

PHASE TRANSITION IN THE RANDALL-SUNDRUM MODEL

Mariano Quirós

Institute of High Energy Physics (IFAE)



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*Based on works done in collaboration with:
T. Konstandin, E. Megías, G. Nardini, A. Wulzer (2006-2021)*

- The *simplest* and perhaps *more elegant* solution to the naturalness problem is provided by **SUPERSYMMETRY**
- It provides a technical solution to the hierarchy problem:
TeV scale is not sensitive to UV physics
- The pros of SUSY are well known,... but of course there are also some cons
 1. SUSY does not explain why $TeV \ll M_{Pl}$
 2. Not clear mechanism of SUSY BREAKING
 3. Not clear solution to the μ problem

Contents

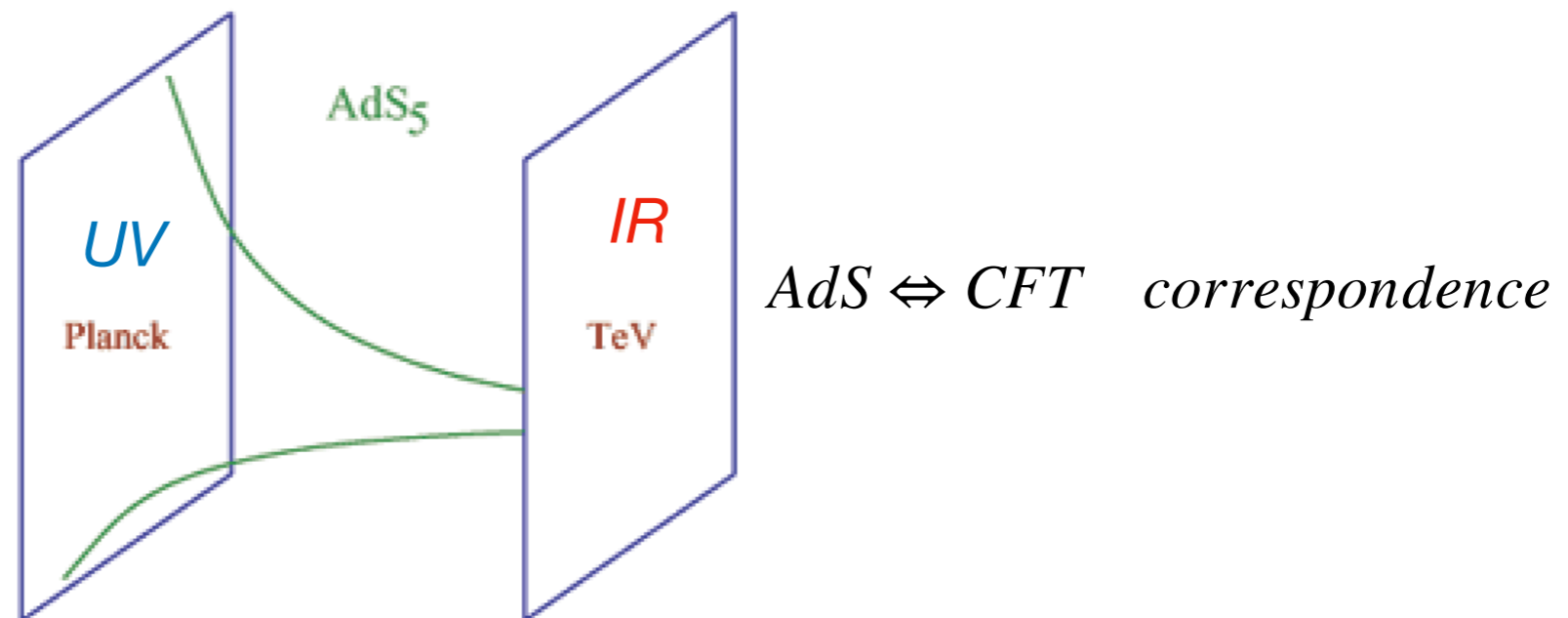
- A (well known) alternative to SUSY: warped extra dimension
- Collider challenges
- First order phase transitions: confinement/deconfinement, electroweak
- Gravitational wave signatures
- Conclusions and Outlook

Warped extra dimension as a solution to the hierarchy problem (in a nutshell)

- Proposed in 1999 by L. Randall and R. Sundrum (RS) *Randall-Sundrum, 9905221*
- It was based on AdS_5 space with line element $ds^2 = e^{-2A} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$, $A = ky$
RS

$$k \sim M_{Pl}, \quad \rho \sim TeV = e^{-A(y_1)} k, \quad A(y_1) \sim 35$$

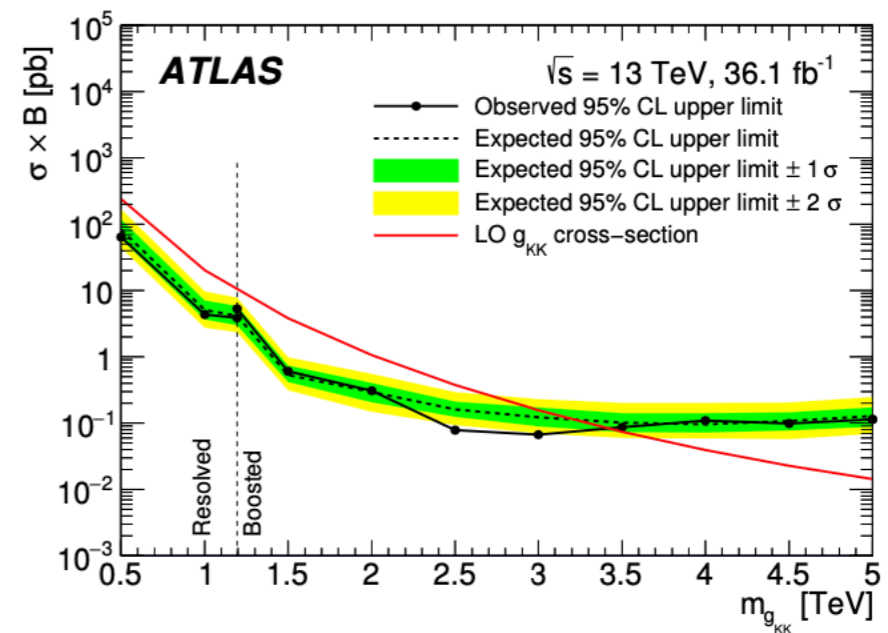
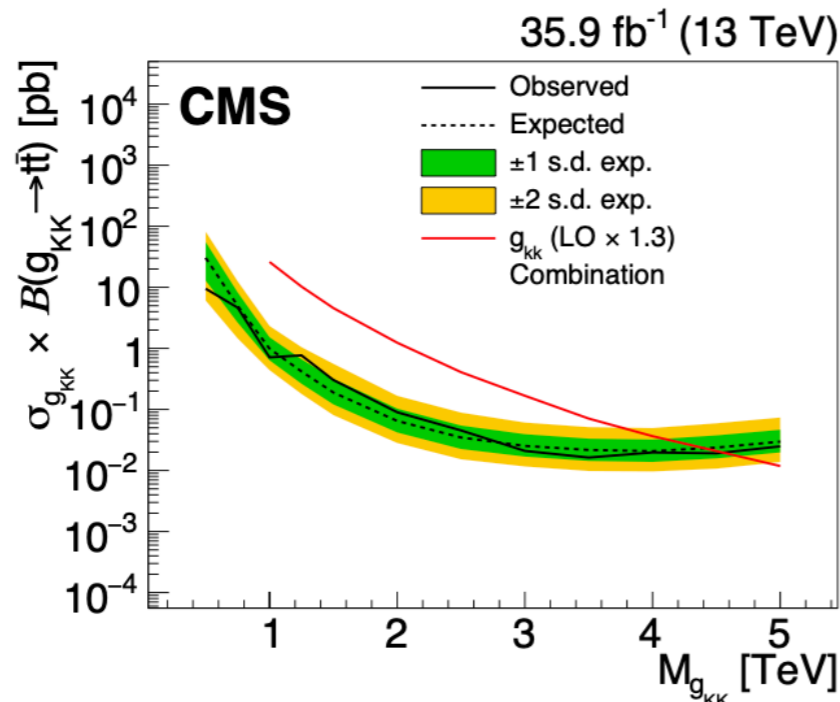
- With two branes



