Can thick vacuum bubbles collide?

Master's thesis at the University of Florence

Supervisor: Prof. Diego Redigolo

Women in Theoretical Physics
Premio Nazionale "Milla Baldo Ceolin" 2024

Eugenia Dallari | University of Sussex

November 4th, GGI institute

First order phase transitions in cosmology

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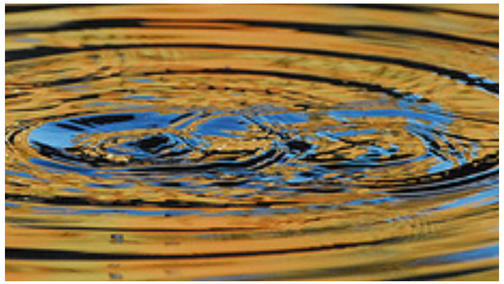
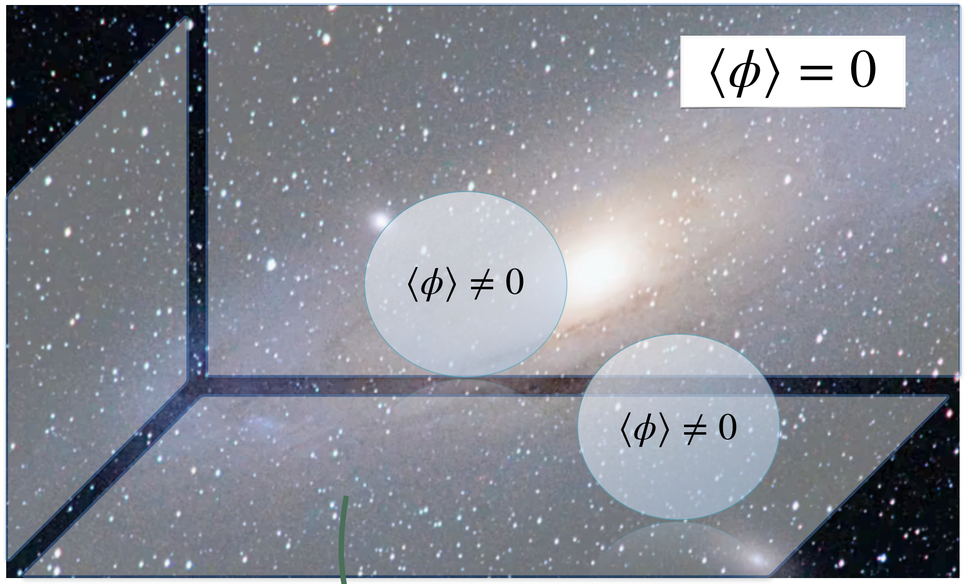
Kitchen scale:

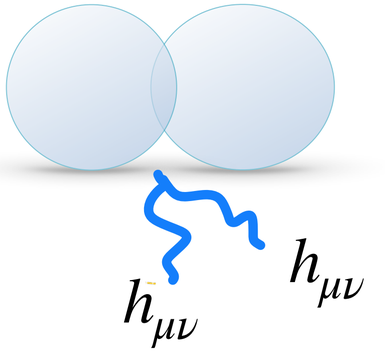
(p, V, T, N)



Early Universe scale:



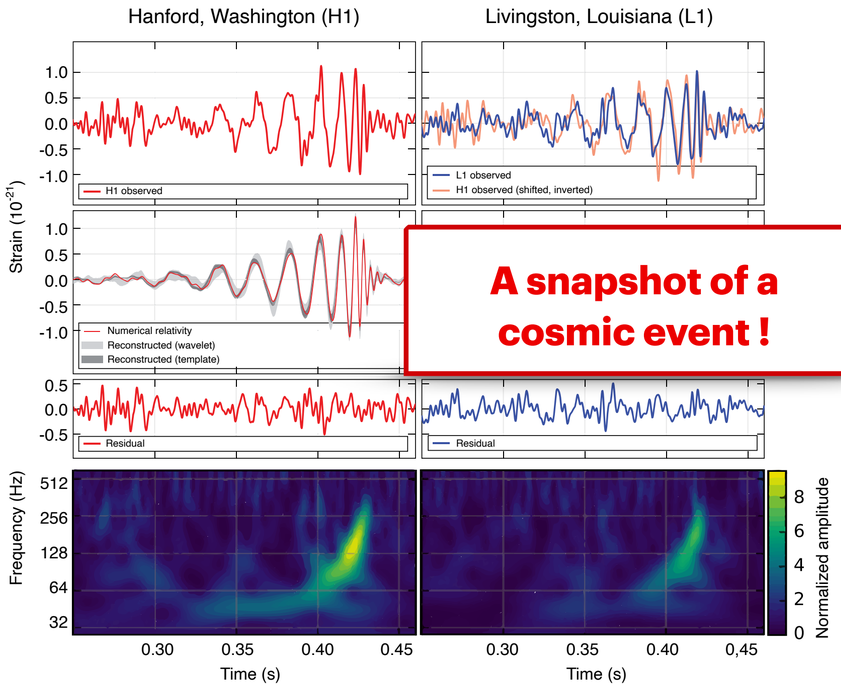
$\left(H(t) = \frac{\dot{a}}{a}\right)$



Why study first order phase transitions?

