Title: The String Soundscape at Gravitational Wave Detectors

Date: Nov 29, 2016 01:00 PM

URL: http://pirsa.org/16110090

Abstract: <p>In this talk, we explore the possibility of gravitational wave production due to ultra-relativistic bubble wall collisions. This occurs due to a process of post-inflationary vacuum decay that takes place via quantum tunnelling within a warped throat (of Randall-Sundrum type). We emphasise the differences between vacuum decay via quantum tunnelling, and a thermal first order phase transition, and how potential gravitational wave signals from both processes differ. We explore a specific example in the context of type IIB string theory, although we argue that our conclusions are more generally applicable to theories with hidden sectors featuring metastable vacua. Many such transitions could have occurred in the post-inflationary Universe, as a large number of throats with exponentially different IR scales can be present in the string landscape, potentially leading to several signals of widely different frequencies â€“ a soundscape connected to the landscape of vacua. Future detectors like LISA will have the required sensitivity to detect these potential signals.</p>

The String Soundscape

what gravity wave detectors can tell us about BSM physics

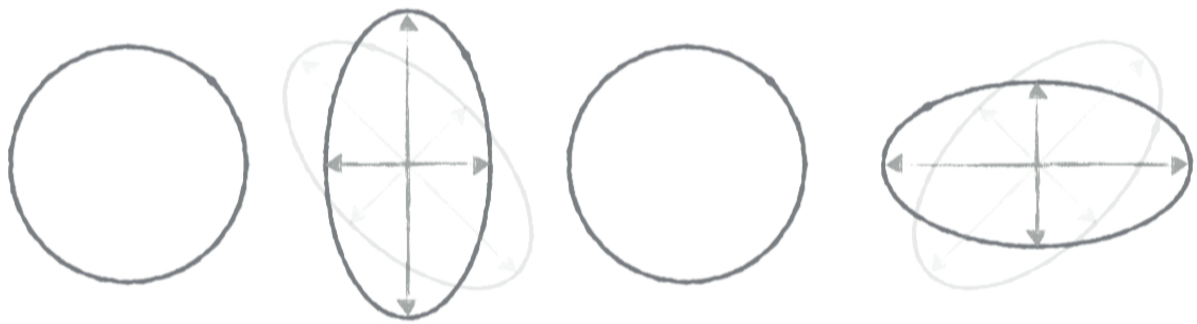
Isabel García García

University of Oxford

IGG, S. Krippendorf, J. March-Russell — arXiv:1607.06813

Gravitational Waves

- GWs are a prediction of GR.



- The amount of relative stretching and squeezing is the strain of the GW, $\tilde{h}$ (it is basically the amplitude of the wave).

falls like $\frac{1}{r}$

GW detectors are designed to detect the (tiny) strain of an incoming GW

Gravitational Waves

- Useful to think of the energy in the GW, rather than just the strain.

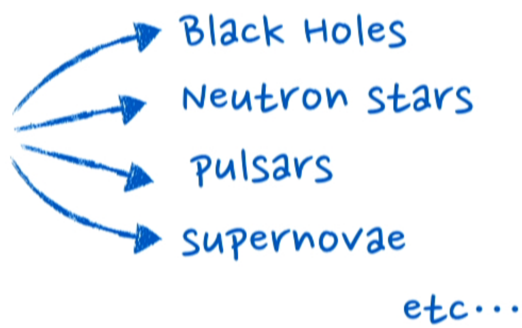
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad t_{\mu\nu} = \frac{M_{\rm Pl}^2}{32\pi} \langle \partial_\mu h_{\rho\sigma}^{\rm TT} \partial_\nu h^{{\rm TT}\ \rho\sigma} \rangle$$

$$\rho_{\rm GW} = t_{00} \propto M_{\rm Pl}^2 f^2 \tilde{h}^2 \qquad \Rightarrow \qquad \Omega_{\rm GW} = \frac{\rho_{\rm GW}}{\rho_{c,0}} \propto f^2 \tilde{h}^2$$

Gravitational Waves

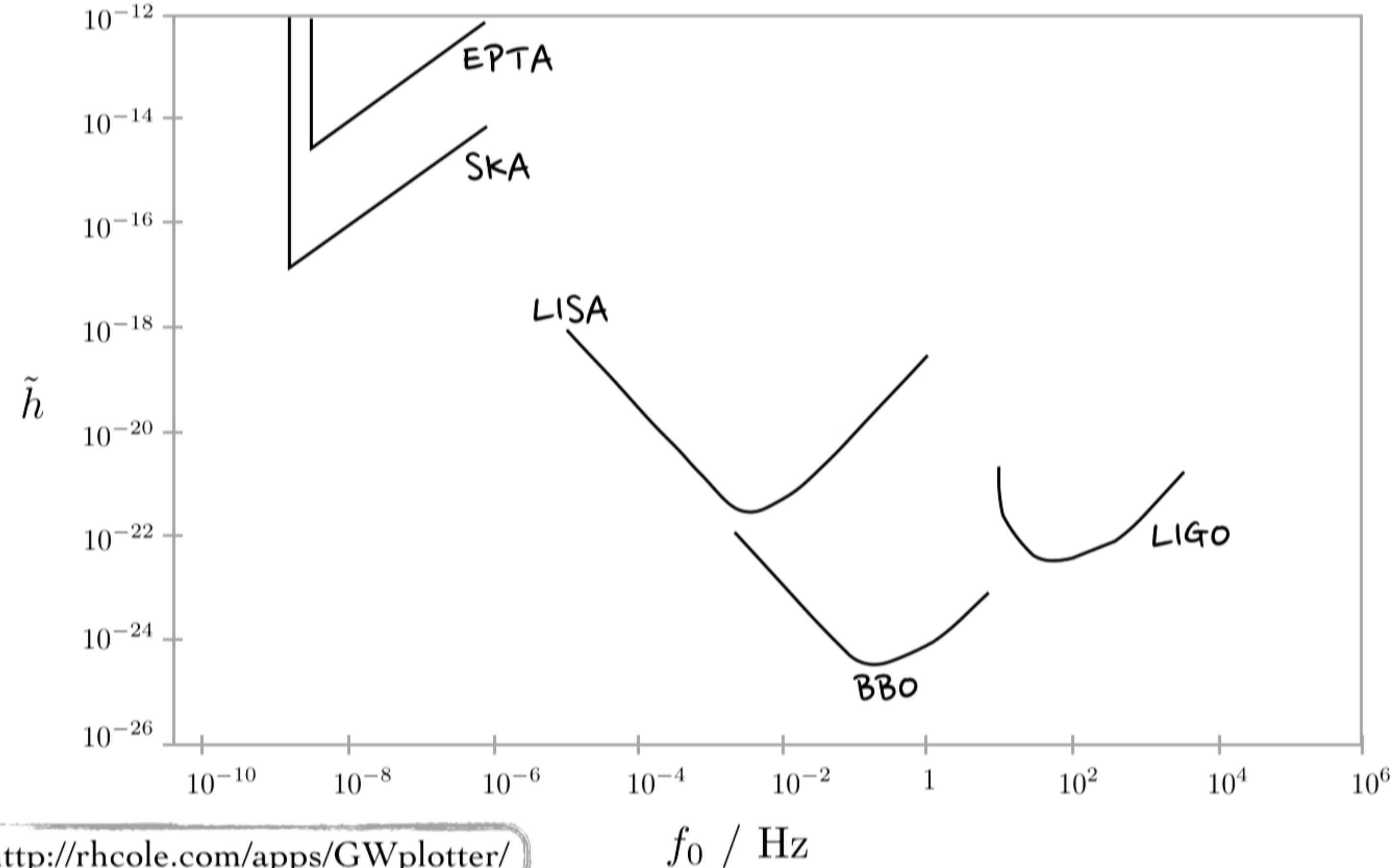
- GW have been directly observed by LIGO. Other (current and future) detectors will do so at different frequencies.

- The astrophysical potential of GW detectors has been deeply studied.



