Hunting KK Modes with Gravitational Waves

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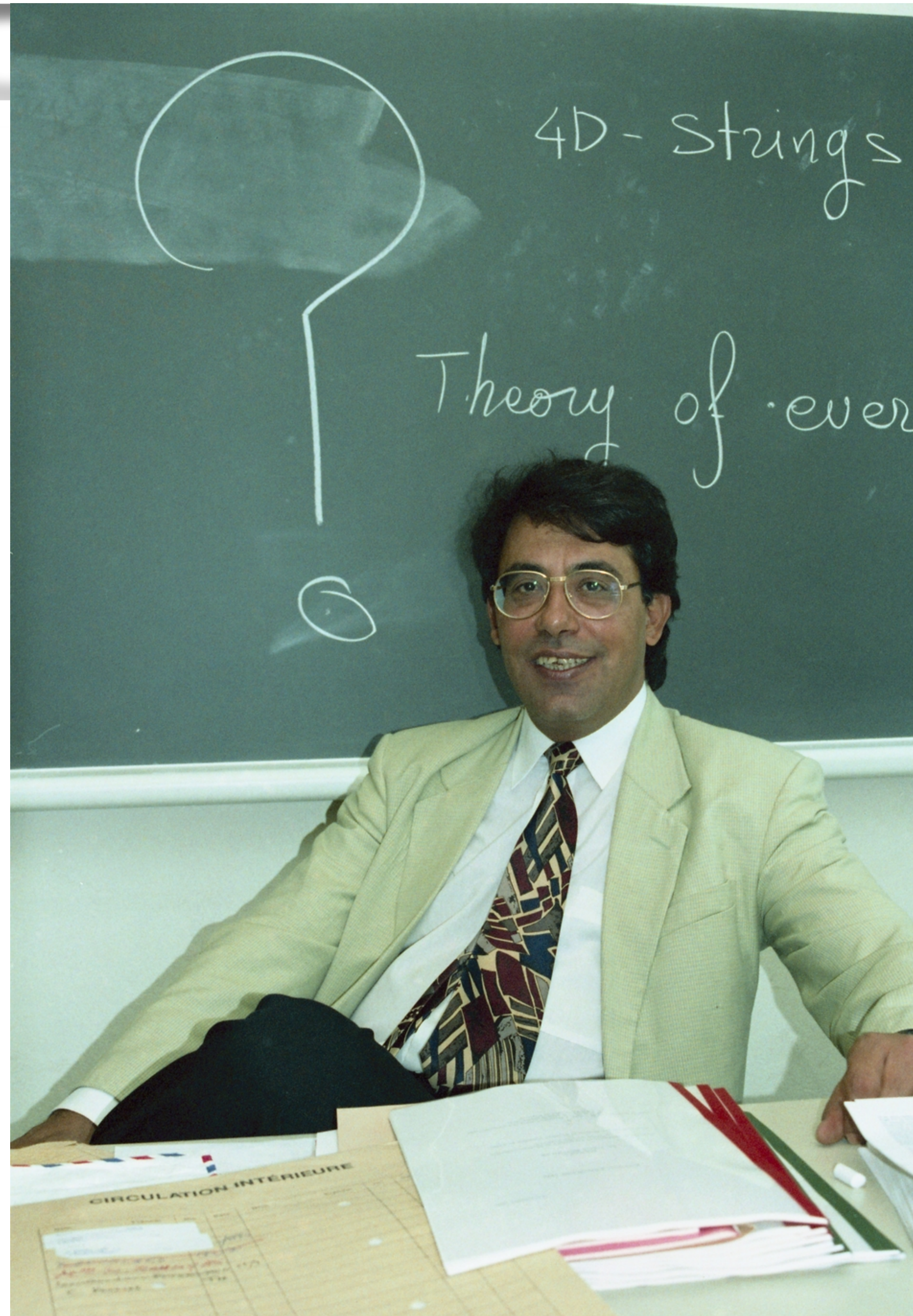
Based on works done in collaboration with:
T. Konstandin, E. Megías, G. Nardini, A. Wulzer (2006-2021)

In Memoriam of Costas Kounnas, my best friend forever



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[2] K. Enqvist, D. V. Nanopoulos, M. Quiros and C. Kounnas, "Nonminimal Supergravity at Finite Temperatures and Cosmological Applications," Nucl. Phys. B **262** (1985), 556-574, 8 citations

[3] K. Enqvist, D. V. Nanopoulos, M. Quiros and C. Kounnas, "PRIMORDIAL TWO COMPONENT MAXIMALLY SYMMETRIC INFLATION," Nucl. Phys. B **262** (1985), 538-555, 8 citations

[4] C. Kounnas and M. Quiros, "A MAXIMALLY SYMMETRIC NO SCALE INFLATIONARY UNIVERSE," Phys. Lett. B **151** (1985), 189-194, 34 citations

[5] C. Kounnas, A. B. Lahanas, D. V. Nanopoulos and M. Quiros, "Low-Energy Behavior of Realistic Locally Supersymmetric Grand Unified Theories," Nucl. Phys. B **236** (1984), 438-466, 428 citations

[6] C. Kounnas, D. V. Nanopoulos and M. Quiros, "Rapid Phase Transitions in Local SUSY GUTs," Phys. Lett. B **129** (1983), 223-228, 18 citations

[7] C. Kounnas, J. Leon and M. Quiros, "Local SUSY Breaking Induced by the GUT Phase Transition in the Early Universe," Phys. Lett. B **129** (1983), 67-71, 18 citations