A first-order phase transition that releases large amounts of energy is a potential source of detectable Gravitational Wave signals

The recent discovery of Gravitational Waves (GWs) from compact object mergers:

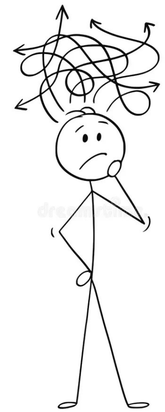


A snapshot of a cosmic event !

B. P. Abbott et al. [LIGO Scientific and Virgo], "Observation of Gravitational Waves from a Binary Black Hole Merger", 2016

.. A new era of cosmology !

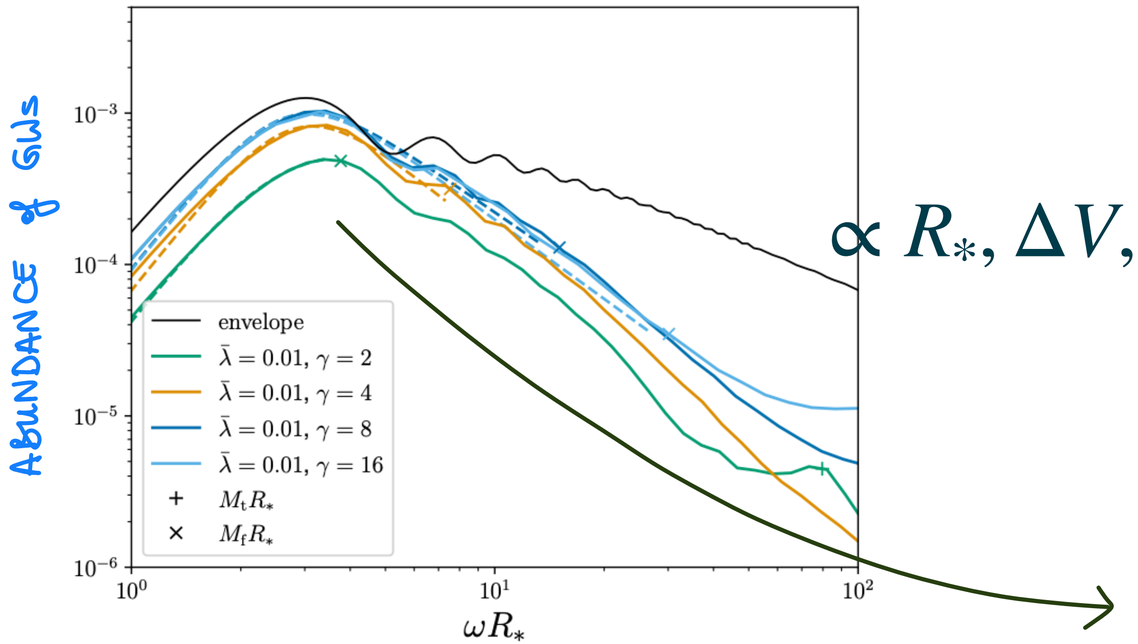
Can we detect a Stochastic Background of GWs from a first order phase transition?



Its gravitational signal has some characteristic features that can help us to detect it?

The GW spectrum for runaway bubbles

The observable:

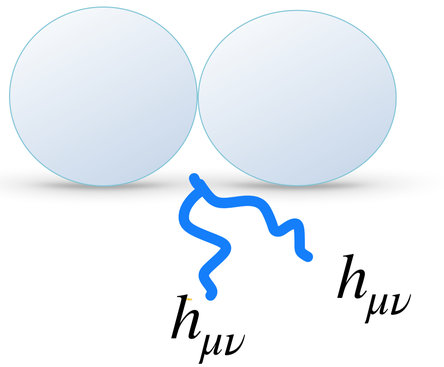


$$\propto R_*, \Delta V, \delta R_*$$

- Latent heat of the transition ΔV
- Bubble radius at collision R_*
- Bubbles thickness at collision δR_*

Jinno R., Konstandin T., Takimoto M., "Relativistic bubbles collisions- a closer look", 2019

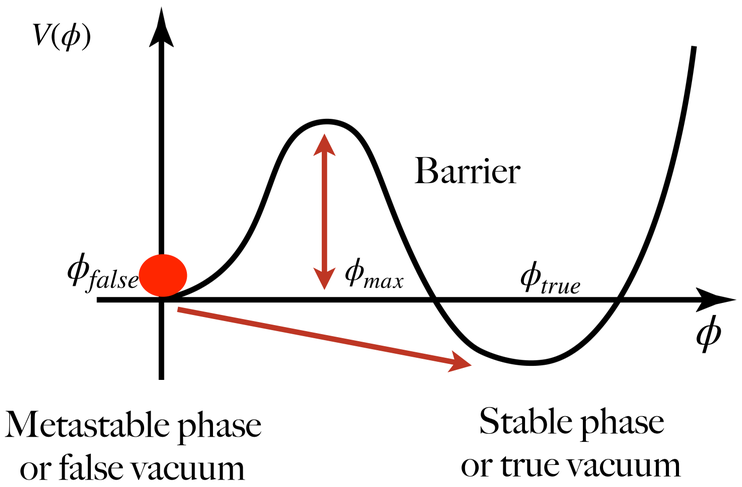
Gould O., Sukuvaara S. and Weir D., "Vacuum bubble collisions: From microphysics to gravitational waves", 2021