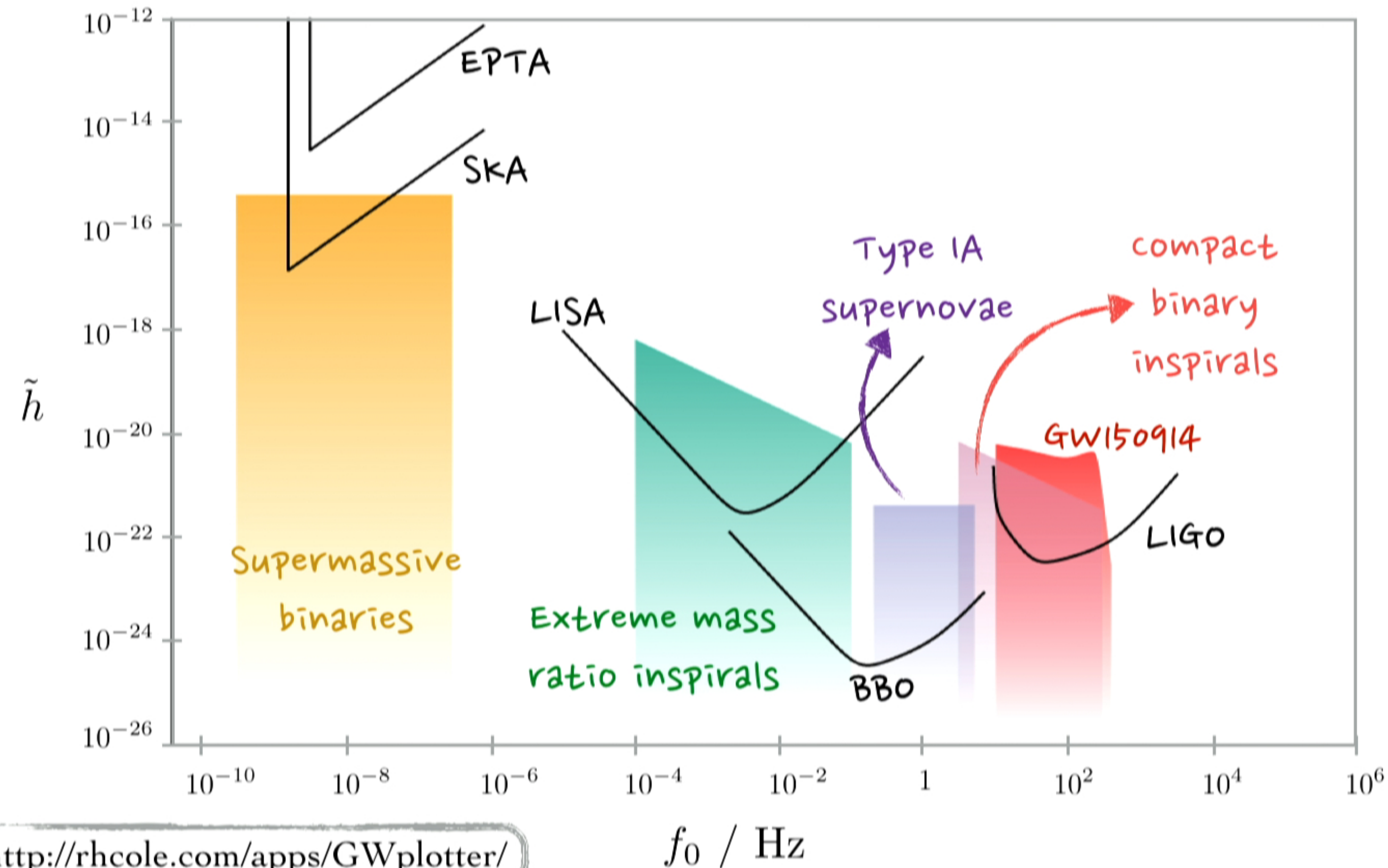
e.g. see Lasky *et al.* arXiv:1511.05994

GW Sensitivity Curves



http://rhcole.com/apps/GWplotter/

GW Sensitivity Curves



http://rhcole.com/apps/GWplotter/


can we use GW detectors
to learn about BSM physics?

GW detectors for BSM

There are *a few* examples:

(but mostly very poorly explored)

- Inflation.

- Strong 1st order EW phase transition.

  perfect for LISa

  a review: Caprini *et al.* arXiv:1512.06239

- Probing the existence of a QCD axion (due to BH superradiance).

  with LIGO

  Arvanitaki *et al.* arXiv:1411.2263, and arXiv:1604.03958.

GW detectors for BSM

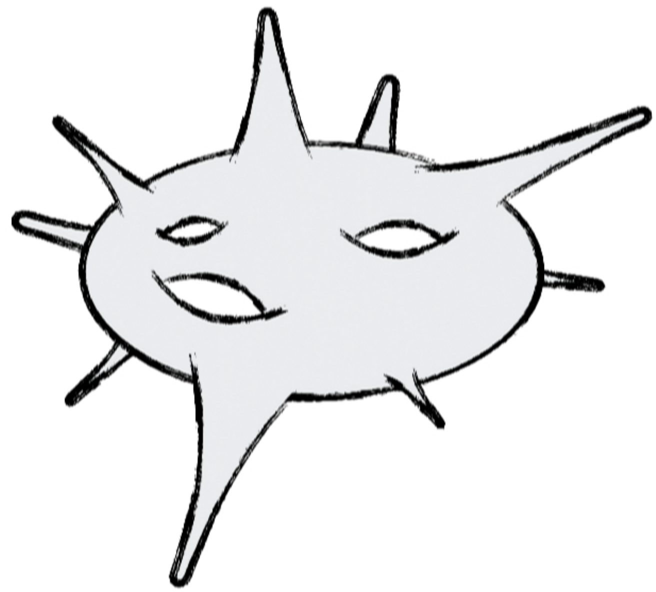
In this talk:

GWs from vacuum decay (at T=0)
in String Theory motivated scenarios.

Our String Set-Up

- Superstring Theory consistently formulated in 10D. The 6 extra spatial dimensions need to be compactified.

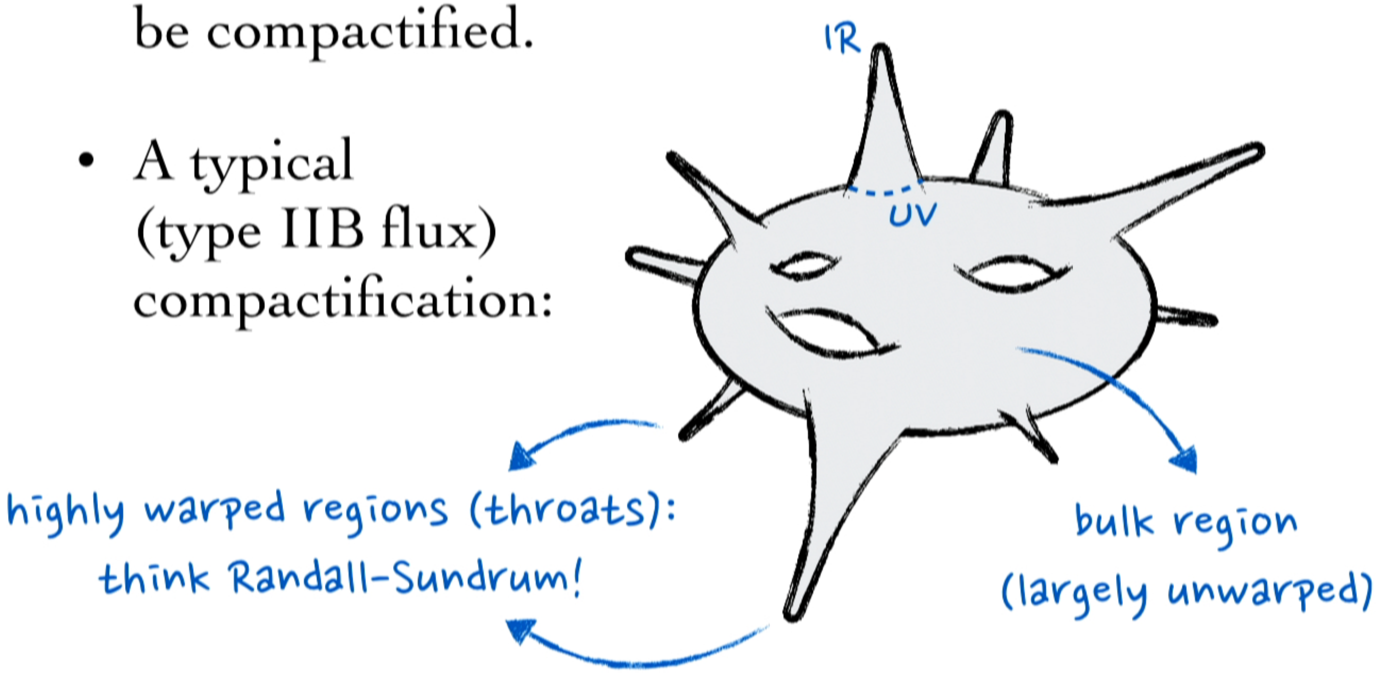
- A typical (type IIB flux) compactification:



Our String Set-Up

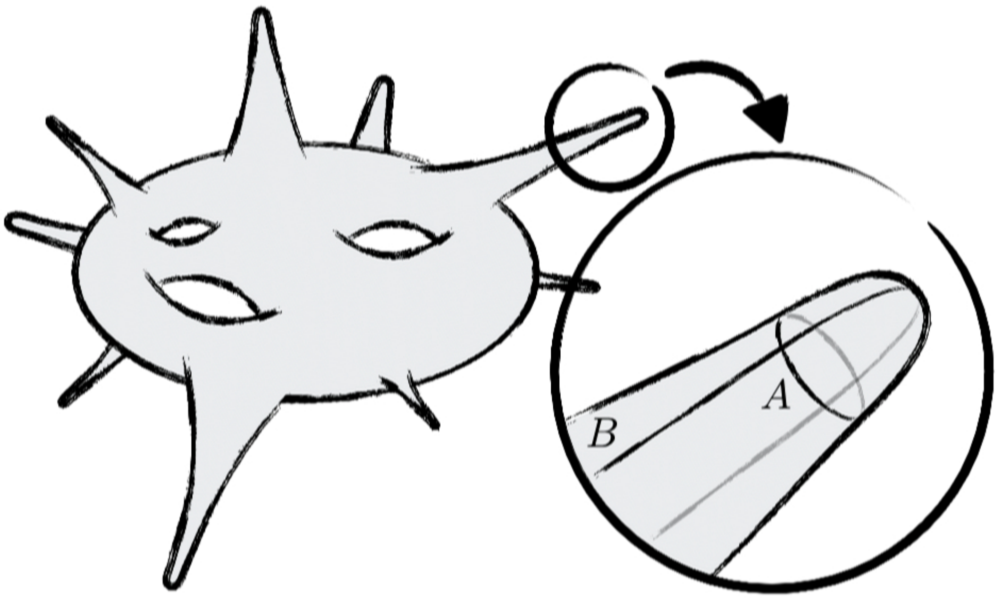
- Superstring Theory consistently formulated in 10D. The 6 extra spatial dimensions need to be compactified.

- A typical (type IIB flux) compactification:



Why Throats?

- Highly warped regions (throats) arise as a backreaction from fluxes on the geometry.

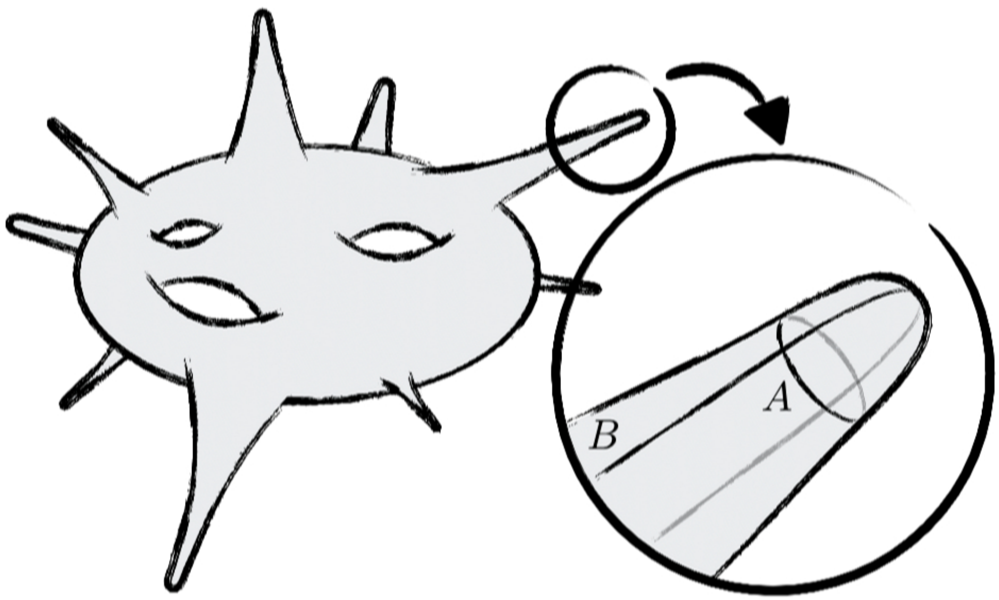


$$\frac{1}{4\pi^2}\int_A F_3 = M$$
$$\frac{1}{4\pi^2}\int_B H_3 = -K$$

Why Throats?

- Highly warped regions (throats) arise as a backreaction from fluxes on the geometry.

- Warp factor *exponentially* dependent on fluxes.



$$\frac{1}{4\pi^2}\int_A F_3 = M$$

$$\frac{1}{4\pi^2}\int_B H_3 = -K$$

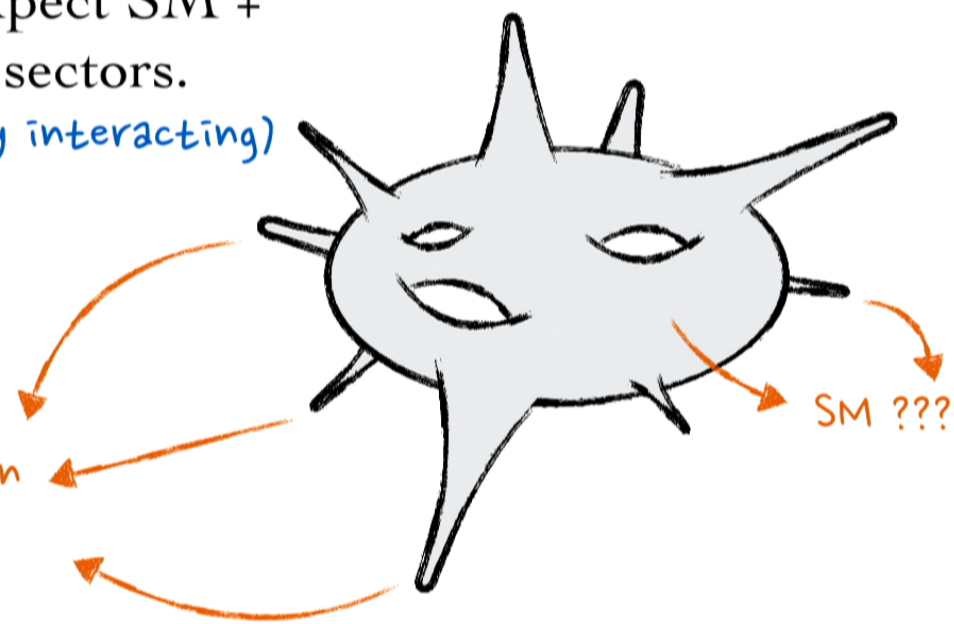
$$w_{\mathrm{IR}} \sim \exp\left(-\frac{4\pi K}{3Mg_s}\right)$$

(at tip of throat)

Throat Hidden Sectors

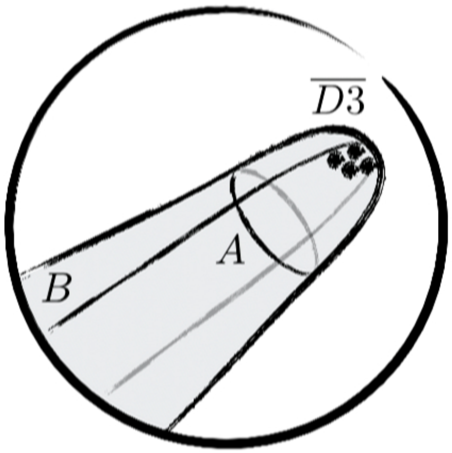
- Degrees of freedom can be localized on the compactification: at the throat tip, or in the bulk.
- In general, expect SM + many hidden sectors.

(typically very weakly interacting)



Why Metastable Vacua?

- D-branes are non-perturbative objects that arise in String Theory, of (D+1)-dimensions.
- A typical throat can have a few anti-D3 branes. These are localised at the tip, and break SUSY.
- But this situation is unstable. The stable vacuum has no anti-D3 branes, and preserves SUSY.