- The Higgs is localized toward the **IR** brane (**composite**):
- Heavy (light) fermions are localized toward the **IR** (**UV**) brane: **composite** (**elementary**)
- The theory predicts **TeV KK resonances**, localized toward the **IR** brane (**composite**)

Collider challenges

- The LHC data are putting severe bound on the mass of the lightest KK resonances, e.g. for KK gluons:



- These limits point toward the possibility that nature might have chosen values of $\rho \gg TeV$
- The warped factor still explaining the relation $\rho \Leftrightarrow M_{Pl}$
- But a **little hierarchy problem** of course would remain for $\rho \gg 1 TeV$
- Heavy KK resonances would **escape LHC detection** \Rightarrow More energetic colliders...

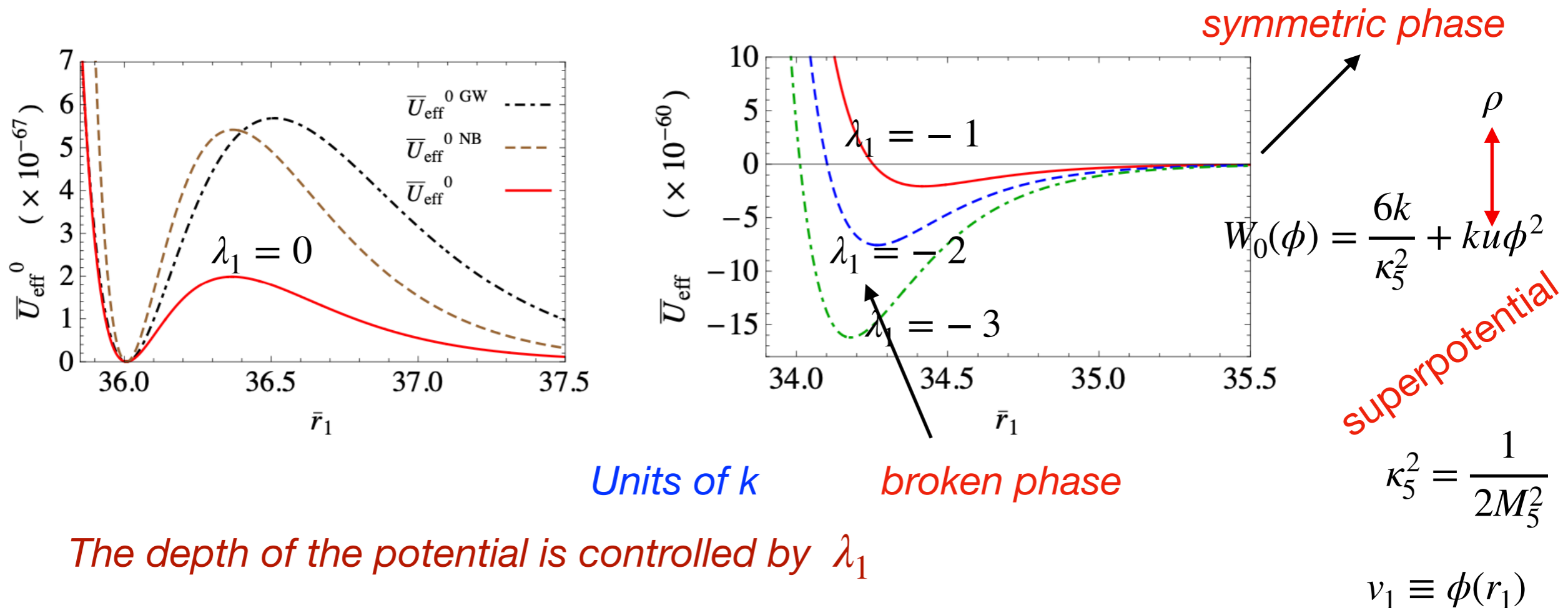
or by GW's detection...? (this talk)

Phases in the RS theory

- The theory with a warped extra dimension and two branes requires stabilization of the brane distance
- This is achieved by a bulk scalar field ϕ with brane (and bulk) potentials, creating an **effective potential** in terms of the **radion field**
Goldberger-Wise, 9907447
- At low temperature the Higgs is confined: **confinement phase**
- At high temperature the Higgs melts and there is another phase: **deconfinement phase**
- The phase transition from the deconfined to the confined phase is first order and can give rise to a stochastic GW background (SGWB).
P. Creminelli et al., 0107141

The confined phase

- The effective potential at zero temperature is a function of the brane distance r_1 and depends on the IR tension λ_1 defined as $\Lambda_1 + W_0(v_1) \equiv 12 k M_5^3 \lambda_1$ *E. Megias et al., 2005.04127*