Why we talk about bubbles: a theory of false vacuum decay

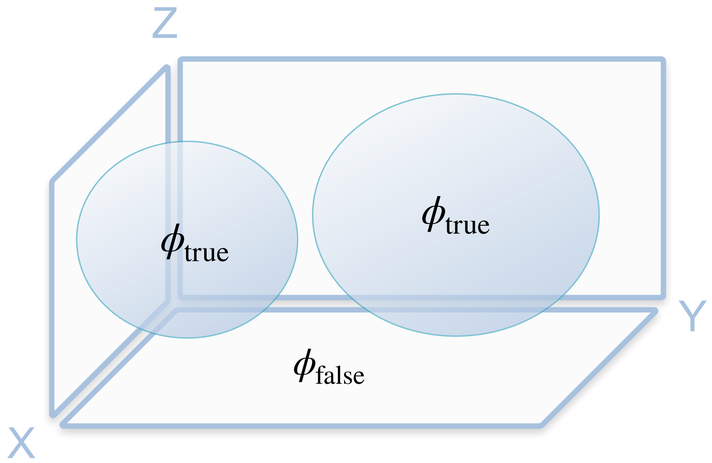
Coleman, S. "Fate of the false vacuum: Semiclassical theory", 1977

Single scalar field theory: $\mathscr{L} = \frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - V(\phi)$



Euclidean picture

$\rho^2 = \tau_E^2 + \vec{x}^2$



$$\Gamma_{decay} \propto R_c^{-4} e^{-S_E}$$

Euclidean action of the tunnelling

Energy scale of the theory

Why we talk about bubbles: a theory of false vacuum decay

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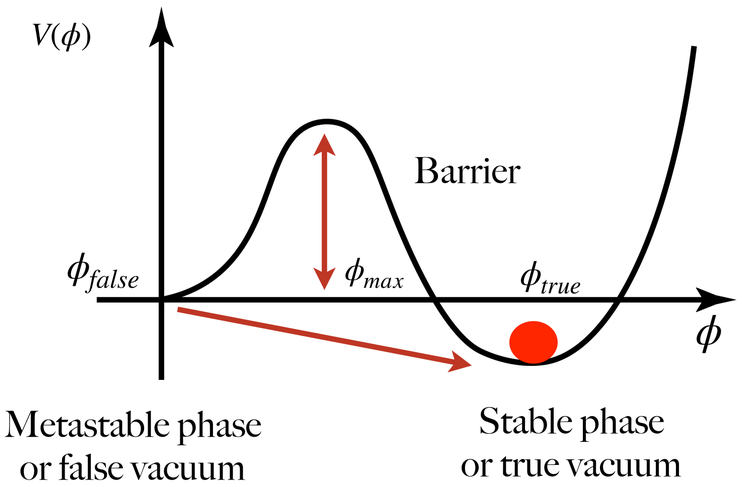

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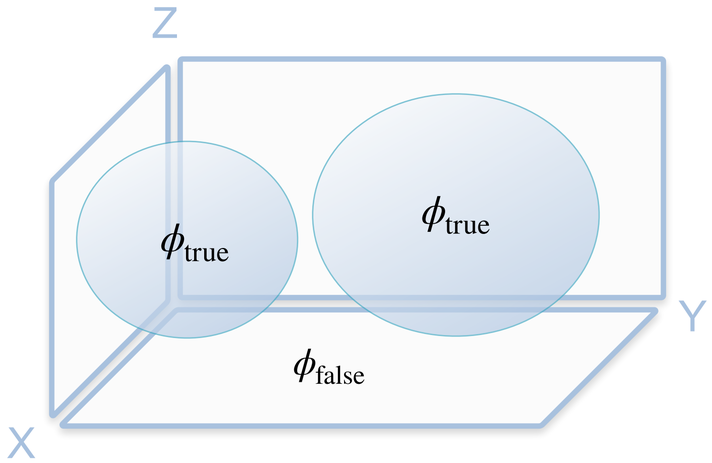

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Euclidean action of the tunnelling

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What is a thick bubble?

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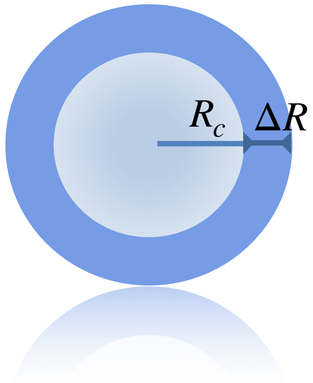
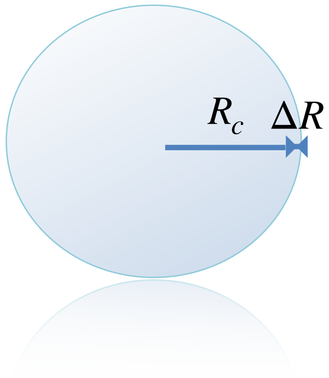
Thick bubble nucleation