Kachru, Pearson, Verlinde: hep-th/0112197

An Effective Description

Kachru, Pearson, Verlinde: hep-th/0112197

- Leading effective lagrangian:

$$\mathcal{L} \approx \frac{\mu_3 M}{g_s} \left\{ -V_2(\psi)\sqrt{1-\partial_\mu\psi\partial^\mu\psi} + \frac{1}{2\pi}(2\psi - \sin 2\psi) \right\}$$

$$V_2(\psi) = \frac{1}{\pi}\sqrt{b_0^4 \sin^4\psi + (\pi\frac{p}{M} - \psi + \frac{1}{2}\sin 2\psi)^2}$$

An Effective Description

Kachru, Pearson, Verlinde: hep-th/0112197

- Leading effective lagrangian:

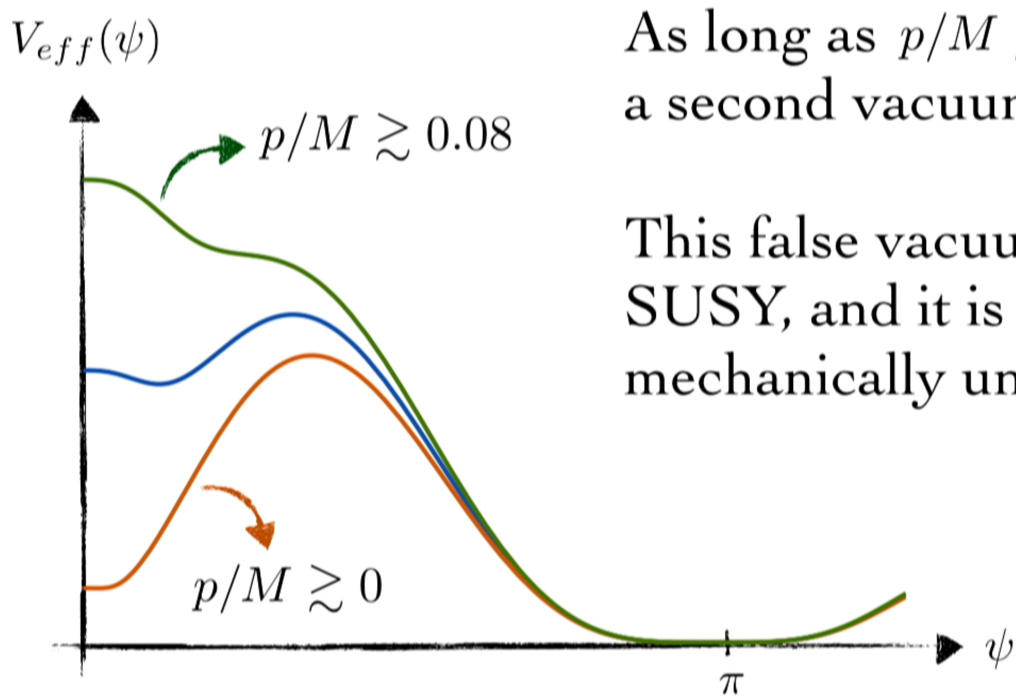
wacky kinetic term

$$\mathcal{L} \approx \frac{\mu_3 M}{g_s} \left\{ -V_2(\psi)\sqrt{1 - \partial_\mu \psi \partial^\mu \psi} + \frac{1}{2\pi}(2\psi - \sin 2\psi) \right\}$$

$$V_2(\psi) = \frac{1}{\pi}\sqrt{b_0^4 \sin^4 \psi + (\pi \frac{p}{M} - \psi + \frac{1}{2}\sin 2\psi)^2}$$

P/M controls the shape of the potential

Metastable Vacua



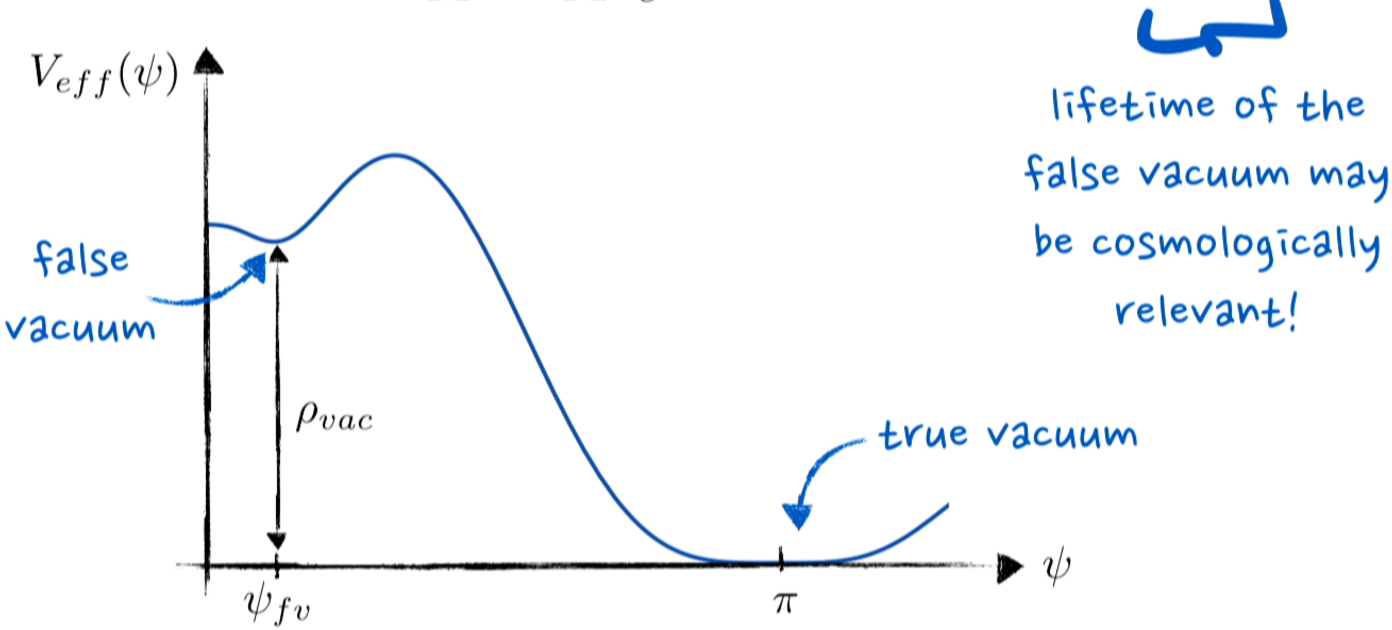
As long as $p/M \lesssim 0.08$, a second vacuum arises.

This false vacuum breaks SUSY, and it is quantum mechanically unstable.

Metastable Vacua

We study the system in the regime

$$\frac{p}{M} = \frac{p}{M}\bigg|_c (1-\delta) \qquad \text{with} \qquad 0 < \delta \ll 1$$



Simplifying Assumptions

- After inflation, throat in its metastable vacuum.

- Visible sector reheated at $T_{rh} \gtrsim 4\ \mathrm{MeV}$ but hidden sector left at $T_{th} \approx 0$.

the decay must occur via quantum tunnelling,
no thermal transition!

Simplifying Assumptions

- After inflation, throat in its metastable vacuum.

- Visible sector reheated at $T_{rh} \gtrsim 4 \text{ MeV}$ but hidden sector left at $T_{th} \approx 0$.

  the decay must occur via quantum tunnelling,
  no thermal transition!

- Early Universe radiation dominated:

$$\rho_{total}(T) = \rho_{rad}(T) + \rho_{vac} \quad \text{with} \quad \alpha(T) \equiv \frac{\rho_{vac}}{\rho_{rad}(T)} \leq 1$$

Epoch of Decay?

$T \sim 10^{18}$ GeV

false vacuum!

T_n

true vacuum!

$T \sim 1$ MeV

Probability of nucleating a bubble of true vacuum in a Hubble volume, in a Hubble time:

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

decay rate per u. volume (depends on throat, independent of T)

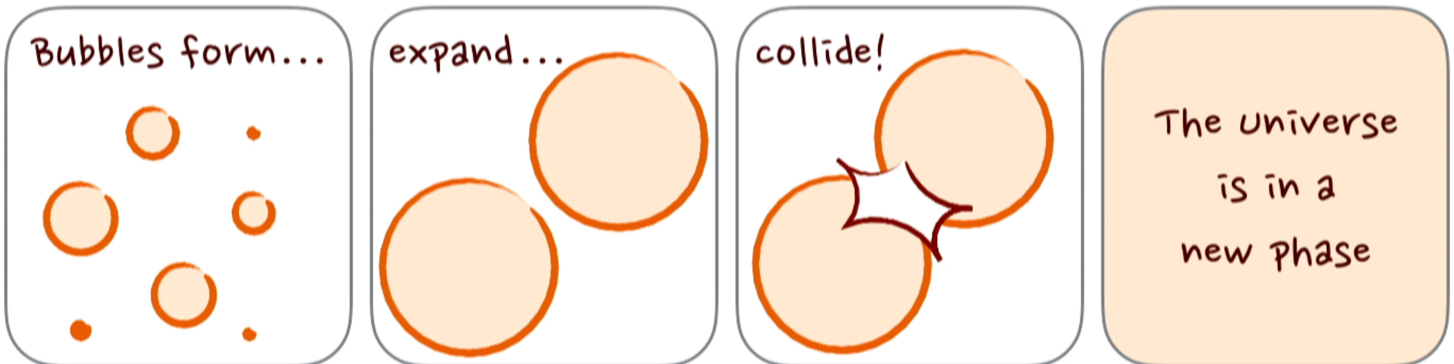
decreases as the temperature drops

with $H(T)^2 = \dfrac{\rho_{total}(T)}{3m_{Pl}^2}$

When $\dfrac{\Gamma}{H(T_n)^4} \approx 1$ the transition starts.