The depth of the potential is controlled by λ_1

The deconfined phase

- At finite temperature the system allows for an additional 5D gravitational solution with a black hole (BH) singularity located in the bulk

$$ds_{BH}^2 = -\frac{1}{h(y)}dy^2 + e^{-2A(y)}[h(y)dt^2 - d\vec{x}^2]$$

blackening factor $h(y_h) = 0$

- In the AdS/CFT correspondence this BH metric describes the high temperature phase of the system where the radion is sent to its symmetric phase
- The phase transition starts when the free energy of the BH deconfined phase equals the free energy of the confined phase


all fields except IR ones (composite)

$$F_d(T) = E_0 + F_{min} - \frac{\pi^2}{90} g_d^{eff} T^4$$


all fields

$$F_c(T) = -\frac{\pi^2}{90} g_c^{eff} T^4$$

Potential depth



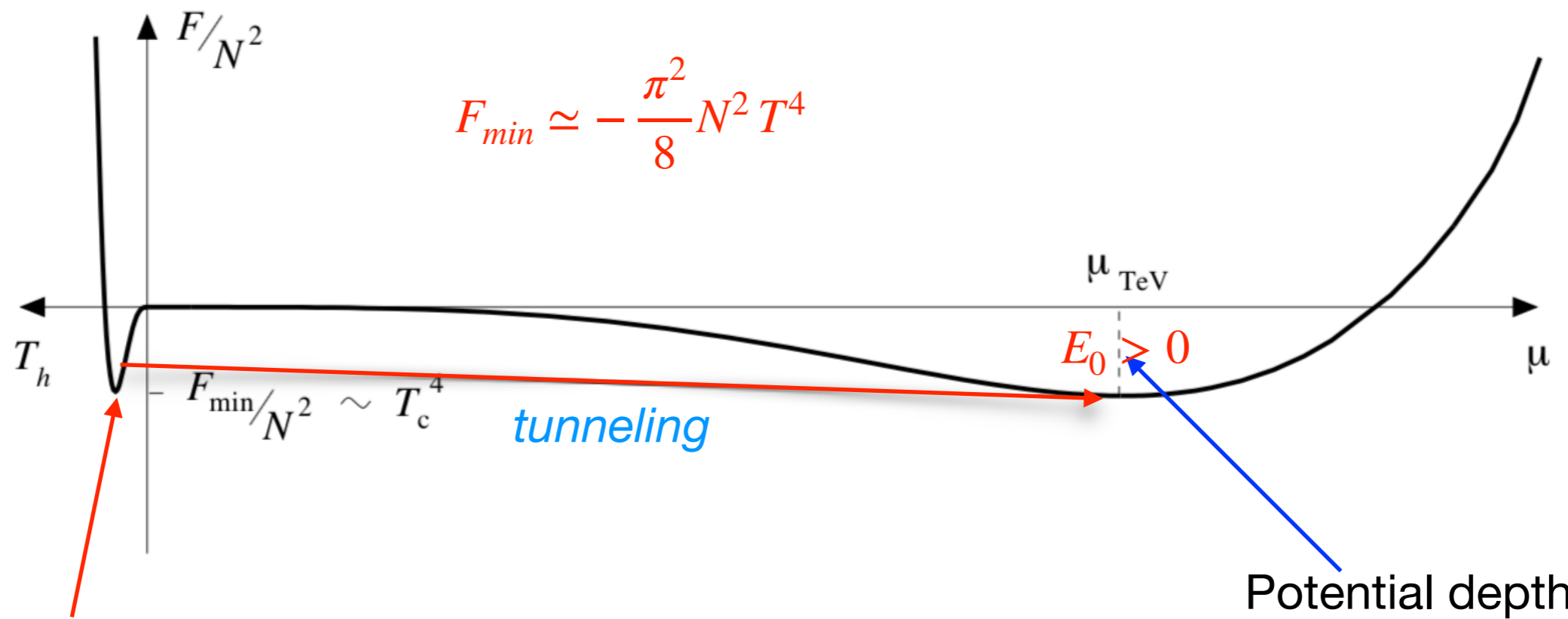
Depth in the BH phase



Deconfinement/confinement phase transition

Cartoon

P. Creminelli et al., 0107141



Depth in the BH phase

The phase transition

- Phase transition takes place when the bubble nucleation rate equals the universe expansion rate at T_n
- This happens when the euclidean action S_n , with $O(n)$ symmetry [$n=3$ ($n=4$) high temperature (low temperature)], becomes $\sim 10^2$
- In the thick wall approximation:

$$S_3(T) \simeq \frac{\sqrt{3}N^2\rho^3}{\pi T\sqrt{E_0 + F_{min}}}, \quad S_4(T) \simeq \frac{9N^2\rho^4}{4(E_0 + F_{min})}$$

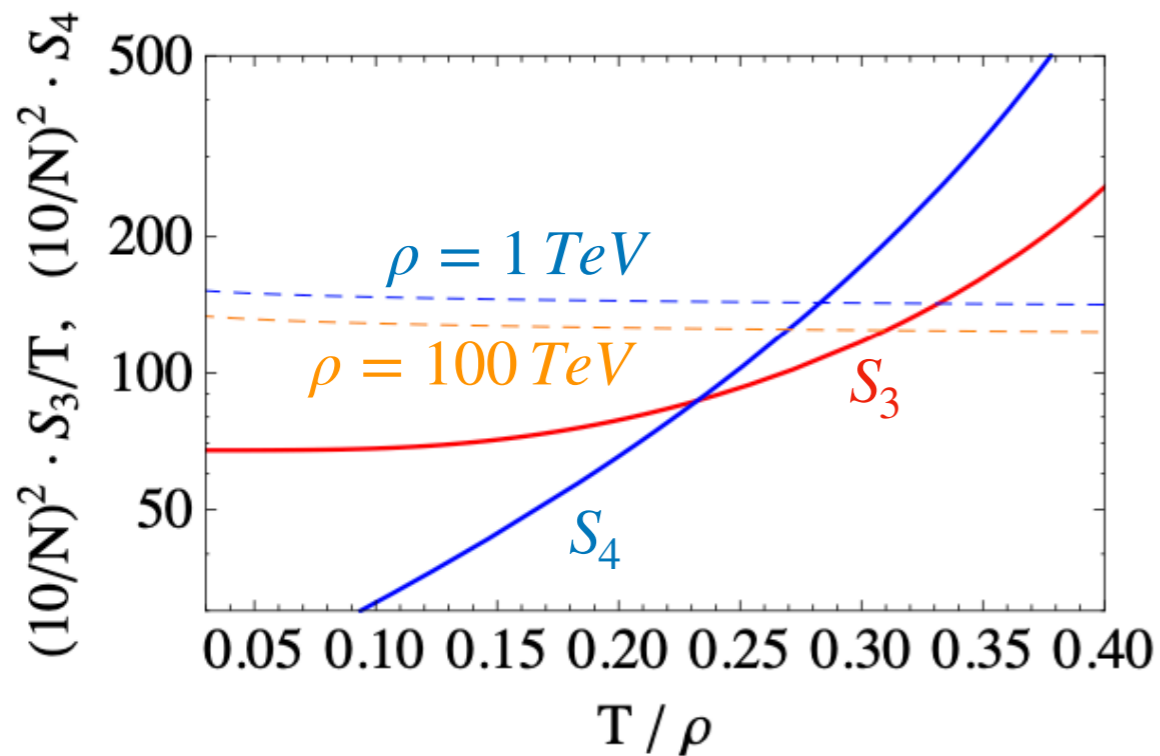
Controlled by λ_1

- The value of nucleation temperature T_n depends on euclidean actions which in turn depend on: (λ_1, N)
- N^2 is the # of degrees of freedom in the holographic theory $SU(N)$
- By means of the AdS/CFT duality, N is connected to k through the 5D square gravitational coupling constant $G_5^2 \equiv (k/M_5)^3$ via

$$\frac{N^2}{16\pi^2} = G_5^{-2}$$
- The 5D gravitational theory is weakly coupled in the limit $N \gg 1$
- However in the limit $N \rightarrow \infty$ there is no phase transition as $S_n \rightarrow \infty$!!!