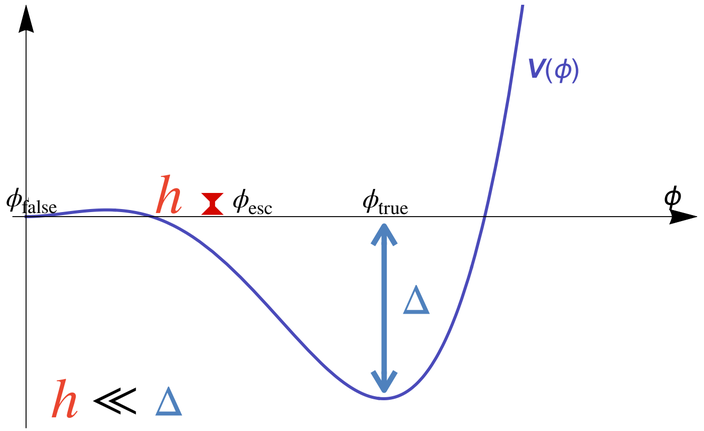


$$r \equiv \frac{V_{\max} - V_{\text{false}}}{V_{\text{false}} - V_{\text{true}}} = \frac{h}{\Delta}$$

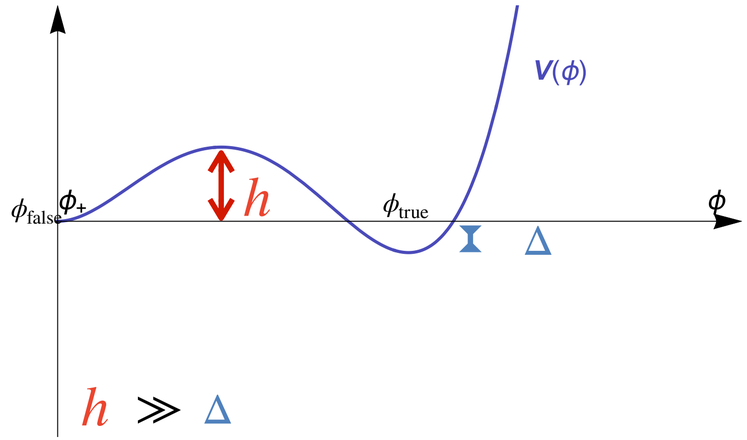
Thin bubble nucleation



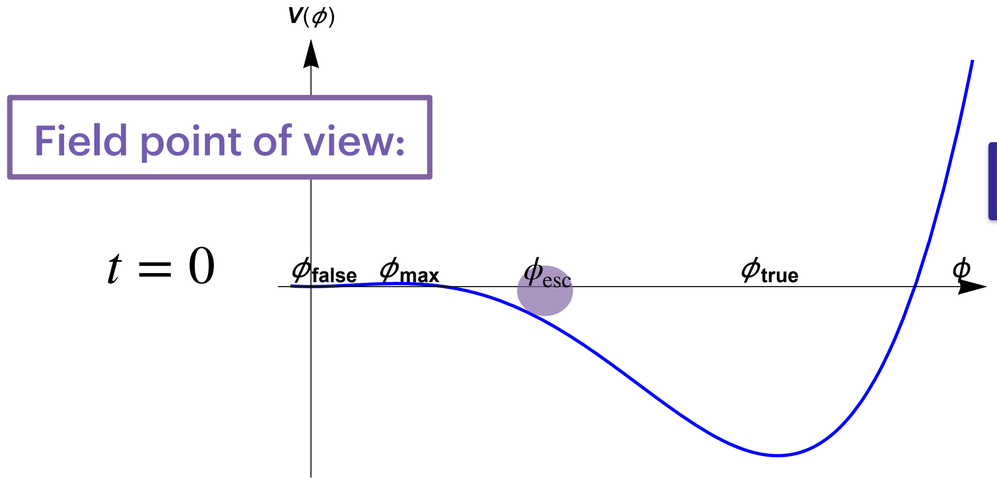
Thick wall regime



Thin wall regime

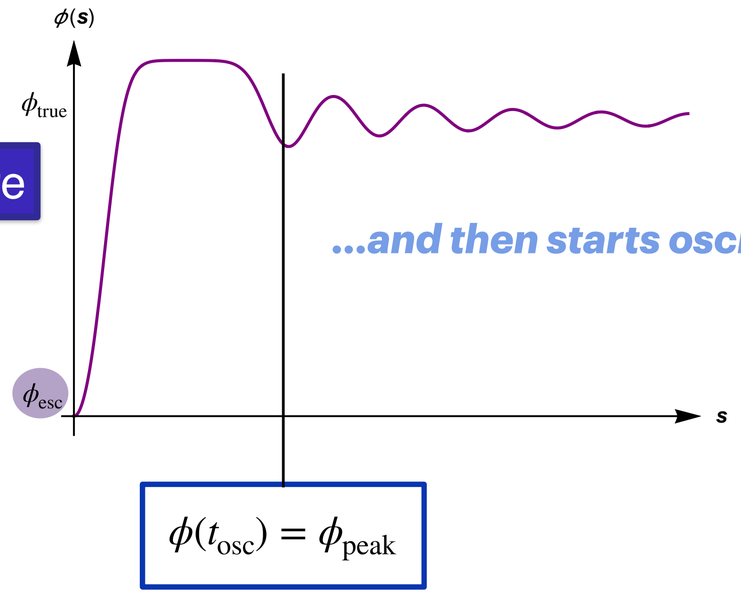


Evolution of a thick bubble in Minkowski



Minkowski picture

$$s = \sqrt{t^2 - x^2}$$



The field rolls towards the minimum…