[8] C. Kounnas, D. V. Nanopoulos, M. Quiros and M. Srednicki, "Natural Triplet - Doublet Splitting From Supergravity," Phys. Lett. B **127** (1983), 82-84, 45 citations

[9] C. Kounnas, A. B. Lahanas, D. V. Nanopoulos and M. Quiros, "Supergravity Induced Radiative SU(2) x U(1) Breaking with Light Top Quark and Stable Minimum," Phys. Lett. B **132** (1982), 95; 168 citations

- 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 by this audience,… 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)

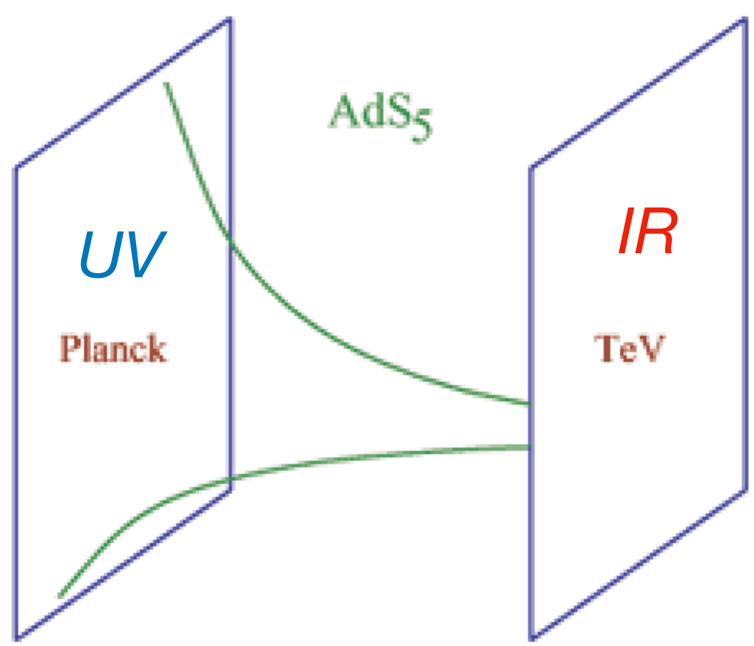
- Proposed in 1999 by L. Randall and R. Sundrum (RS) *Randall-Sundrum, 9905221*

- 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

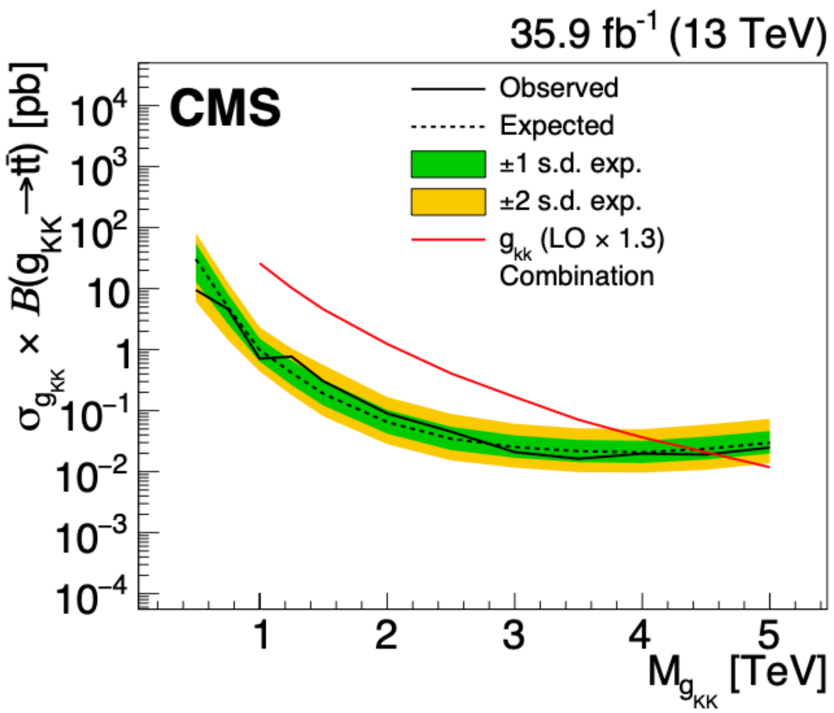


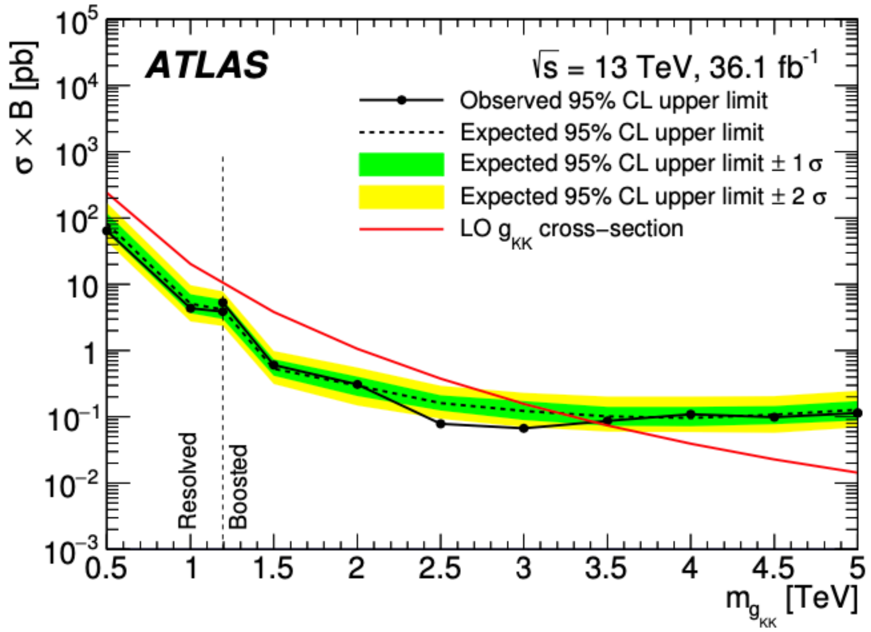
$AdS \Leftrightarrow CFT \quad correspondence$