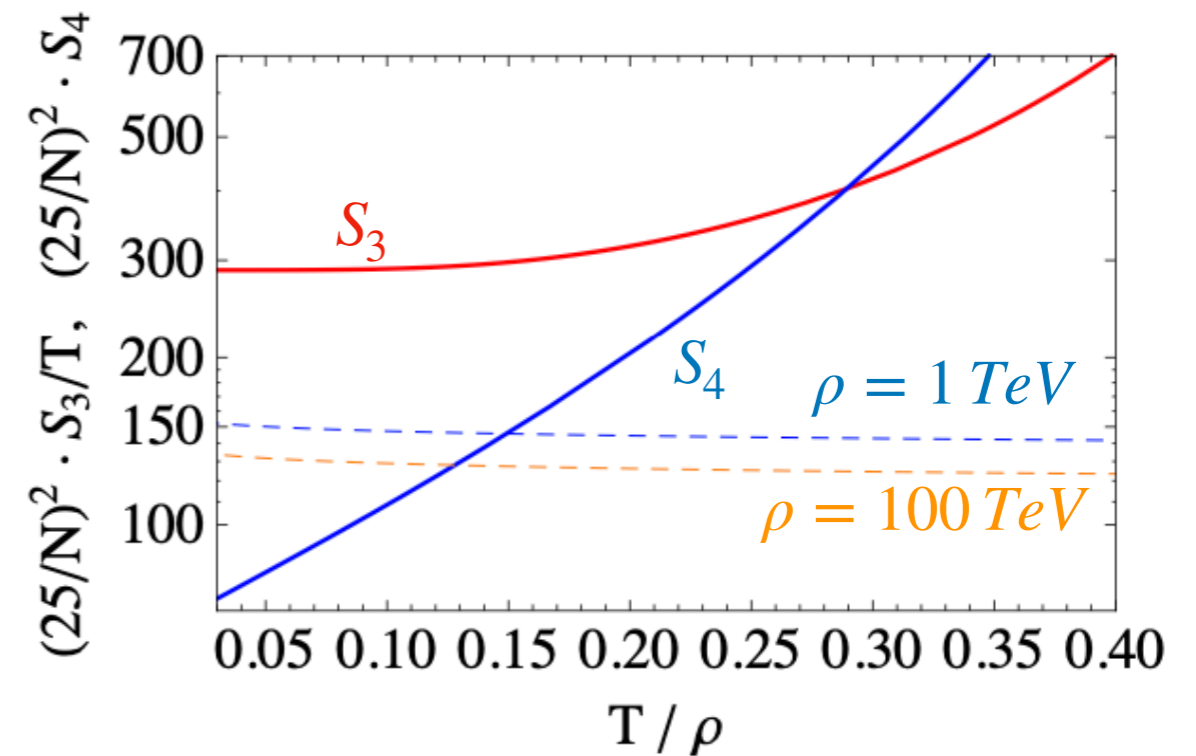
- The idea is to keep N large, but not too much to not forbid the phase transition
- T_n decreases with increasing N and decreasing $|\lambda_1|$