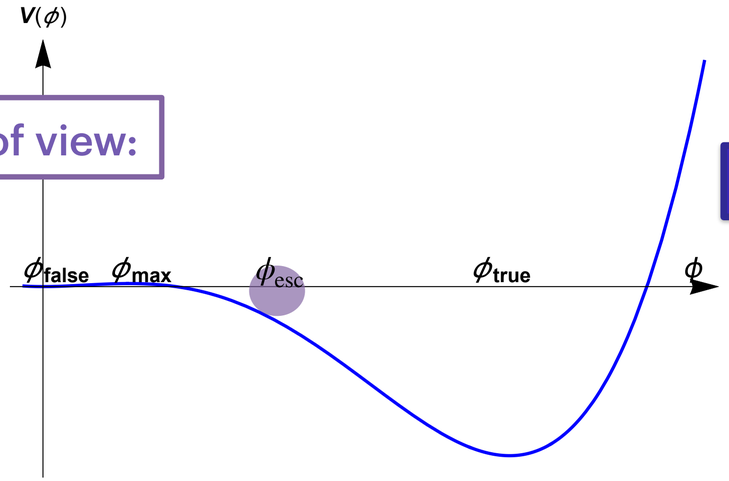
…and then starts oscillates around it

$$\phi(t_{osc}) = \phi_{peak}$$

Evolution of a thick bubble in Minkowski

Field point of view:

$t = 0$



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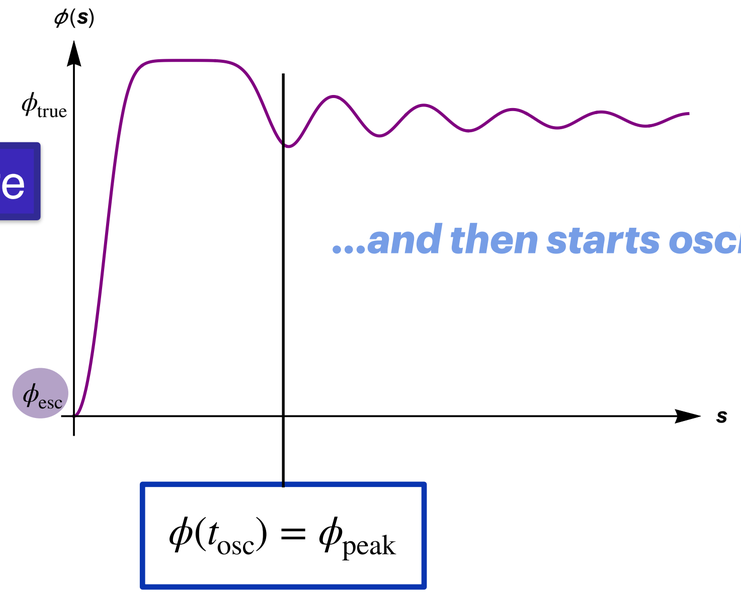
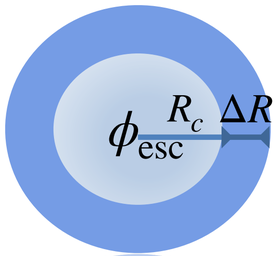


…and then starts oscillates around it

$\phi(t_{\rm osc}) = \phi_{\rm peak}$

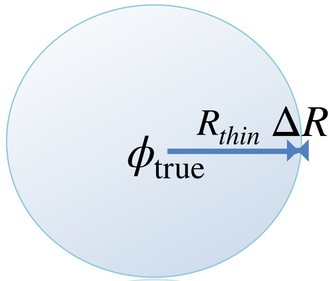
Bubble point of view:

$t = 0$



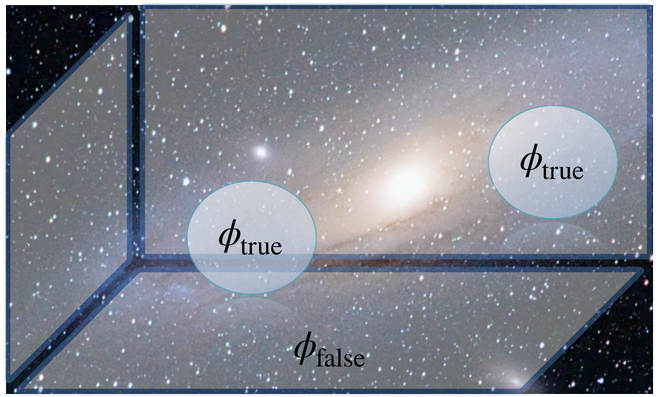
$\Delta E_{vol} = -\Delta E_{wall}$

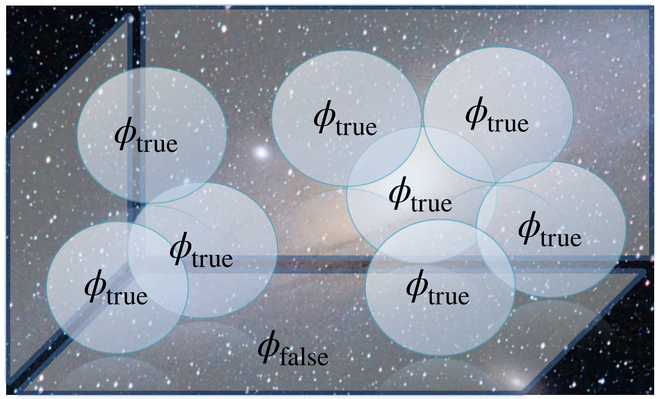
$R_c^2 = \vec{x}(t)^2 - t^2$



t_{osc}

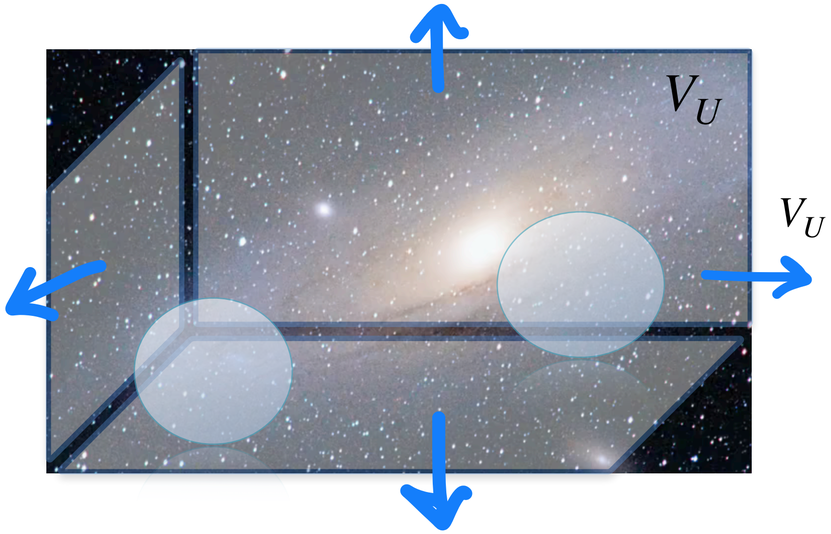
Macroscopic evolution of the transition I





t

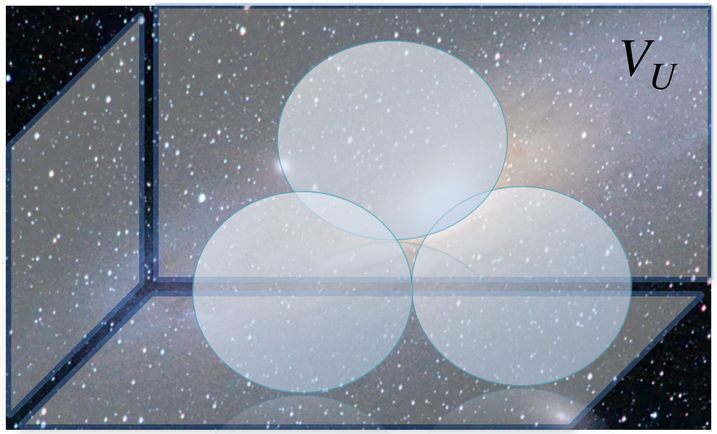
Macroscopic evolution of the transition II



$$V_U \sim \frac{1}{H(T)^4}$$

The transition rate competes with Hubble expansion..

$$\frac{\Gamma_{decay}}{H^4} \simeq 1 \rightarrow t_n$$



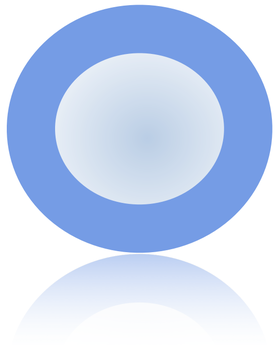
The average time of collision

$$V_{Bubble} \simeq \frac{1}{3} V_{total} \rightarrow t_p$$

Duration of the transition:

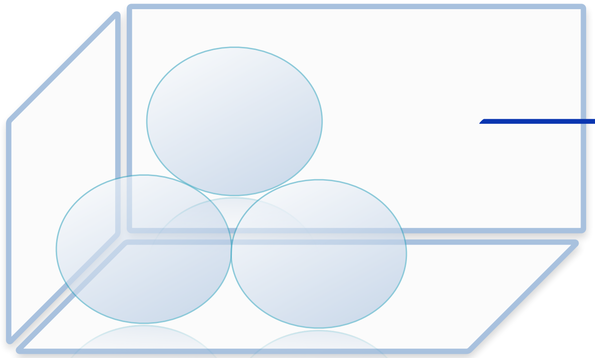
$$\beta = H_* T_* \frac{dS_E}{dT}\bigg|_{T_*} = H_* \, \beta_H$$

Can we collide thick bubbles?



Previous work assumptions:

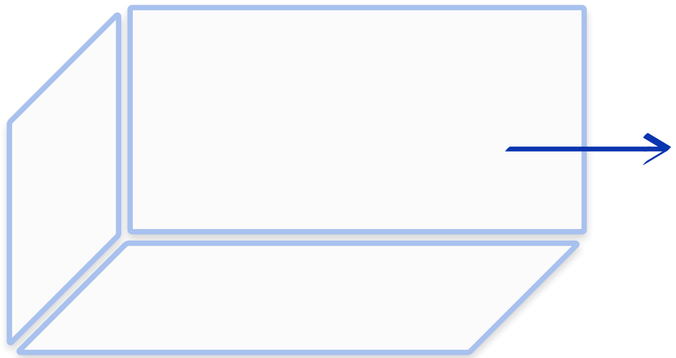
$$t_p > t_{osc}$$



Thin bubble collision

Our question:

$$t_p < t_{osc}$$



Thick bubbles collision

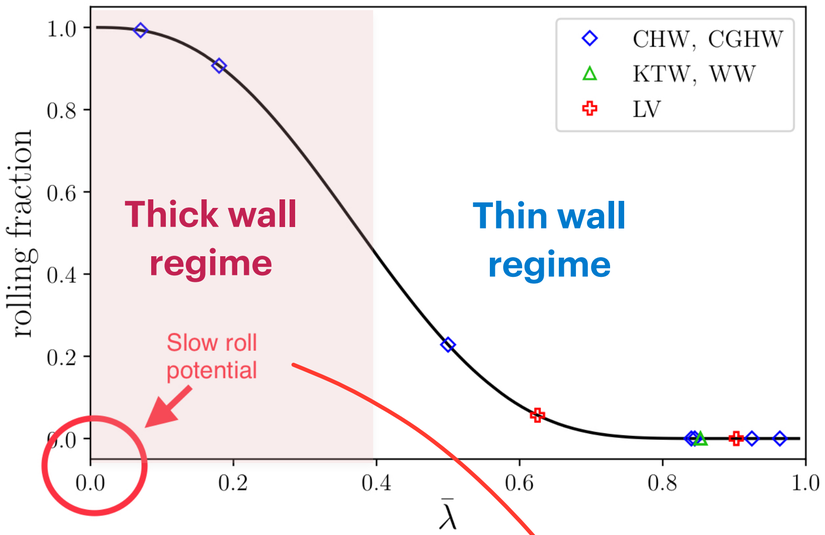
What is next?

Model-independent parametric for slow roll scenarios

$$t_p < t_{osc} \quad \longleftrightarrow \quad \frac{m}{|\Delta V|^{1/2}} < \#\frac{\beta_H}{M_{\rm Pl}} \quad \longrightarrow$$

Upper bound from the signal of SGWB su $\beta_H \lesssim 10^3$

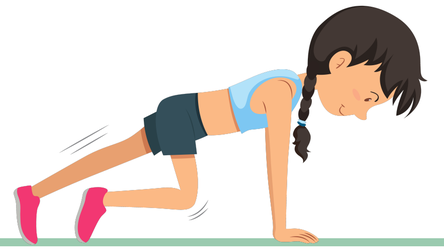
Existent simulations



Gould O., Sukuvaara S. and Weir D., "Vacuum bubble collisions: From microphysics to gravitational waves", 2021

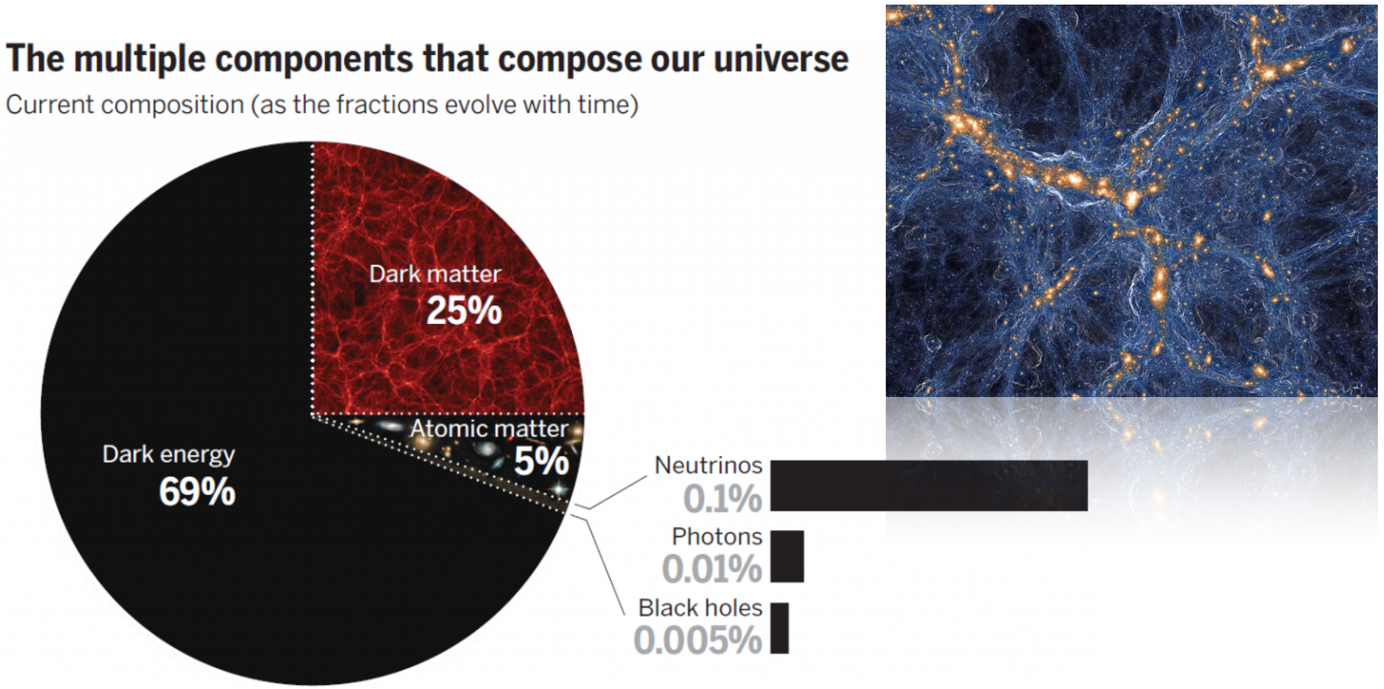
We are simulating them !