- 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

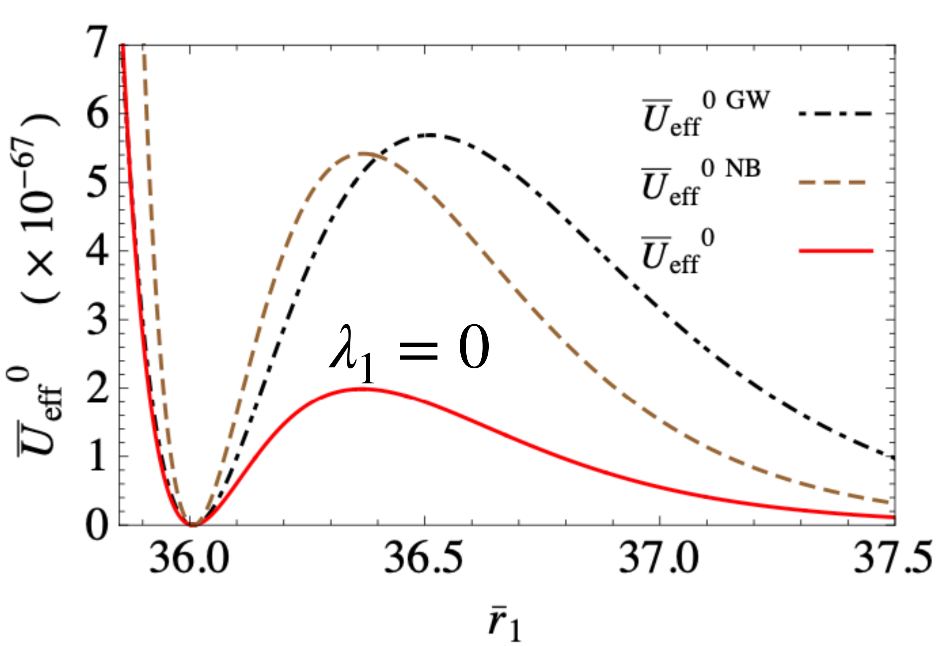
- The theory with a warped extra dimension and two branes requires stabilization of the brane distance
- This is achieved by a bulk scalar field ϕ with brane potential, creating an effective potential in terms of the radion field

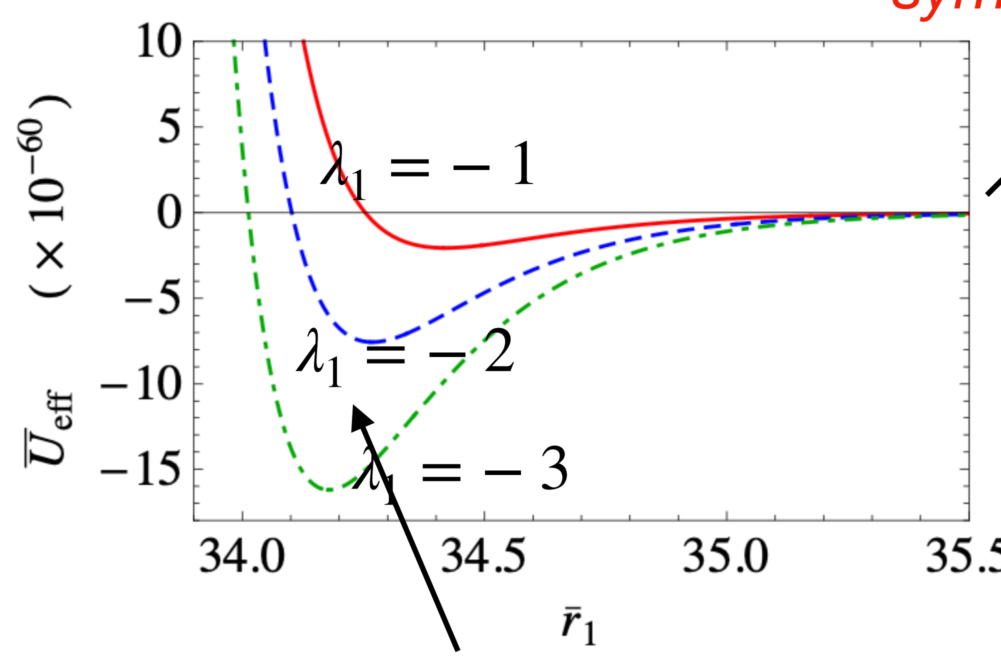
  Goldberger-Wise, 9907447
- At low temperature the Higgs is confined: confinement phase
- At high temperature the Higgs melts and there is another phase: deconfinement phase
- The phase transition from the deconfined to the confined phase is first order and can give rise to a stochastic GW background (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 $\Lambda_1 + W_0(\mathrm{v}_1) \equiv 12\, k M_5^3\, \lambda_1$ *E. Megias et al., 2005.04127*