$$N = 10, \quad \lambda_1 = -3$$



At high temperature

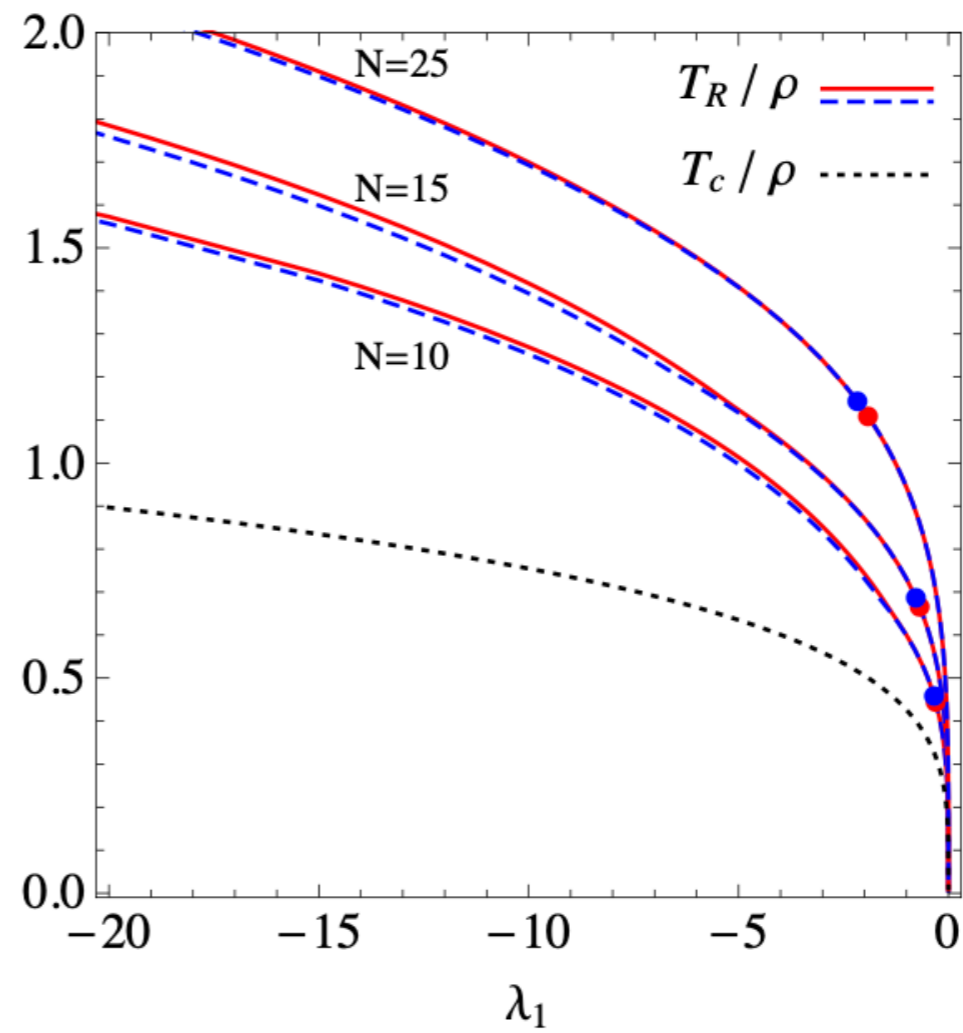
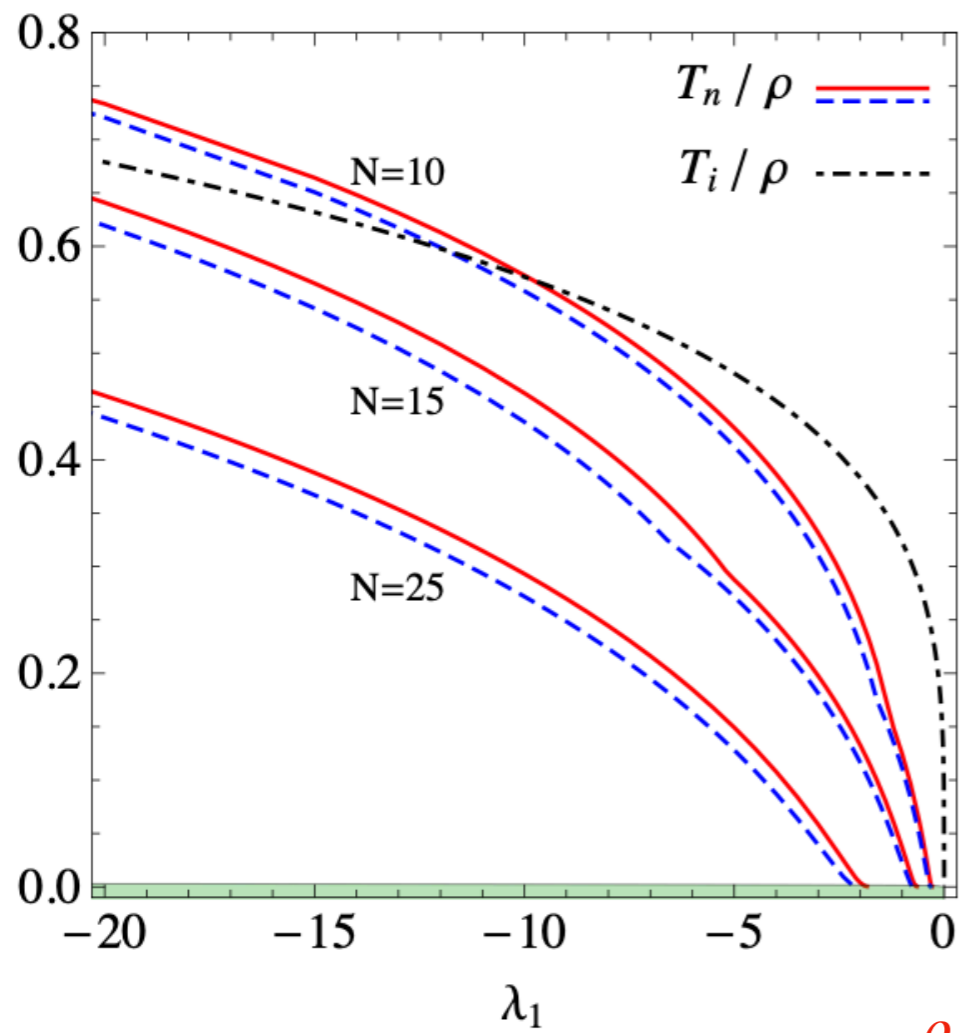
$$N = 25, \quad \lambda_1 = -5$$



At low temperature

- When the radion χ [$\langle\chi\rangle = \rho$] phase transition happens the nucleation temperature is smaller than the VEV: $\rho/T_n \gg 1$ and the phase transition is **very** strong first order
- The cooling can trigger a brief period of cosmological inflation with few e-folds of inflation
- The universe ends up in the confined phase at the reheat temperature $T_R > T_n$
- In most cases (but not always) the reheat temperature is around the ρ scale

