# EXTRA DIMENSIONS

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- The *simplest* and perhaps *more elegant* solution to the naturalness problem is provided by SUPERSYMMETRY

Howie Baer, Tianjin Li,… talks @ this conference

- 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 $\mu$ problem

# Contents

- A (well known) alternative to SUSY: warped extra dimension
- First order phase transitions: confinement/deconfinement, electroweak
- Gravitational wave signatures
- Collider phenomenology
- Gapped continuum KK modes
- Conclusions

# An alternative to SUSY

- Proposed in 1999 by Randall and Sundrum (RS)

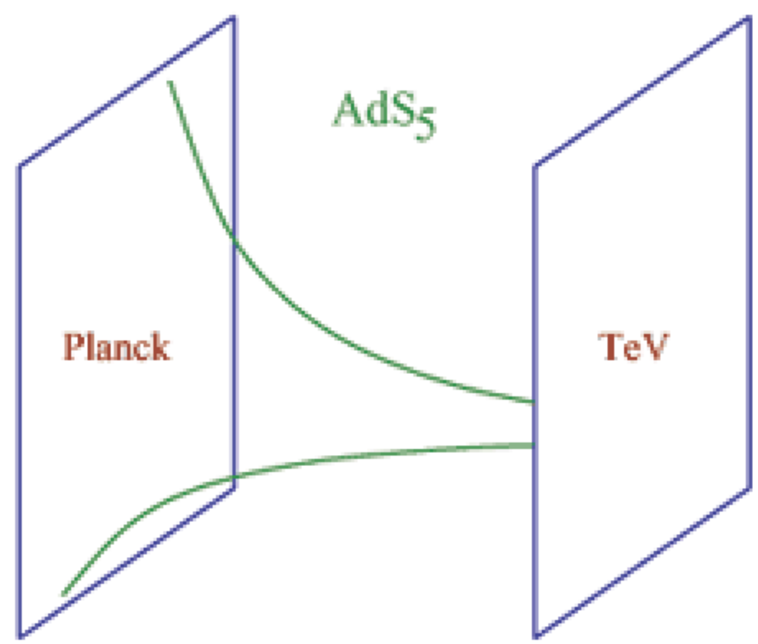
L. Randall, R. Sundrum, 9905221

- It was based on a 5D space with line element

$$ds^2 = e^{-2A}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2,\ A = ky$$

RS

- and two branes




$$TeV = e^{-ky_1}M_{Pl}, \quad ky_1 \sim 35$$

$$AdS \Leftrightarrow CFT \quad correspondence$$

$$h(y) \propto e^{aky}, \quad a > 2$$

- The Higgs is mainly localized on the IR brane (composite):
- Heavy (light) fermions are mainly localized on the IR (UV) brane: composite (elementary)
- Zero mode gauge bosons are flat
- KK modes are mainly localized on the IR brane (composite)

- In RS model the brane distance has to be stabilized by a bulk field $\phi$ breaking conformal invariance with bulk and brane potentials fixing its VEVs

*W. Goldberger, M. Wise, 9907218*

- It then appears a “light state”: the radion/dilaton with interesting Higgs-like phenomenology

- The RS model has problems when confronting the electroweak precision measurements, e.g. oblique observables

- $\alpha T = s_W^2 c_K^2 k y_1 \dfrac{(a-1)^2}{a(2a-1)} \dfrac{m_Z^2}{m_{KK}^2}$ $\qquad$ $\alpha S = 2 s_W^2 c_W^2 c_K^2 \dfrac{a^2-1}{a^2} \dfrac{m_Z^2}{m_{KK}^2}$