Post-Nucleation

Bubbles of the true vacuum are nucleated in the early universe



They quickly start expanding at the speed of light

Bubbles then collide, emitting energy in the form of gravity waves

Vacuum Decay

Coleman, PRD 15, 10 (1977) & Callan, Coleman, PRD 16, 6 (1977)

- To find out the decay rate of the false vacuum, one computes (the imaginary part of) its energy:

$$\langle\psi_{fv}|e^{-\hat{H}\tau}|\psi_{fv}\rangle = \int [d\psi] e^{-S_E[\psi]}$$

$\sim e^{-E_{fv}\tau}$

dominated by field configuration that extremizes S_E

Vacuum Decay

Coleman, PRD 15, 10 (1977) & Callan, Coleman, PRD 16, 6 (1977)

- Bounce solution ψ_B is the non-trivial field configuration that extremises S_E.

$$E_{fv} \supset N \frac{e^{-S_E[\psi_B]}}{\sqrt{\det'(\delta^2 S_E[\psi_B])}}$$

Vacuum Decay

Coleman, PRD 15, 10 (1977) & Callan, Coleman, PRD 16, 6 (1977)

- Bounce solution ψ_B is the non-trivial field configuration that extremises S_E.

$$E_{fv} \supset N \frac{e^{-S_E[\psi_B]}}{\sqrt{\det'(\delta^2 S_E[\psi_B])}}$$

imaginary if negative eigenvalue

Coleman, N. Phys. B298 (1988)

$$\Gamma = m^4 e^{-B}$$

$B = S_E[\psi_B] - S_E[\psi_{fv}]$

set by curvature scale at the top of the barrier

The Bounce Solution

- The bounce solution is the $t = 0$ boundary condition for the nucleated bubble:

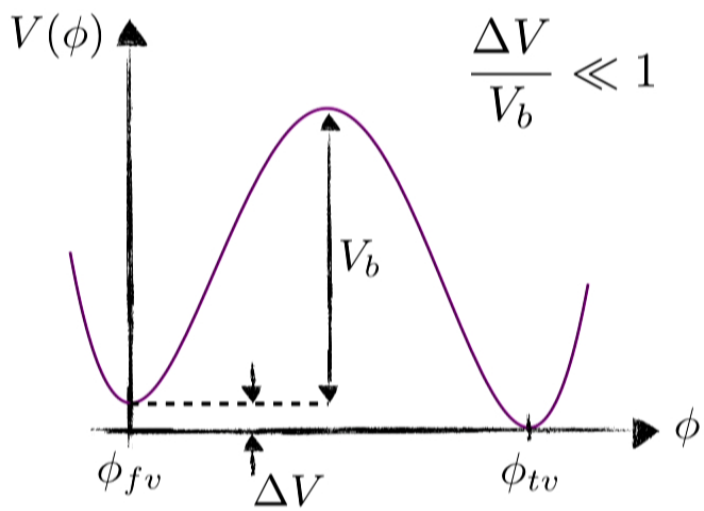
$$\psi(t = 0, r) = \psi_B(\tau = 0, r)$$

- Later evolution of the bubble is obtained through analytic continuation from the bounce.

- **How does the bounce look like?** In general, it requires a dedicated computation, but there is one limiting case → thin wall

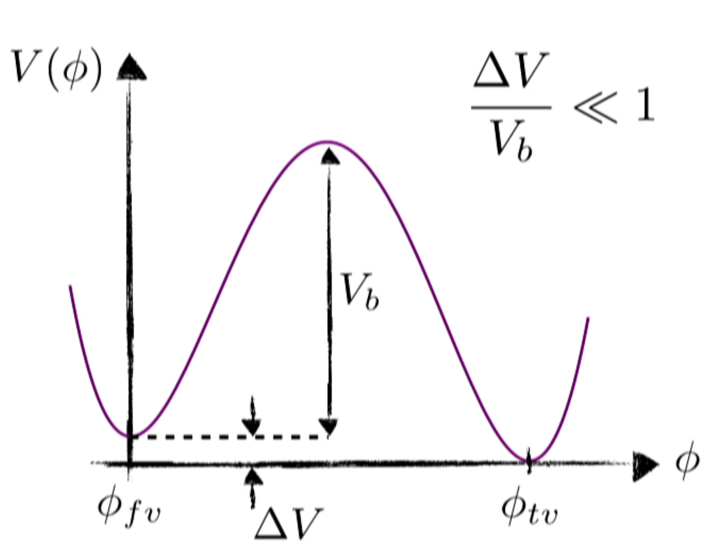
Thin-Wall Bounce

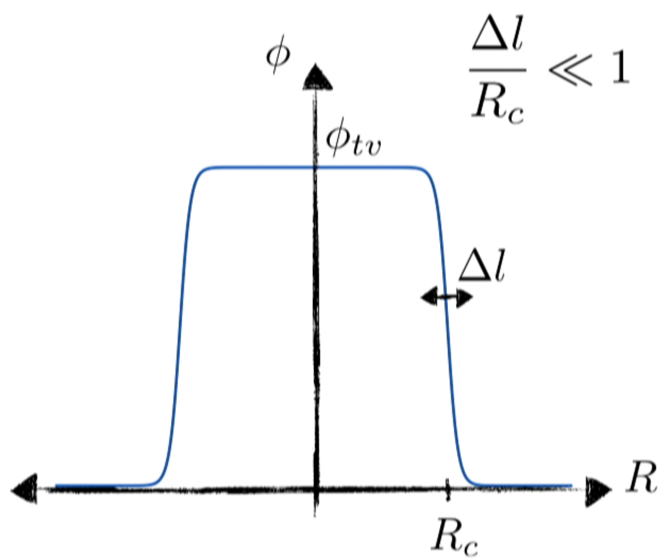
- **Thin wall** bubbles arise in the case of nearly degenerate vacua:



Thin-Wall Bounce

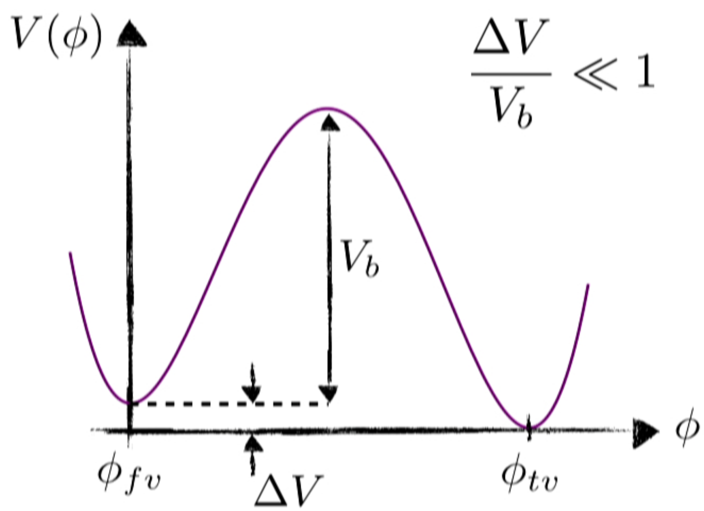
- **Thin wall** bubbles arise in the case of nearly degenerate vacua:

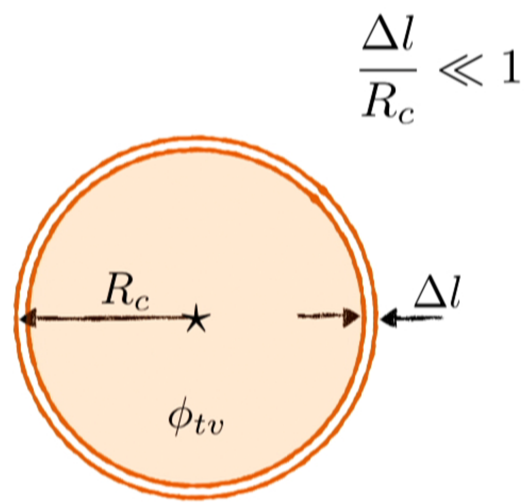




Thin-Wall Bounce

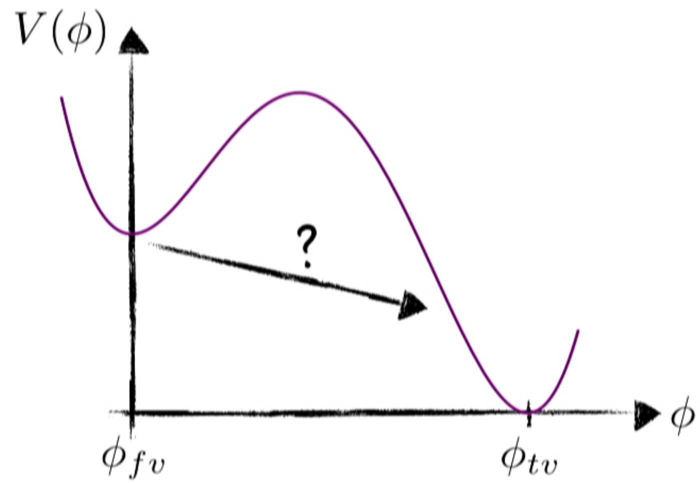
- **Thin wall** bubbles arise in the case of nearly degenerate vacua:





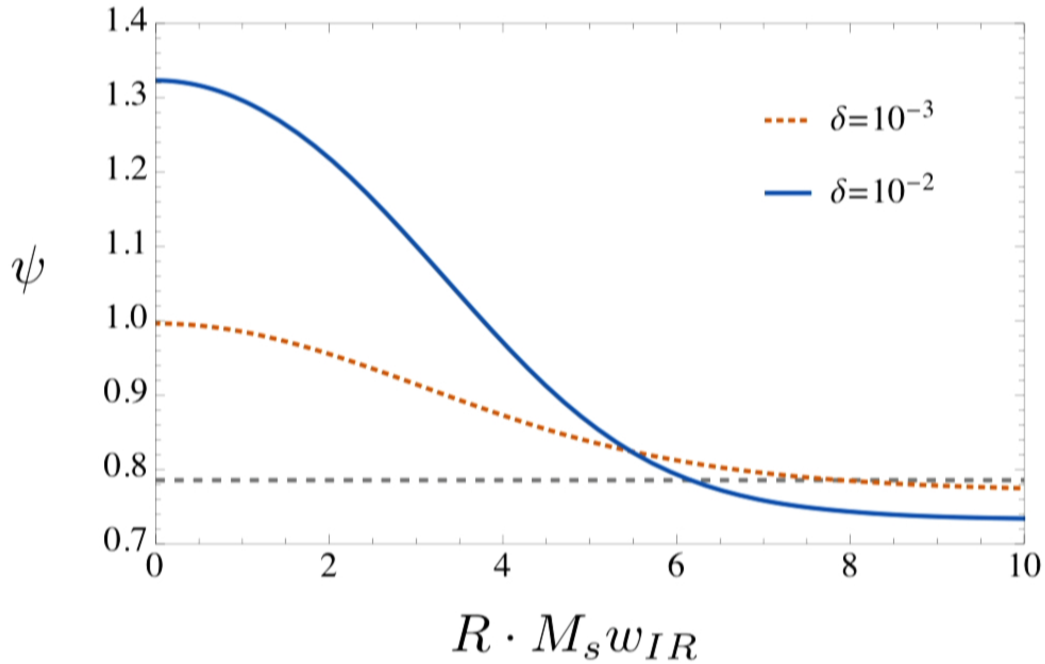
General Bounce?

- In general, finding the bounce solution requires a numerical calculation. Moreover, the value of the field at the centre is typically **not the true vacuum…**



Our Bounce

- In our case, we always find thick-wall bounces:



Our Decay Rate

- And a decay rate per unit volume:

$$\Gamma \sim m^4 e^{-B}$$

set by curvature scale at the top of the barrier

$$B = 2\pi^2 \mu_3 b_0^4 g_s M^3 f(\delta) \approx 36 \frac{g_s}{0.03} \left(\frac{M}{10^2} \right)^3 \frac{f(\delta)}{f(10^{-3})}$$

$$f(\delta) \approx 0.38\ \delta^{1/2} + 6.0\ \delta$$

$$m^4 \approx \frac{2^{11} \pi b_0^8 r_c}{(1+b_0^4)^5} (M_s w_{IR})^4\ \delta \approx 17\ (M_s w_{IR})^4\ \delta$$

Nucleation & Expansion

- Bubbles of true vacuum start being nucleated when $\Gamma/H(T_n)^4 \approx 1$, and they are (approximately) spherical and at rest.

on average, one bubble per Hubble volume

Nucleation & Expansion

- Bubbles of true vacuum start being nucleated when $\Gamma/H(T_n)^4 \approx 1$, and they are (approximately) spherical and at rest.

  on average, one bubble per Hubble volume

- Moreover:

$$\frac{R_c}{H^{-1}(T_n)} \ll 1$$

Bubbles are tiny!

The mean separation between nucleated bubbles is a Hubble length

Nucleation & Expansion

- Bubbles of true vacuum start being nucleated when $\Gamma/H(T_n)^4 \approx 1$, and they are (approximately) spherical and at rest.

  on average, one bubble per Hubble volume

- Moreover:

$$\frac{R_c}{H^{-1}(T_n)} \ll 1$$

Bubbles are tiny!

The mean separation between nucleated bubbles is a Hubble length

- These bubbles start growing, and quickly start expanding with wall velocities very close to c.

Nucleation & Expansion

- But as bubbles expand, T drops, so $\Gamma/H(T)^4$ grows.

How does the transition complete?

A few bubbles become very large?

very large number of small bubbles?

Nucleation & Expansion

- But as bubbles expand, T drops, so $\Gamma/H(T)^4$ grows.

How does the transition complete?

A few bubbles become very large?

very large number of small bubbles?

- For us, $\Gamma/H(T)^4$ grows slowly as T drops.
The transition completes when a few large bubbles collide. This happens a time Δt after nucleation:

$$\Delta t \approx 1.6\ t_n \sim H(T_n)^{-1} \qquad T_c \approx 0.6\ T_n$$

~ radius of colliding bubbles

Nucleation & Expansion

- At the time of collision, our bubbles are expanding ultra-relativistically:

$$v_{\rm wall}(t_c) = \frac{t_c}{\sqrt{t_c^2 + R_c^2}} \approx \frac{H(t_n)^{-1}}{\sqrt{H(t_n)^{-2} + R_c^2}} \approx 1$$

- and have a very large gamma factor — the bubble wall is now very Lorentz contracted:

$$\gamma(t_c) = \frac{\sqrt{t_c^2 + R_c^2}}{R_c} \sim \frac{H(t_n)^{-1}}{R_c} \sim 10^4$$

Differences With Thermal

T= 0 case

- Bubble walls reach ultra-relativistic limit:

$$v \approx 1$$

Thermal case

- Thermal plasma (usually) prevents relativistic limit:

$$v \sim 0.01 - 0.1$$

see e.g. Caprini *et al.* arXiv:1512.06239

Differences With Thermal

T= 0 case

- Bubble walls reach ultra-relativistic limit:

$$v \approx 1$$

- $\Gamma/H(T)^4$ grows slowly as T drops:

$$t_* \sim \Delta t \sim H(T_n)^{-1}$$

Thermal case

- Thermal plasma (usually) prevents relativistic limit:

$$v \sim 0.01 - 0.1$$

- $\Gamma(T)/H(T)^4$ grows very fast (exponentially!):

$$t_* \ll H(T_n)^{-1}$$

see e.g. Caprini *et al.* arXiv:1512.06239

Differences With Thermal

T= 0 case

- Bubble walls reach ultra-relativistic limit:

$$v \approx 1$$

- $\Gamma/H(T)^4$ grows slowly as T drops:

$$t_* \sim \Delta t \sim H(T_n)^{-1}$$

- Main source of GW is bubble wall collisions.