symmetric phase





Units of k *broken phase*

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

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

$blackening\ \ factor\ h(y_h) = 0$

- 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

all fields

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

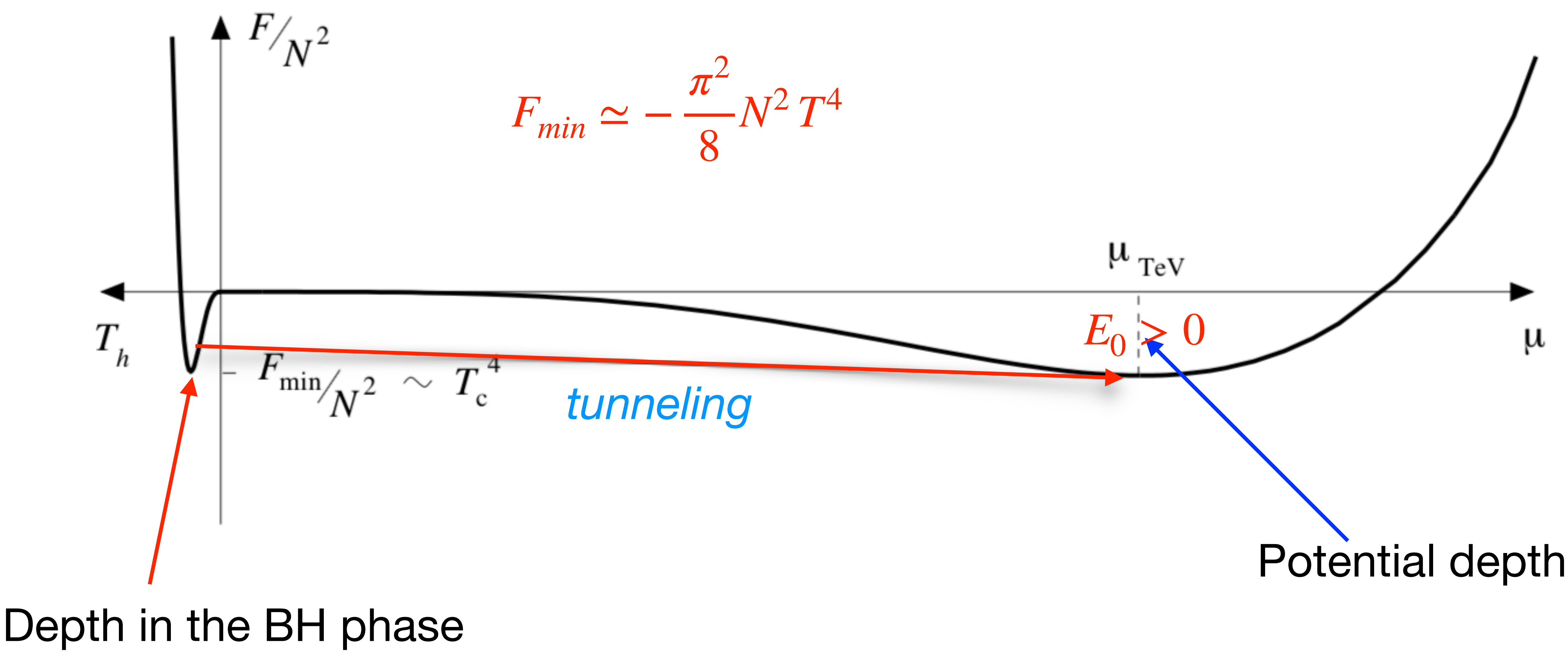
Potential depth

Depth in the BH phase

Deconfinement/confinement phase transition

Cartoon

P. Creminelli et al., 0107141



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:

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

Controlled by λ_1

- The value of nucleation temperature T_n depends on euclidean actions which in turn depend on: (λ_1, N)

- N is the # of degrees of freedom in the holographic theory

- 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 $\dfrac{N^2}{16\pi^2} = G_5^{-2}$