- The slow roll scenario requires **new simulations**
- Develop **realistic potential** in which we collide thick bubbles
- Identify a series of **new bubble shapes** which depends on the slope of the potential after the tip of the barrier



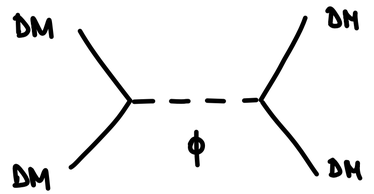
WORK IN PROGRESS !!

My current interests, besides bubbles:

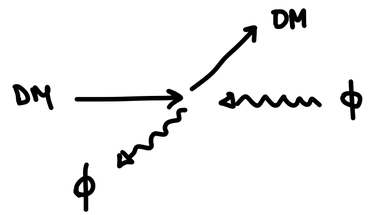


Very dark, dark sectors

- *Dark long range interactions*



- *Recoupling Dark Matter*



What if visible and dark sector interact only gravitationally?

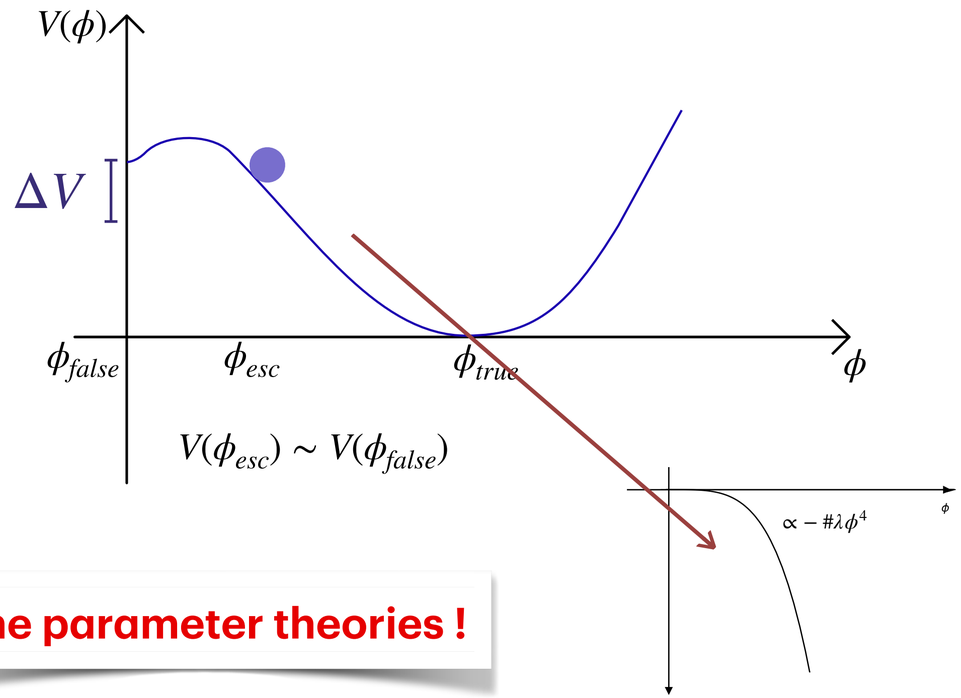
Cosmology & astrophysics are the only probes of these dark sector dynamics!


Thank you for your attention !

How do we realise thick bubble collisions?

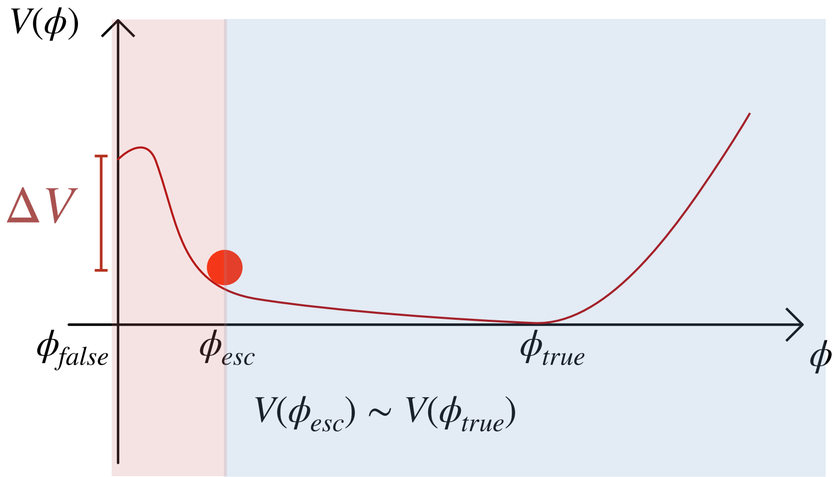
Rethink the thick wall regime:

$\phi_{esc} \ll \phi_{true}$ **Steep potential**



One parameter theories !

$\phi_{esc} \ll \phi_{true}$ **Slow roll potential**



$$\Delta V = \phi_{esc}^4 \lambda_{esc}$$

$$g_{roll} = \frac{m}{\phi_{esc}}$$

Two parameter theories !

$$m \ll \sqrt{\Delta V}$$