The behavior of the different temperatures as functions of N and λ_1



$\rho = 1 \text{ TeV}$

$\rho = 100 \text{ TeV}$

Gravitational waves

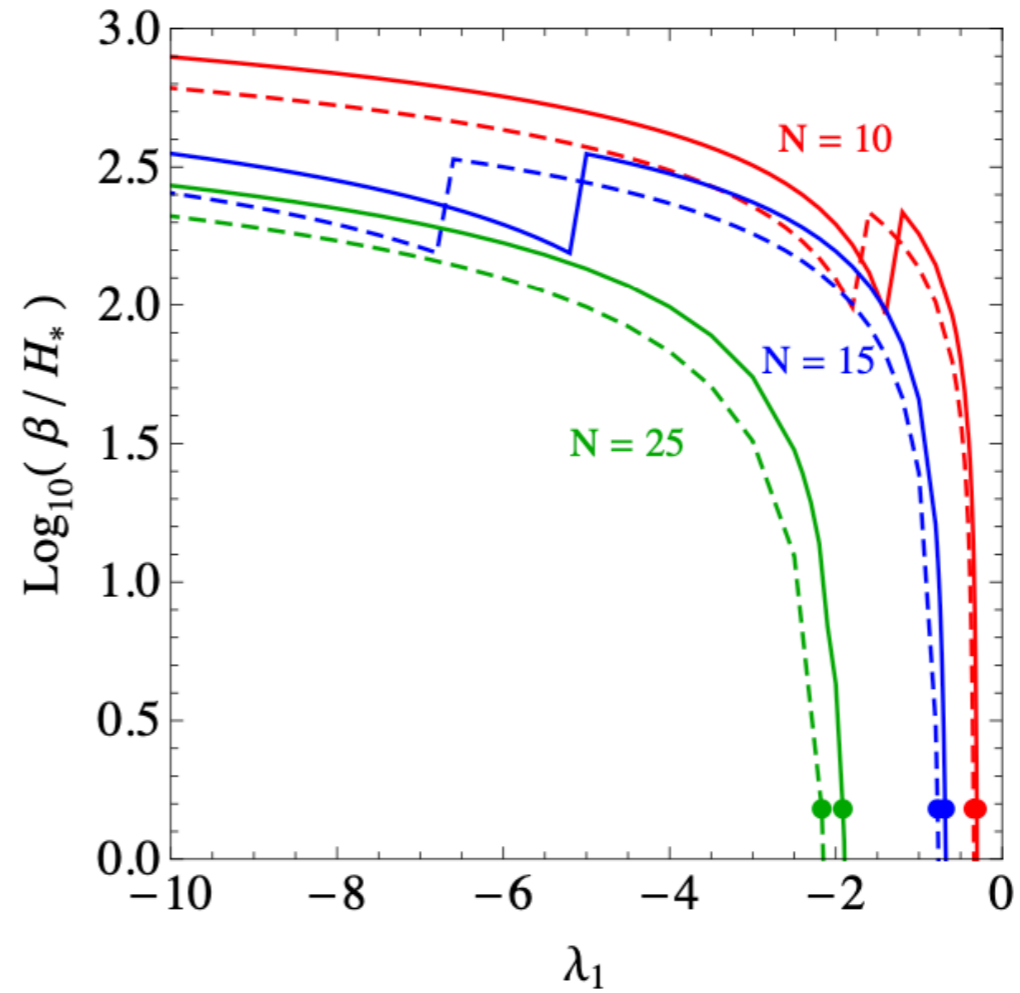
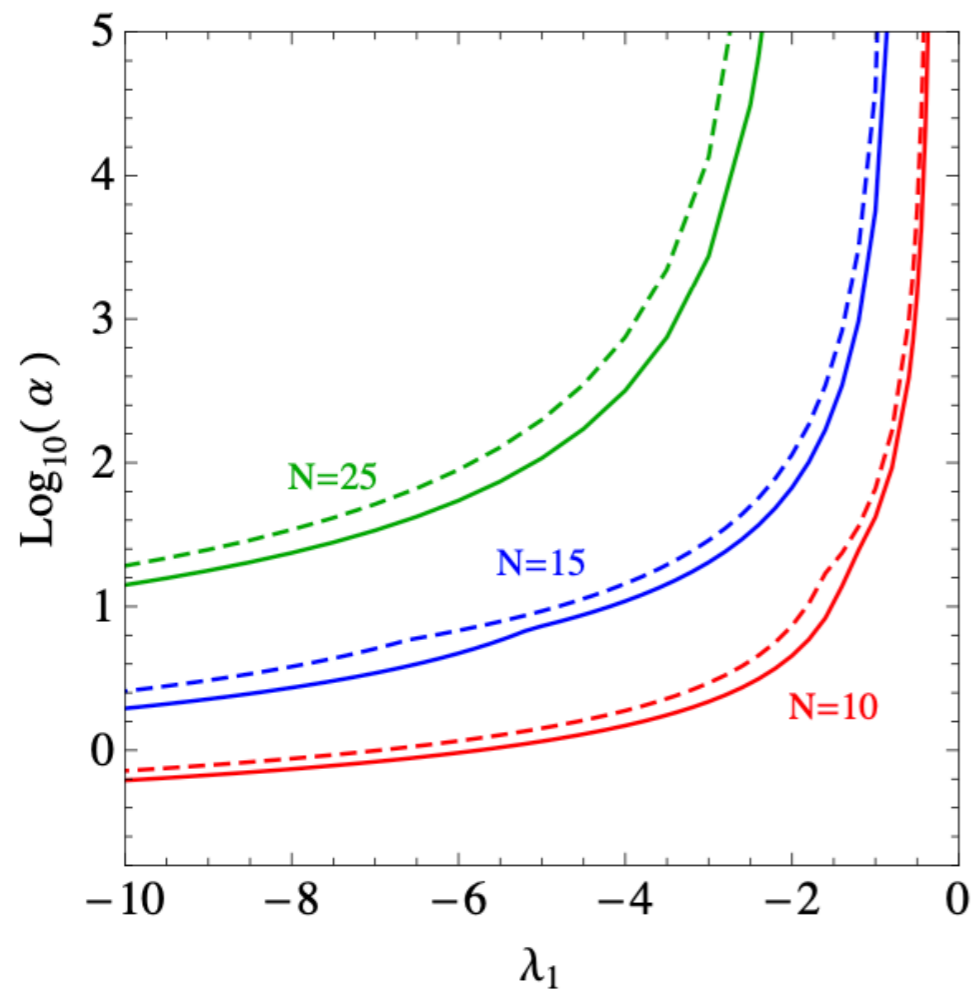
- A cosmological first order phase transition generates a **stochastic gravitational wave background** (SGWB)
- The power spectrum depends on phase transition quantities

inverse duration of phase transition

$$\alpha \simeq \frac{F_d(T_n) - F_c(T_n)}{\rho_d(T_n) - E_0} \quad \frac{\beta}{H_\star} \simeq T_n \left. \frac{dS_E}{dT} \right|_{T=T_n}$$

- In the next two decades several GW observatories will have the potential to observe, or constrain, the SGWB produced in the confinement/deconfinement phase transition

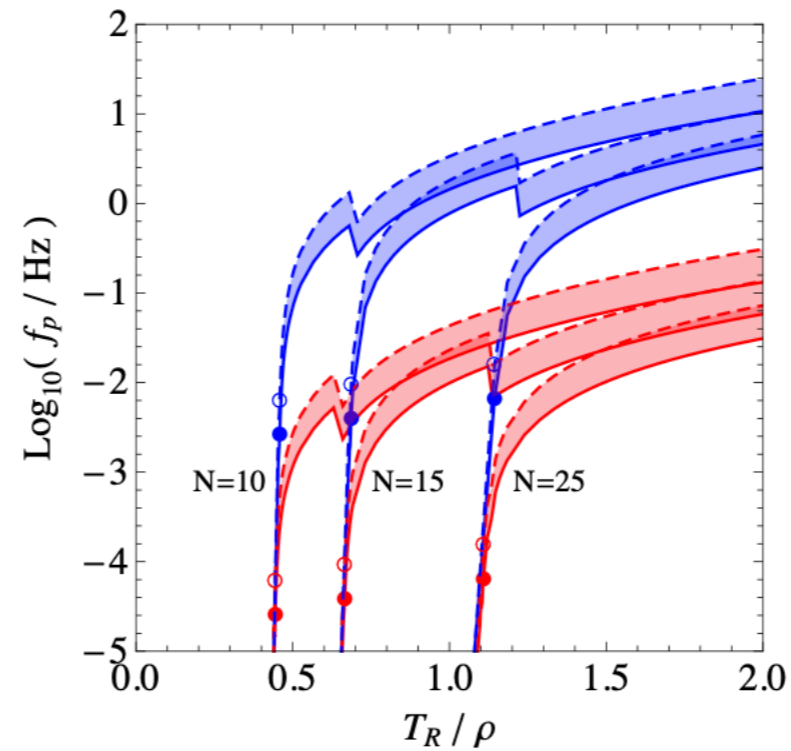
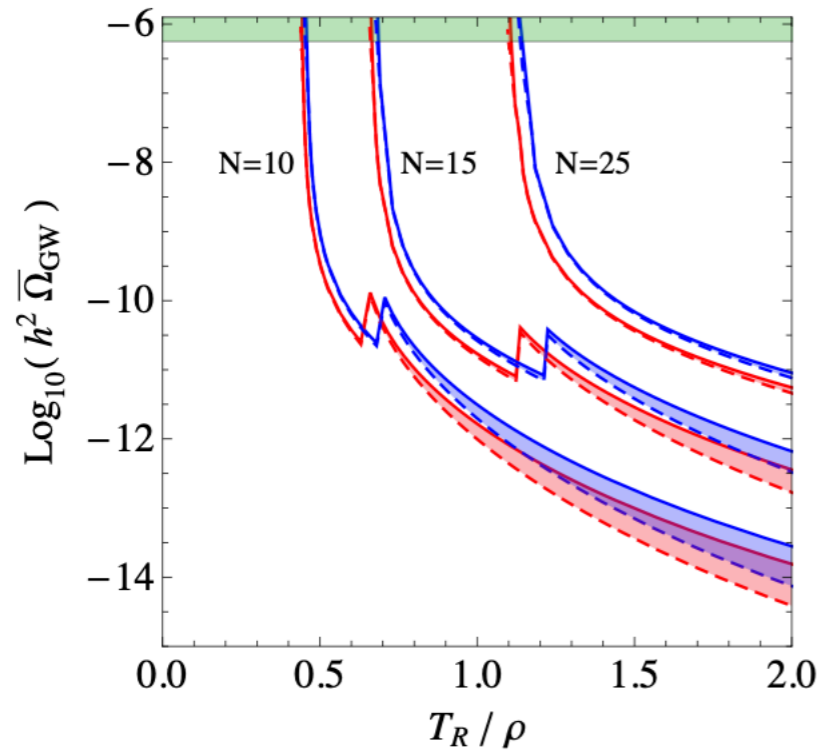
The behavior of the GW parameters in RS as functions of N and λ_1