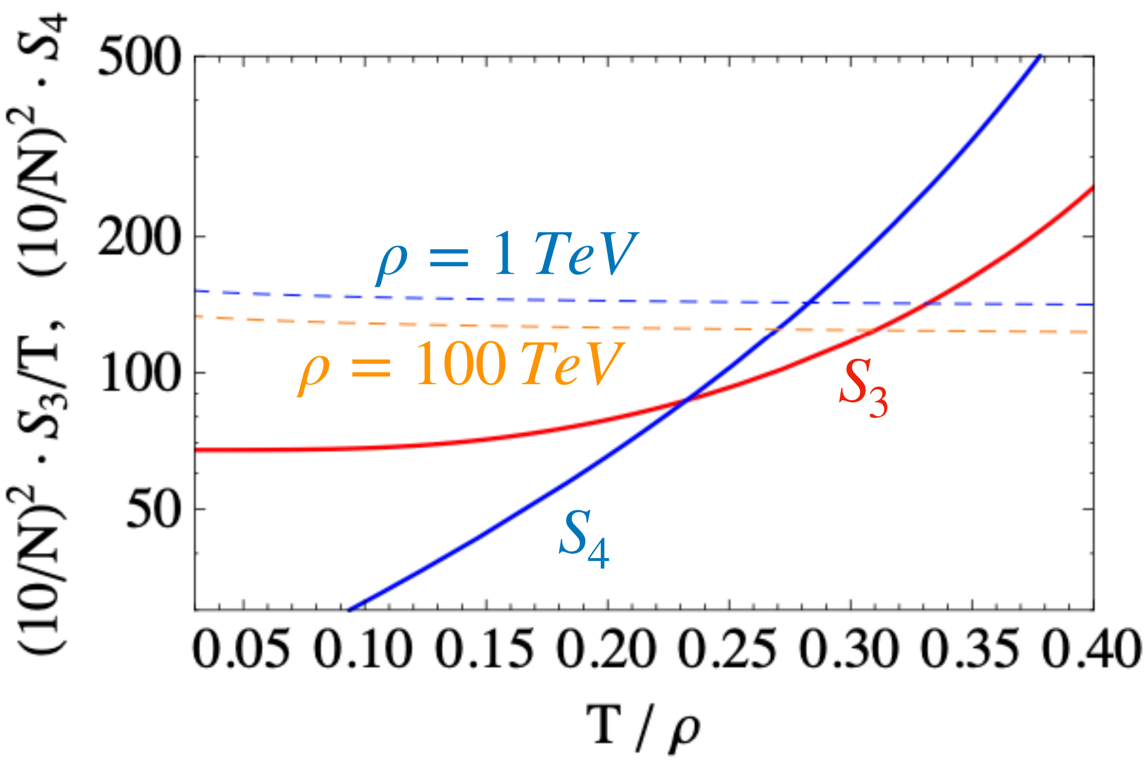
- The 5D gravitational theory is weakly coupled in the limit $N \gg 1$

- However in the limit $N \to \infty$ there is no phase transition as $S_n \to \infty$!!!

- The idea is to keep N large, but not too much to not forbid the phase transition

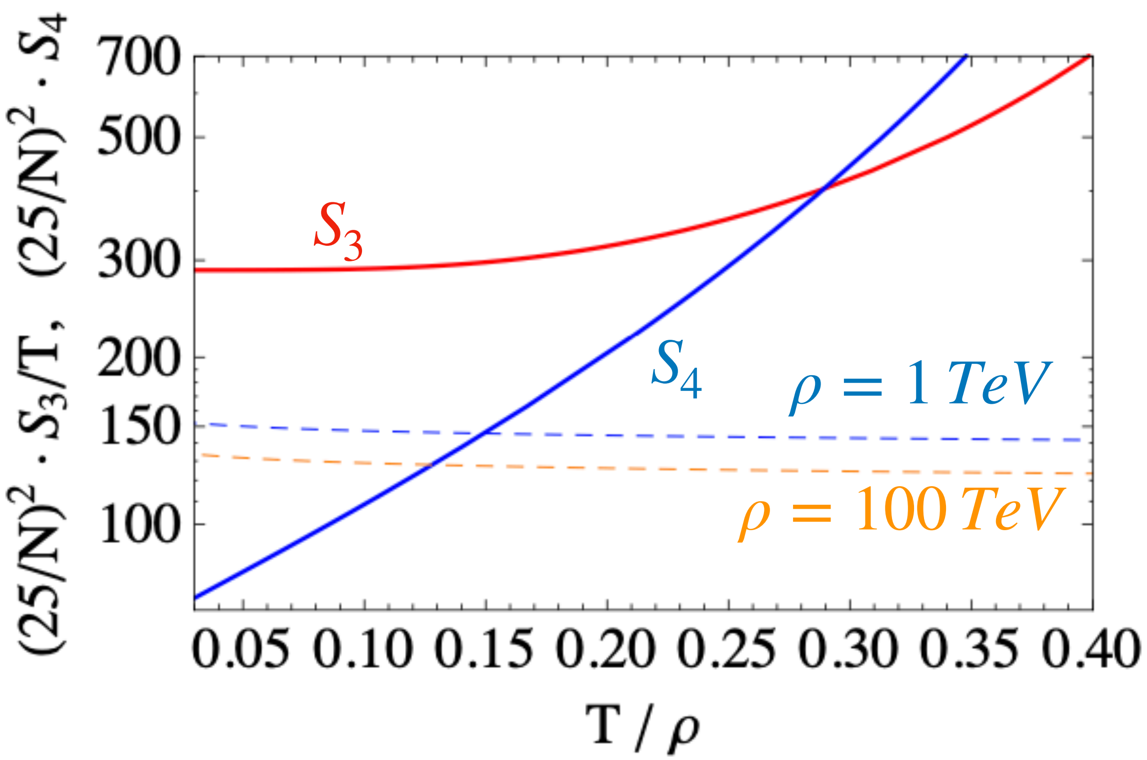
- T_n decreases with increasing N and decreasing $|\lambda_1|$

