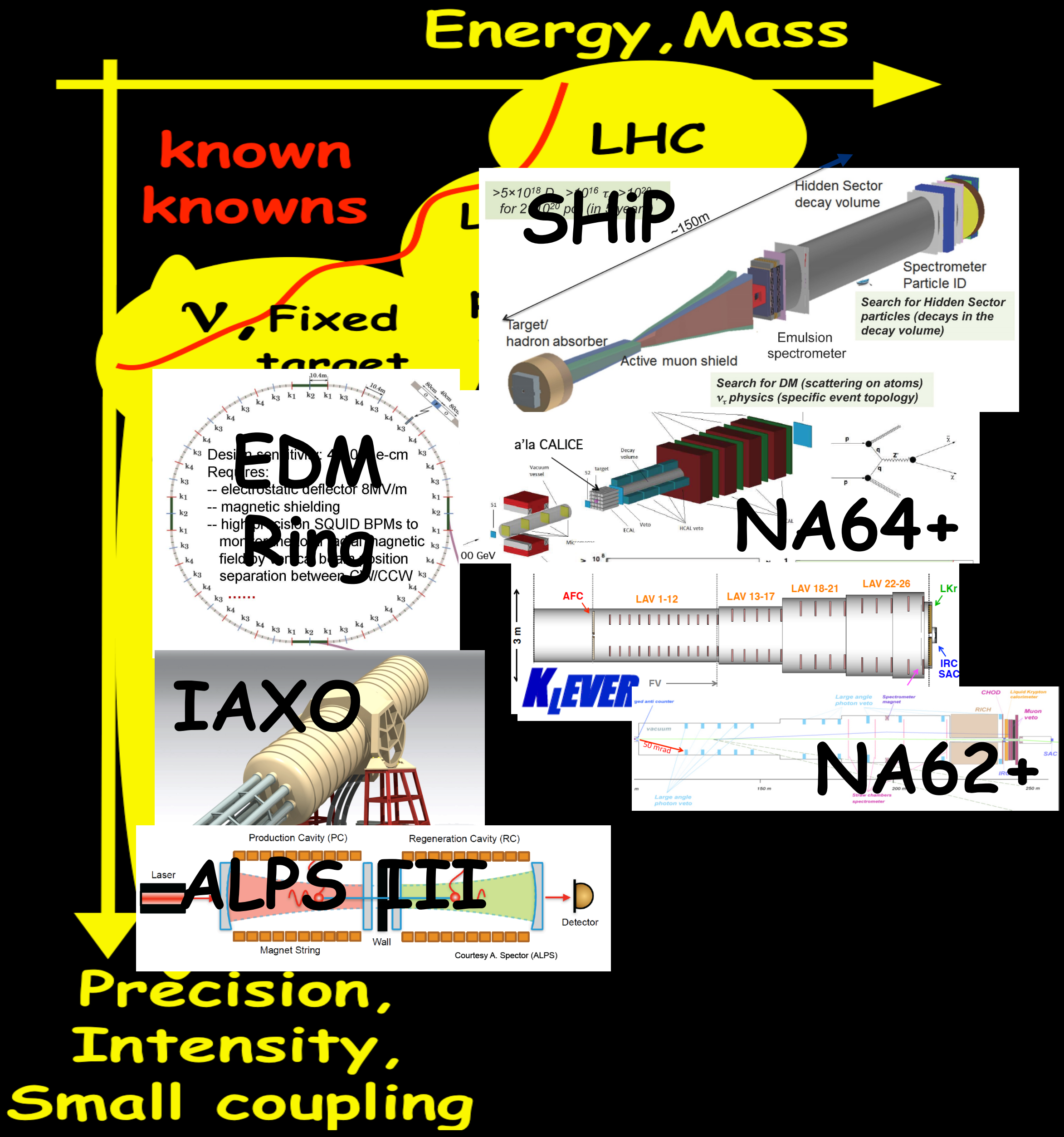
(coordinators Mike Lamont, Claude Vallee, JJ)

"Explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world" (Excerpt from the mandate)

Time scale ~ 2040

pbc.web.cern.ch

Here we want to go in the Future…



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