Thermal case

- Thermal plasma (usually) prevents relativistic limit:

$$v \sim 0.01 - 0.1$$

- $\Gamma(T)/H(T)^4$ grows very fast (exponentially!):

$$t_* \ll H(T_n)^{-1}$$

- Other sources of GW: e.g. turbulence in plasma.

see e.g. Caprini *et al.* arXiv:1512.06239

GW Signal — Frequency

- Ultra-relativistic bubble wall collisions lead to a stochastic GW spectrum with an approximate peak frequency today:

$$f_0 \sim 10^{-5}\ \text{Hz}\ \left(\frac{g_*(T_c)}{100}\right)^{1/6}\left(\frac{T_c}{100\ \text{GeV}}\right)\frac{1}{t_* H(T_c)}$$

temperature of the visible sector at collision

$$T_c \approx 0.6\ T_n$$

duration of transition

$$t_* H(T_c) = \mathcal{O}(1)$$

GW Signal — Frequency

- Ultra-relativistic bubble wall collisions lead to a stochastic GW spectrum with an approximate peak frequency today:

$$f_0 \sim 10^{-5}\ \text{Hz} \left(\frac{g_*(T_c)}{100}\right)^{1/6} \left(\frac{T_c}{100\ \text{GeV}}\right) \frac{1}{t_* H(T_c)}$$

temperature of the visible sector at collision

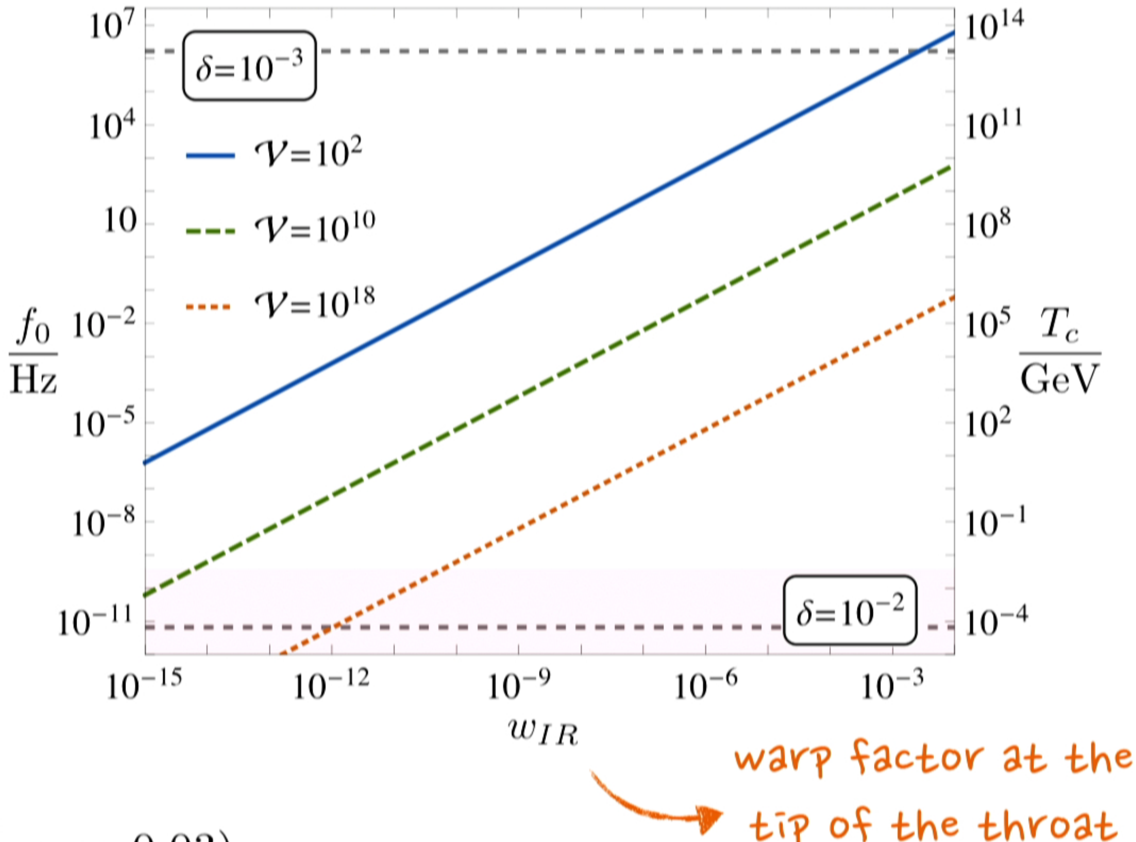
$T_c \approx 0.6\, T_n$

duration of transition

$t_* H(T_c) = \mathcal{O}(1)$

- T_c is very sensitive to the underlying details of the throat: f_0 scans the possible parameter space.