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



At high temperature

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



At low temperature

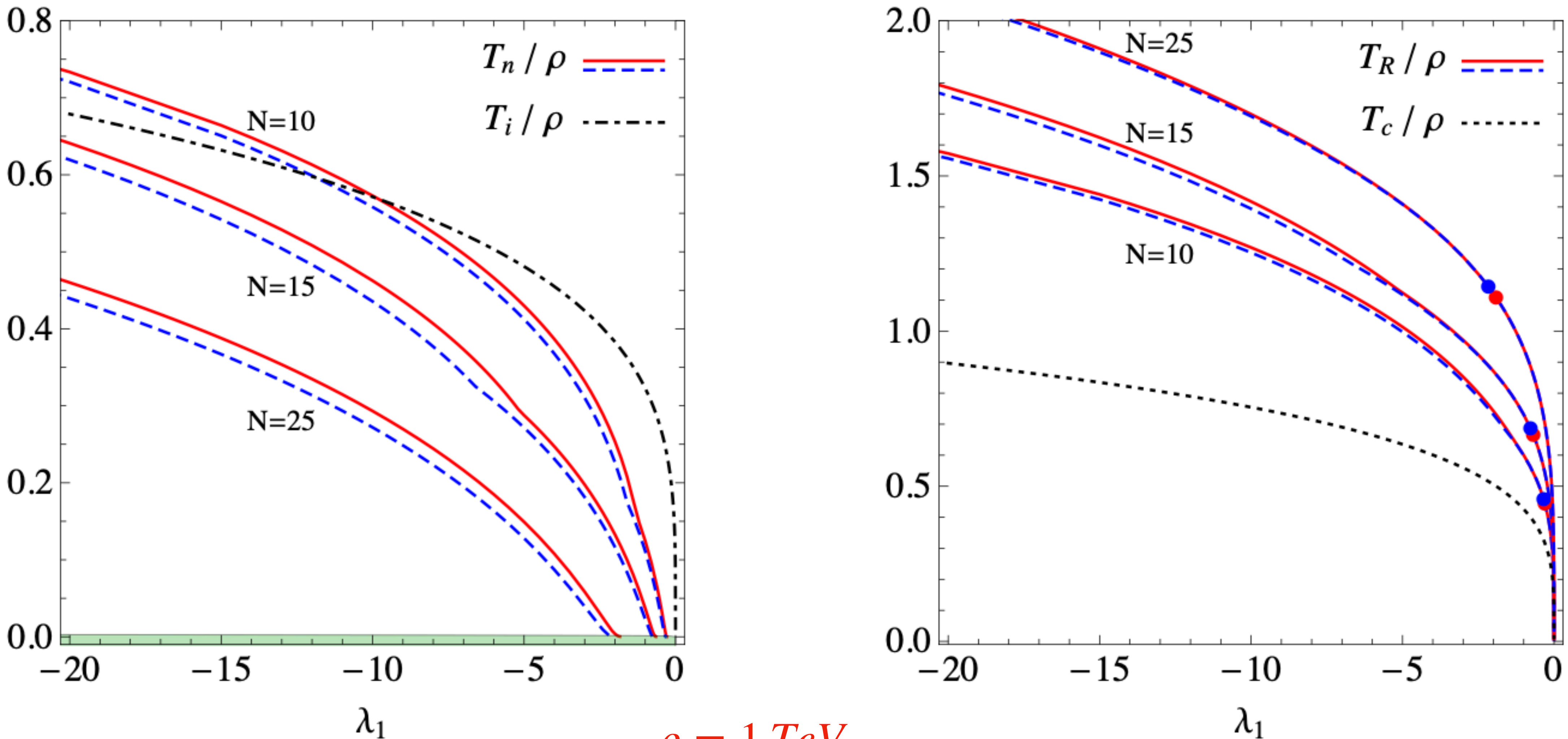
- When the radion $\chi\,[\langle\chi\rangle = \rho]$ phase transition happens the nucleation temperature is smaller than the VEV: $\rho/T_n \gg 1$ and the phase transition is very strong first order

- 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



$\rho = 1\,TeV$

$\rho = 100\,TeV$

Gravitational waves

- A cosmological first order phase transition generates a stochastic gravitational wave background (SGWB)

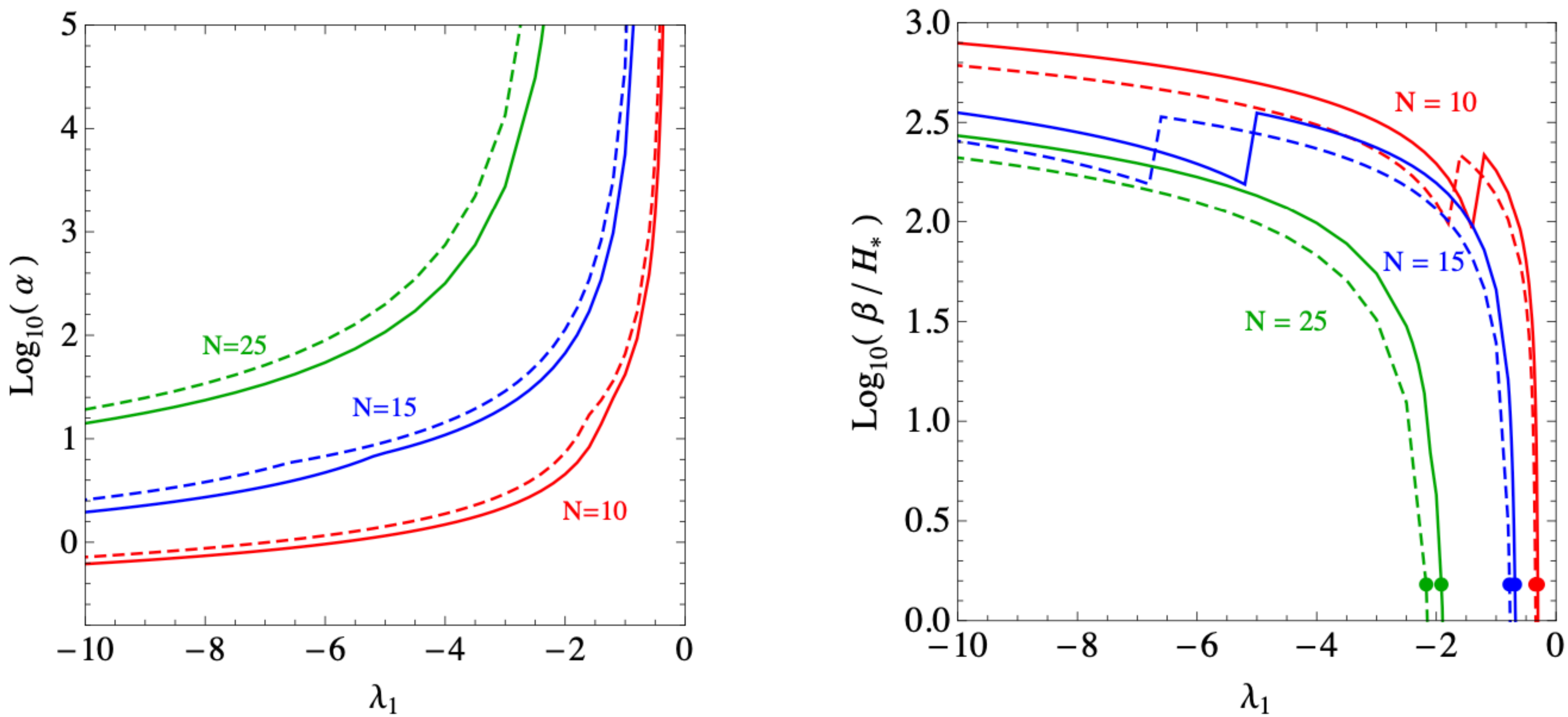
- The power spectrum depends on phase transition quantities