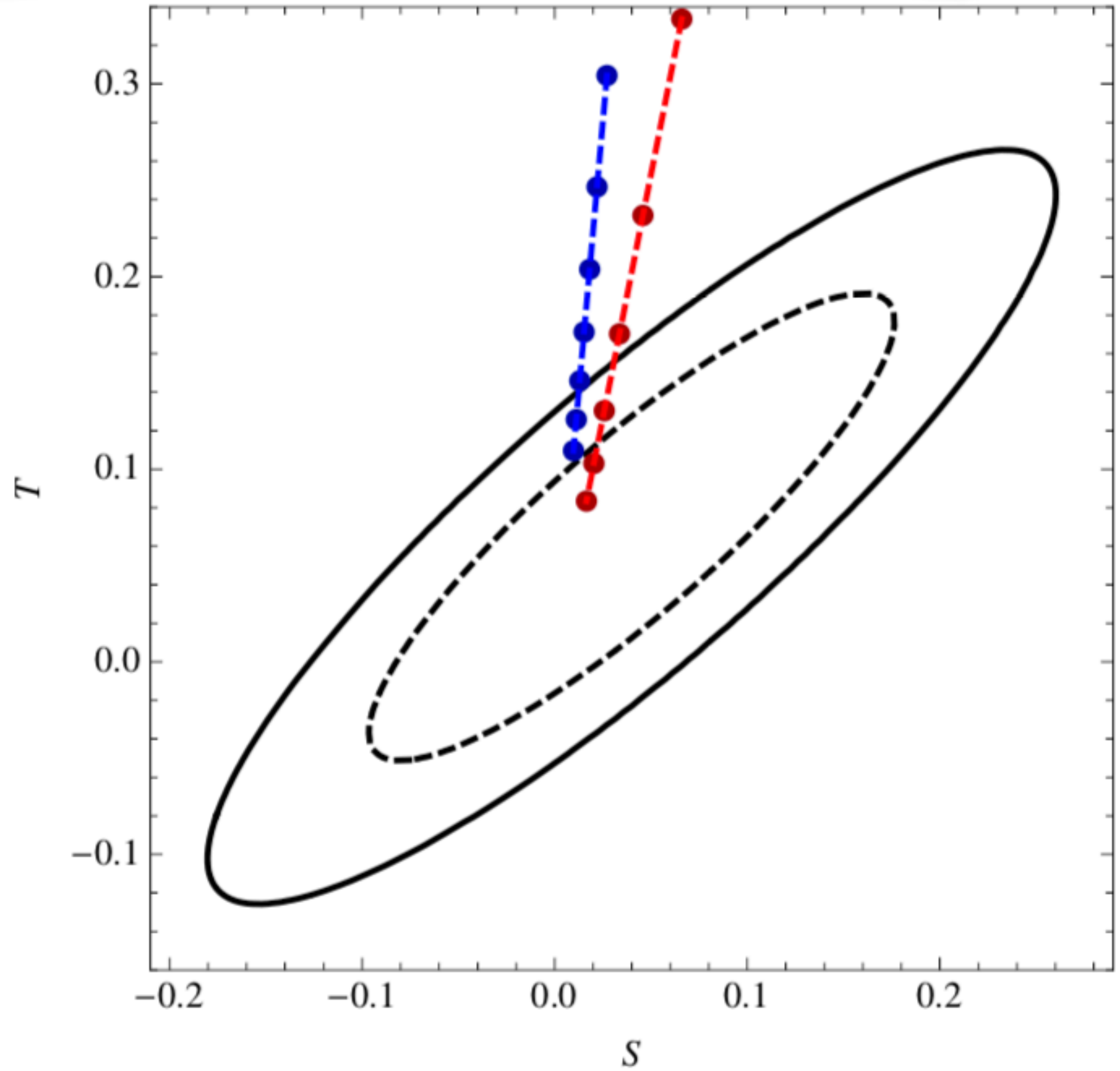
$$c_{KK} = \frac{m_{KK}}{k} e^{k y_1}, \quad k y_1 \simeq 35$$

Using the RPP fit for the S and T parameters

$$S = 0.02 \pm 0.07 \quad T = 0.06 \pm 0.06 \quad r \simeq 0.92$$

$9\ TeV \leq m_{KK} \leq 15\ TeV, a \to \infty$

$5\ TeV \leq m_{KK} \leq 10\ TeV, a = 2$




**Leads to**

$$m_{KK} \gtrsim 10\, TeV$$

- *Creates a little hierarchy problem*
- *Too heavy for detection at LHC*

# WAY OUT 1: CUSTODIAL MODELS

- Promote the custodial symmetry to gauge symmetry in the bulk broken by orbifold boundary conditions

  - The simplest one is:

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

- ***Higgs***=PNGB

$$\mathcal{G} \rightarrow \mathcal{H}_{UV}\,(\mathcal{H}_{IR})$$

G. Senjanovic talk @ this conference

$$\begin{aligned} W_L^{1,2,3} &= (N,N) \\ W_R^{1,2} &= (D,N) \\ \mathcal{Z} = \frac{1}{\sqrt{g_R^2+g_{\mathcal{X}}^2}}\left[g_R W_R^3 - g_{\mathcal{X}}\mathcal{X}\right] &= (D,N) \\ B = \frac{1}{\sqrt{g_R^2+g_{\mathcal{X}}^2}}\left[g_R W_R^3 + g_{\mathcal{X}}\mathcal{X}\right] &= (N,N) \end{aligned}$$