$\rho = 1 \text{ TeV}$

$\rho = 100 \text{ TeV}$

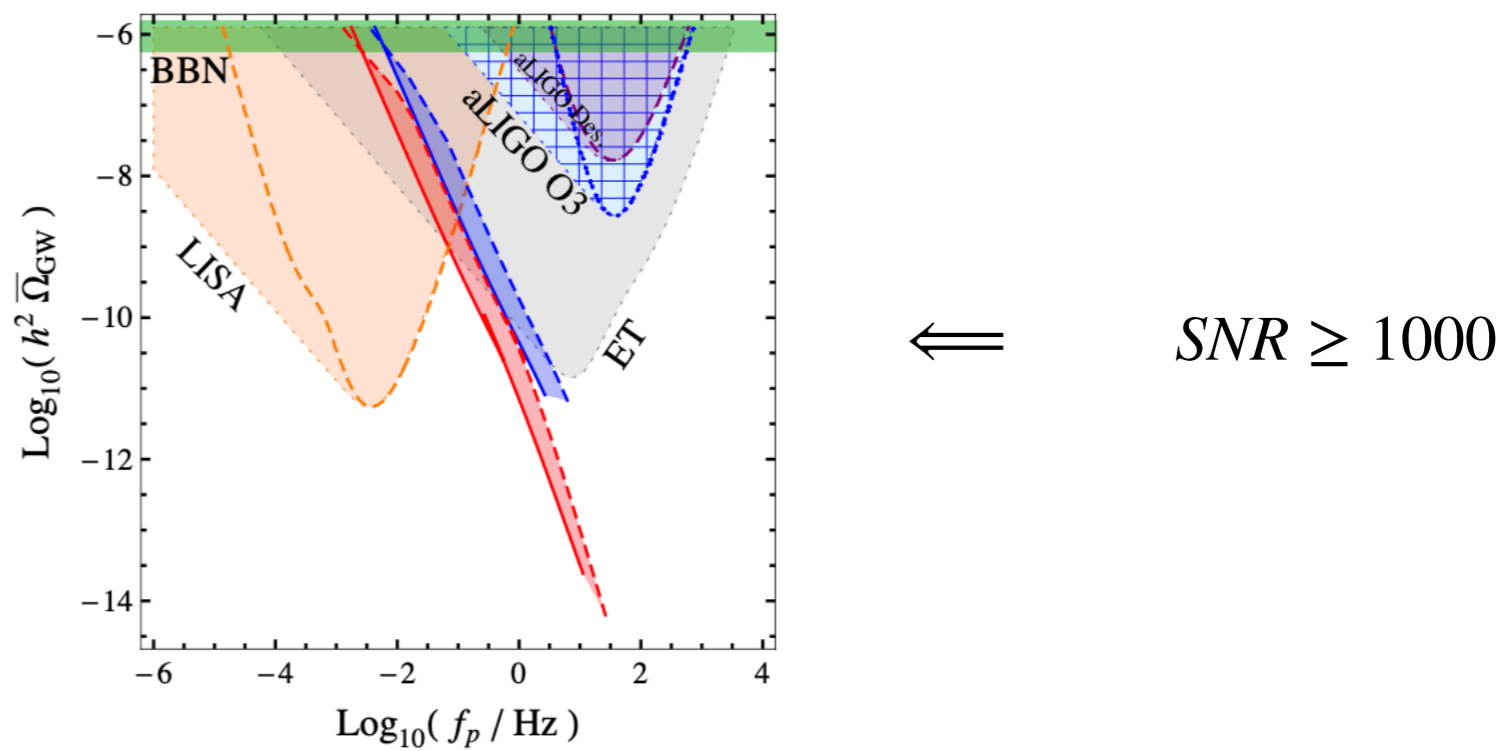
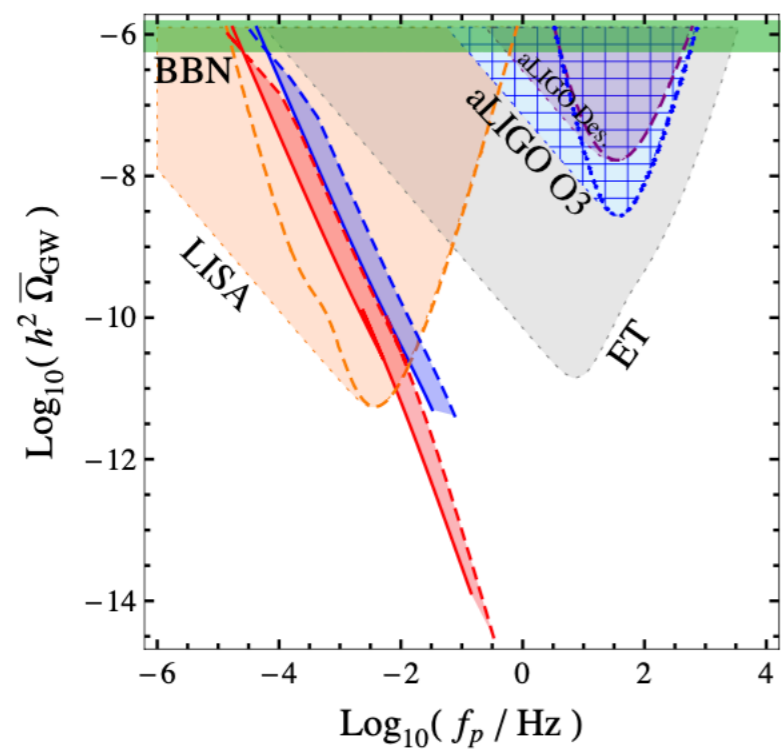
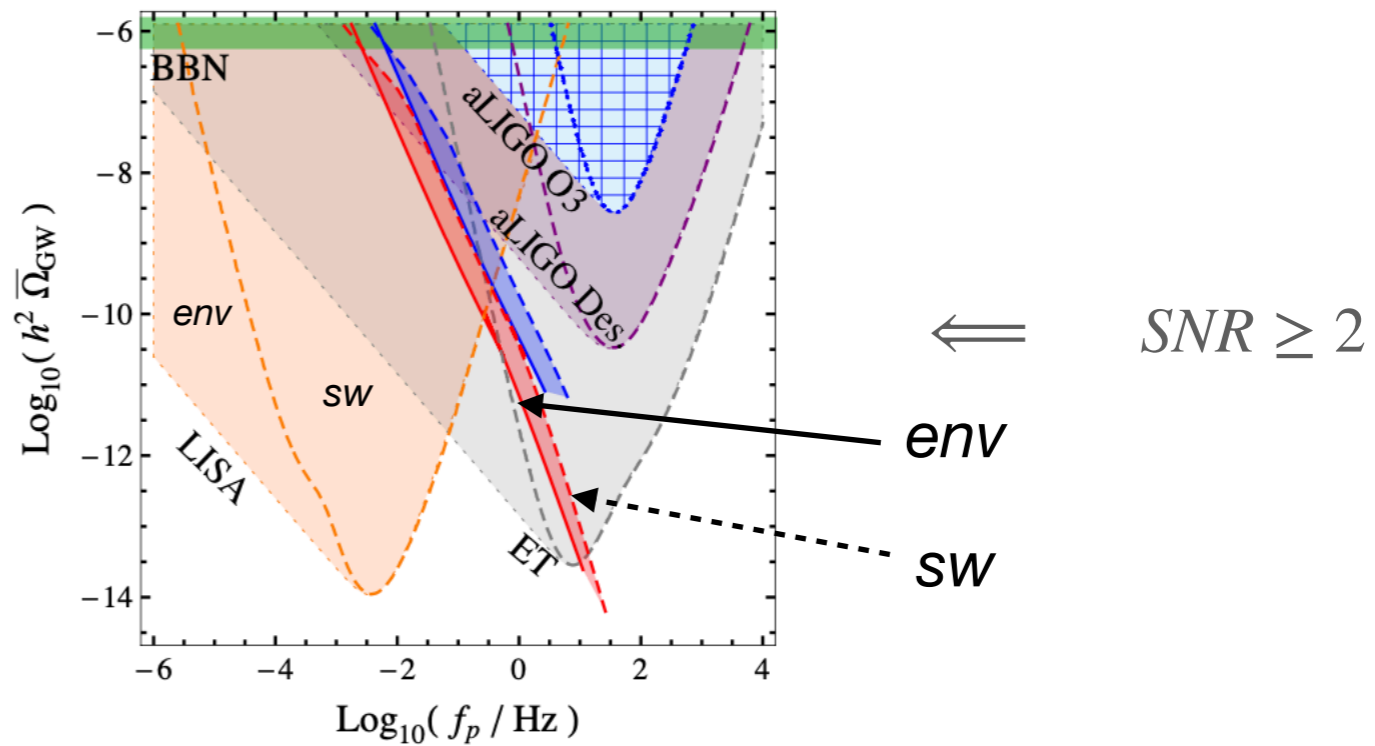
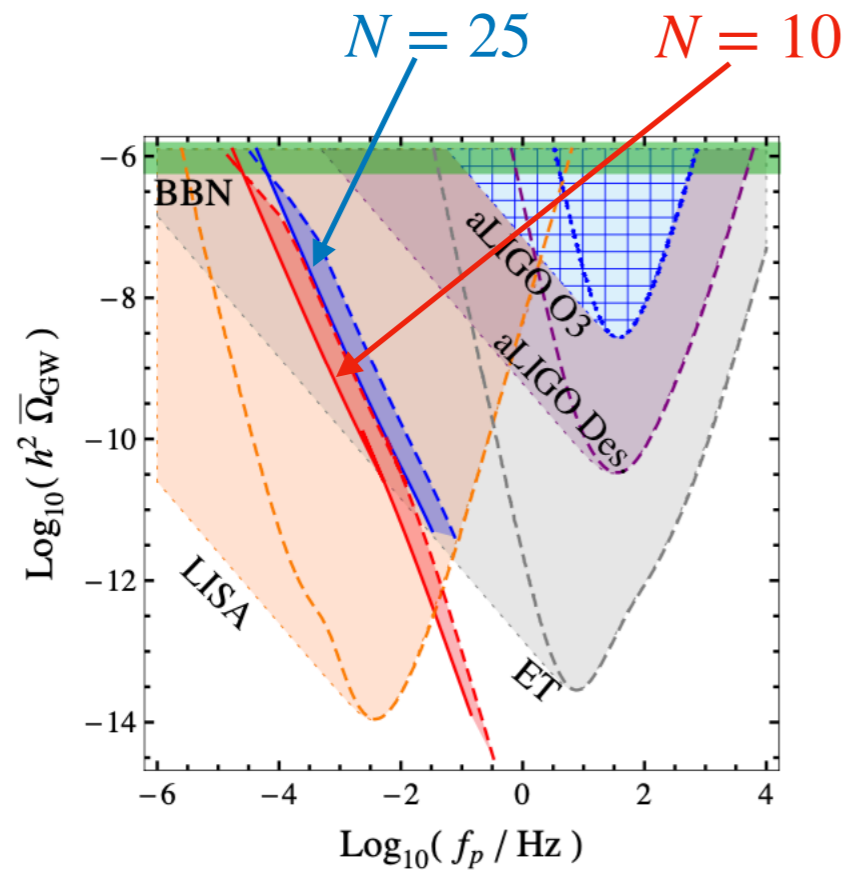
The amplitude and peak frequency in RS



Strips are between envelop (solid) and sound-wave (dashed) approximations

Red strips are for $\rho = 1 \text{ TeV}$

Blue strips are for $\rho = 100 \text{ TeV}$



\Uparrow
 $\rho = 1 \text{ TeV}$

\Uparrow
 $\rho = 100 \text{ TeV}$

Conclusions

- Warped extra dimension is an interesting possibility to solve the hierarchy problem (dual to CFT,...)
- It triggers a confinement/deconfinement first order phase transition
- Gravitational waves are useful tools to rule out the existence of the confinement/deconfinement phase transition
- If SBGW is found, different possibilities open up. Confinement/deconfinement phase transition is one of them

Outlook

- Future interferometers will thus probe heavy resonances

$$m_{KK} \lesssim 10^5 \text{ TeV (LISA)}$$

$$10^2 \text{ TeV} \lesssim m_{KK} \lesssim 10^8 \text{ TeV (aLIGO Design)}$$

$$m_{KK} \lesssim 10^9 \text{ TeV (ET)}$$

E. Megías, G. Nardini, M.Q., 2005.04127, 2103.02705