inverse duration of phase transition

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

- 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

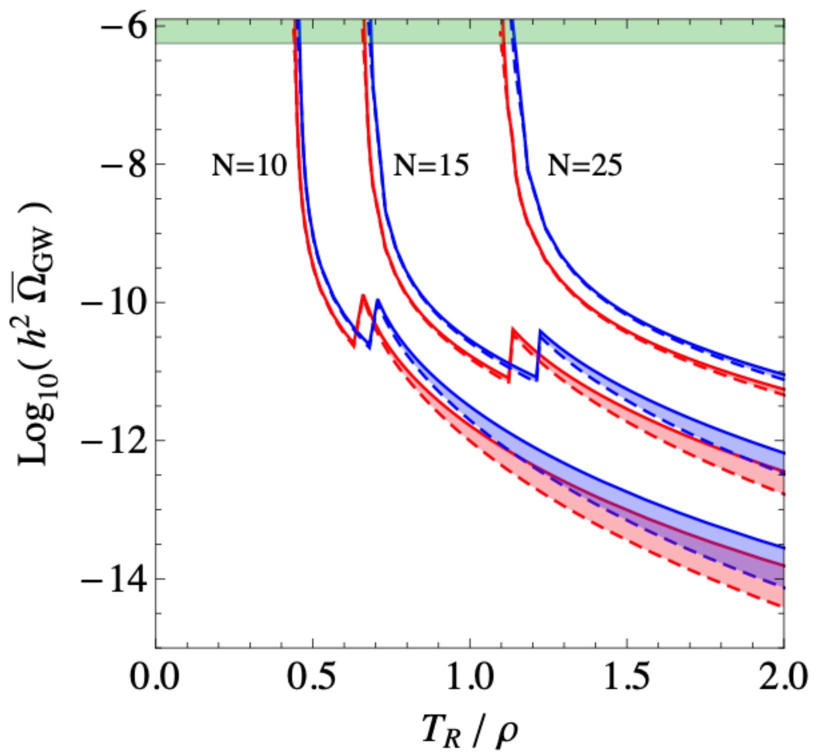
The behavior of the GW parameters in RS as functions of N and λ_1