GW Signal — Frequency

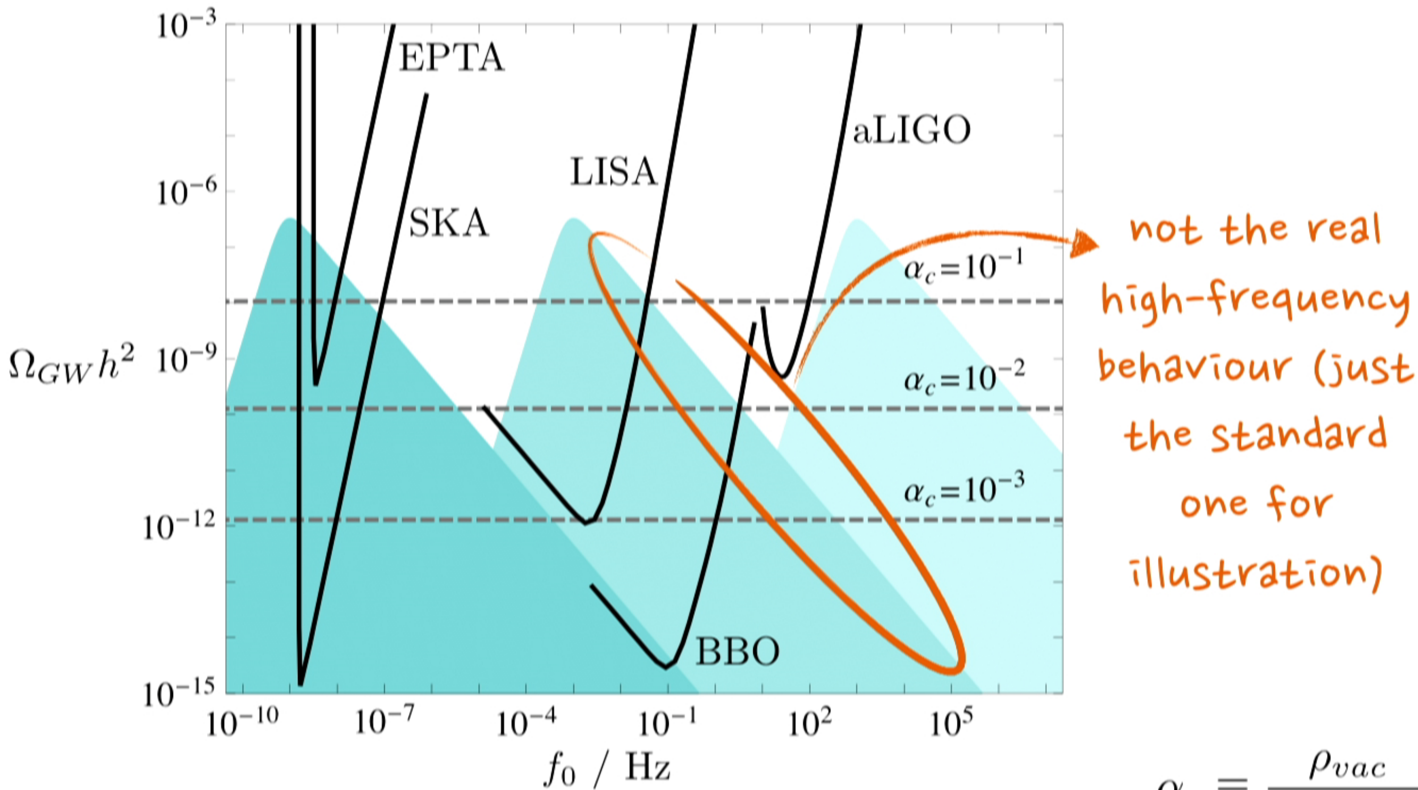


$(M = 10^2, g_s = 0.03)$

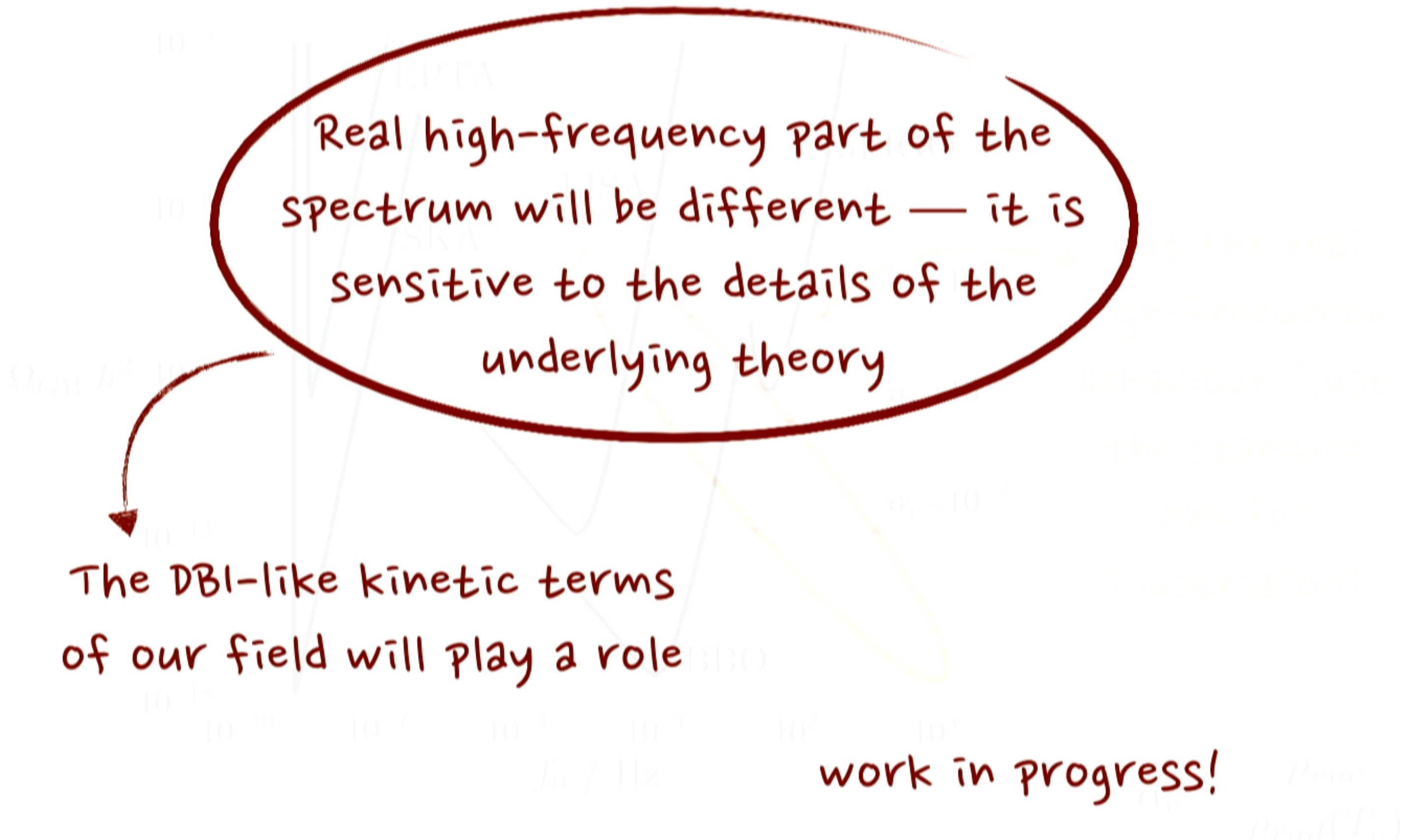
All that is required is at least one of the throats being in the false vacuum, with δ in a suitable range

of course this is not guaranteed, but not unreasonable

GW Signal — Strength



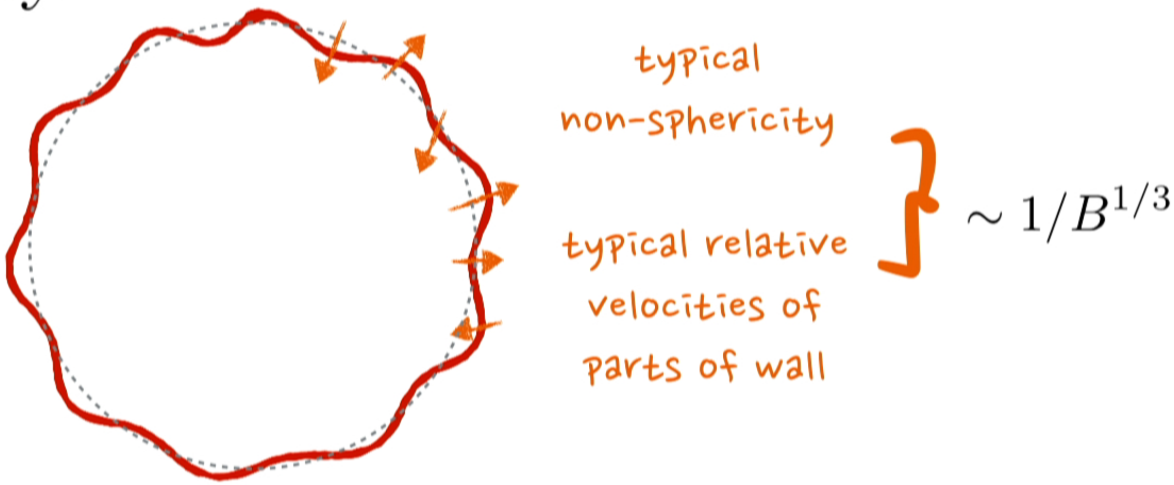
$$\alpha_c \equiv \frac{\rho_{vac}}{\rho_{rad}(T_c)}$$


Real high-frequency part of the spectrum will be different — it is sensitive to the details of the underlying theory
The DBI-like kinetic terms of our field will play a role
work in progress!

High-f Behaviour

- Nucleated bubbles are spherical and at rest… up to small corrections due to field configurations whose action is $\hbar$ from $S_E[\psi_B]$.

Really:



High-f Behaviour

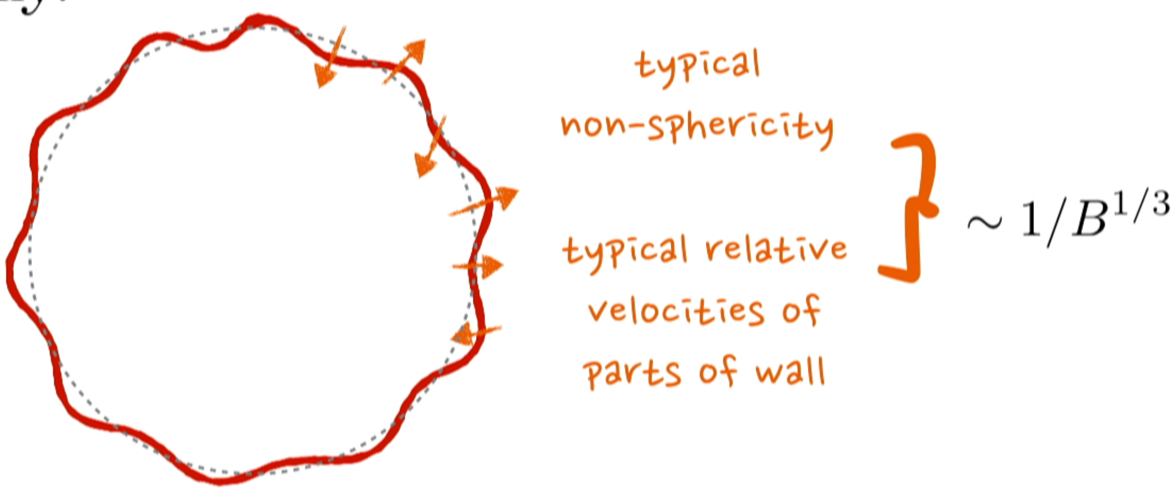
- These fluctuations define a new length scale in the transverse direction to the bubble expansion (they do not get Lorentz contracted).

- Later evolution of these fluctuations is complicated (in general, not known).

High-f Behaviour

- Nucleated bubbles are spherical and at rest… up to small corrections due to field configurations whose action is $\hbar$ from $S_E[\psi_B]$.

Really:



High-f Behaviour

- These fluctuations define a new length scale in the transverse direction to the bubble expansion (they do not get Lorentz contracted).

High-f Behaviour

- These fluctuations define a new length scale in the transverse direction to the bubble expansion (they do not get Lorentz contracted).
- Later evolution of these fluctuations is complicated (in general, not known).
- Likely to play a role in the shape of the high-frequency region of the GW signal, as well as in the exciting possibility of BH production at collision.

very much work in progress!

Conclusions

- GW detectors will help shape the future of physics in the coming century.
- They can complement the information we get from particle colliders and DM detection experiments.
- GW signals from string theory is just an example of how they might help probe the highest energy scales!

exciting !!!