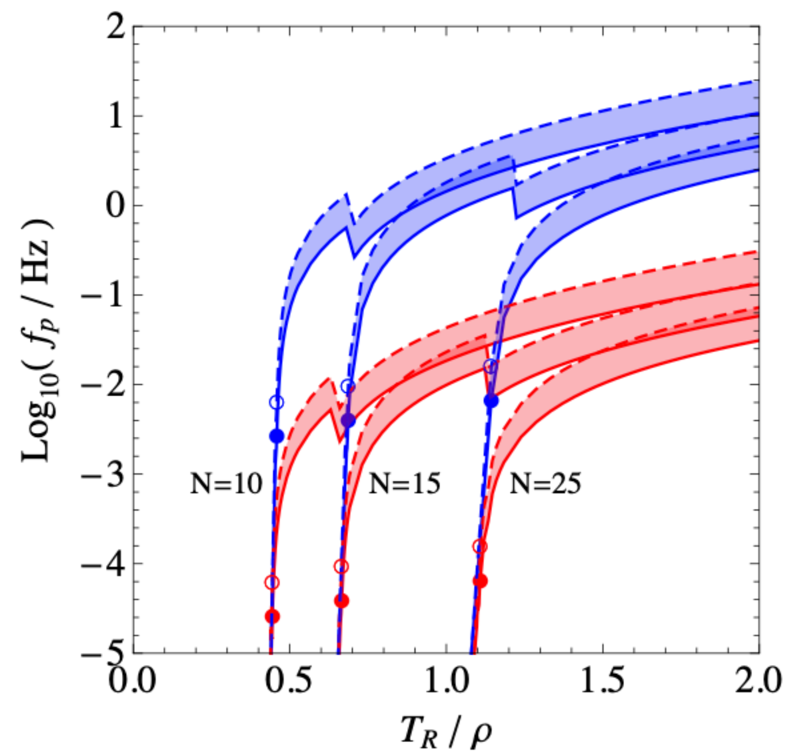


$\rho = 1\,TeV$

$\rho = 100\,TeV$

The amplitude and peak frequency in RS

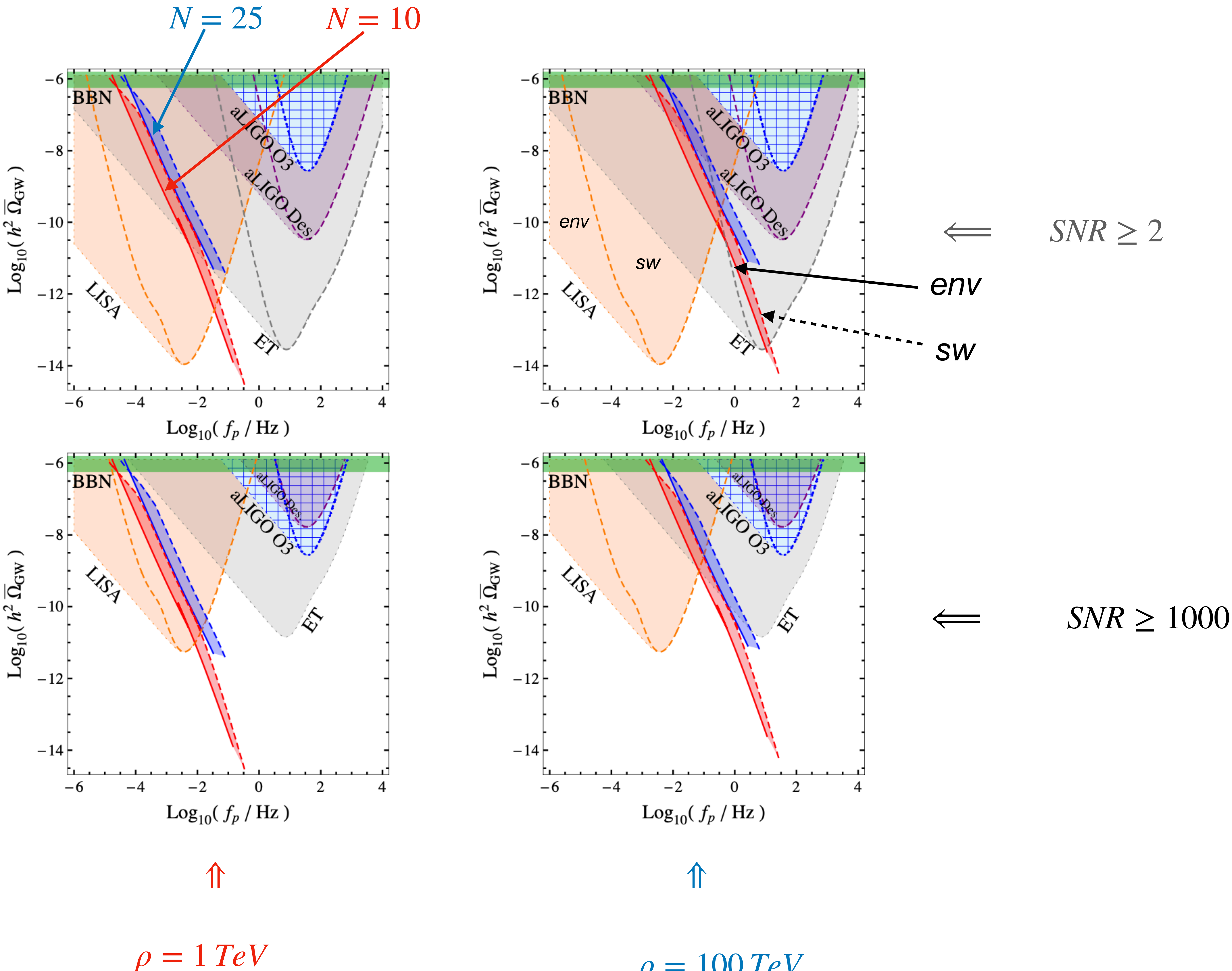




Strips are between envelop (solid) and sound-wave (dashed) approximations

Red strips are for $\rho = 1\,TeV$

Blue strips are for $\rho = 100\,TeV$



$N = 25$
$N = 10$
BBN
aLIGO O3
aLIGO Des
LISA
ET
env
sw
$\mathrm{Log}_{10}(\, h^2\, \overline{\Omega}_{\mathrm{GW}}\,)$
$\mathrm{Log}_{10}(\, f_p\, /\, \mathrm{Hz}\,)$
$\Longleftarrow \quad SNR \geq 2$
$\Longleftarrow \quad SNR \geq 1000$
$\rho = 1\, TeV$
$\rho = 100\, TeV$

Conclusions

- Warped extra dimension is an interesting alternative to SUSY to solve the hierarchy problem (dual to CFT,…)
- It triggers a confinement/deconfinement first order phase transition
- Gravitational waves are useful tools to detect the existence of the confinement/deconfinement phase transition

Outlook

- Future interferometers will thus probe heavy resonances

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

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

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

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