*K. Agashe et al., 0308036*

B. Batell talk @ this conference Friday 14:30

| Model | # PGB ($A_5^{\hat{a}}$) |
|---|---|
| SO(4)/SO(3) | 6-3=3 (Higgsless SM) |
| SU(3)/SU(2)⊗U(1) | 8-4=4($H_{SM}$) |
| SO(5)/SO(4) | 10-6=4 ($H_{SM}$) |
| SO(6)/SO(5) | 15-10=5 ($H_{SM}$ + singlet) |
| SO(6)/SO(4)⊗SO(2) | 15-6-1=8 ($H_u, H_d$) |

*R. Contino et al., 0306259*

# WAY OUT 2: NON-CUSTODIAL MODELS

- Another possibility is to have large back reaction on the metric such as to create a singularity
- Typical example is the metric $$A(y) = ky - \frac{1}{\nu^2}\log(1 - y/y_s)$$
- Which is AdS on the UV: y=0

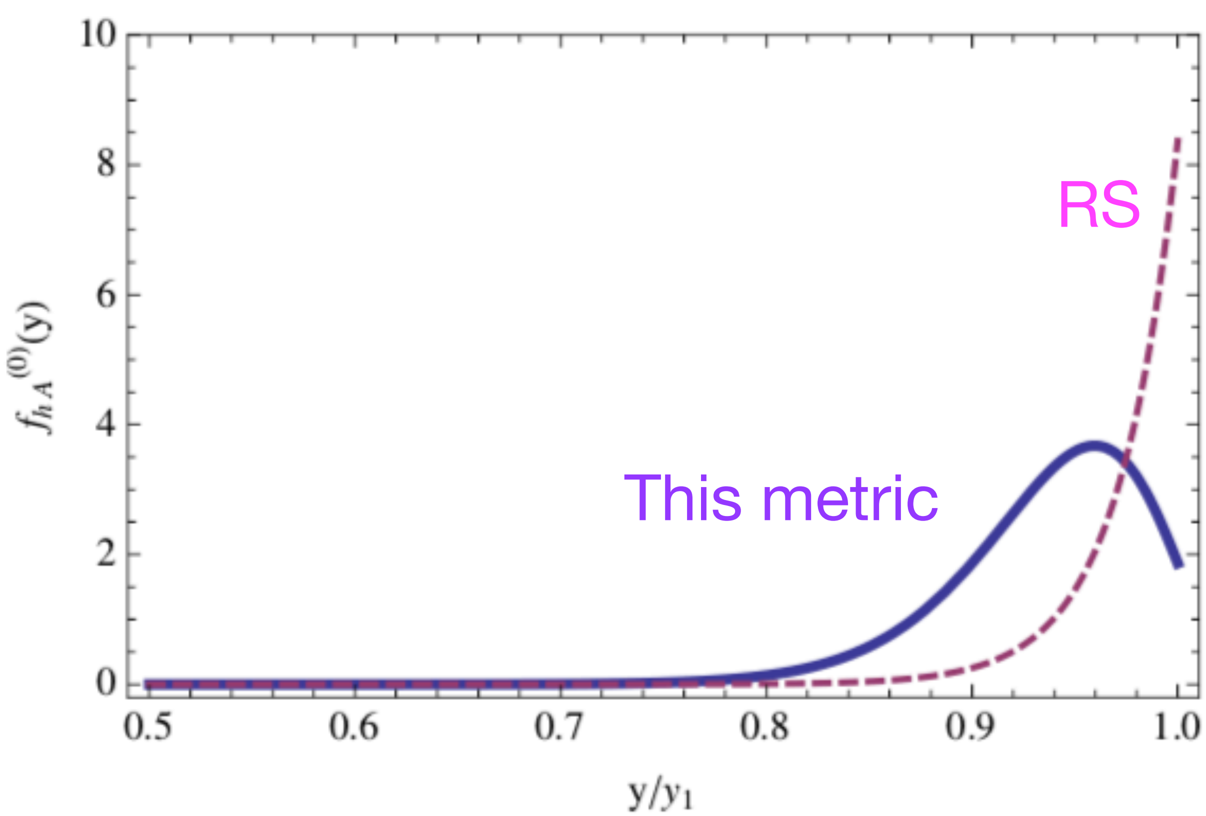
*J. Cabrer et al., 1103.1388*

- Strong departure from conformality on the IR: $y = y_s$
- Singularity admissible as it supports finite temperature in the form of a black-hole horizon

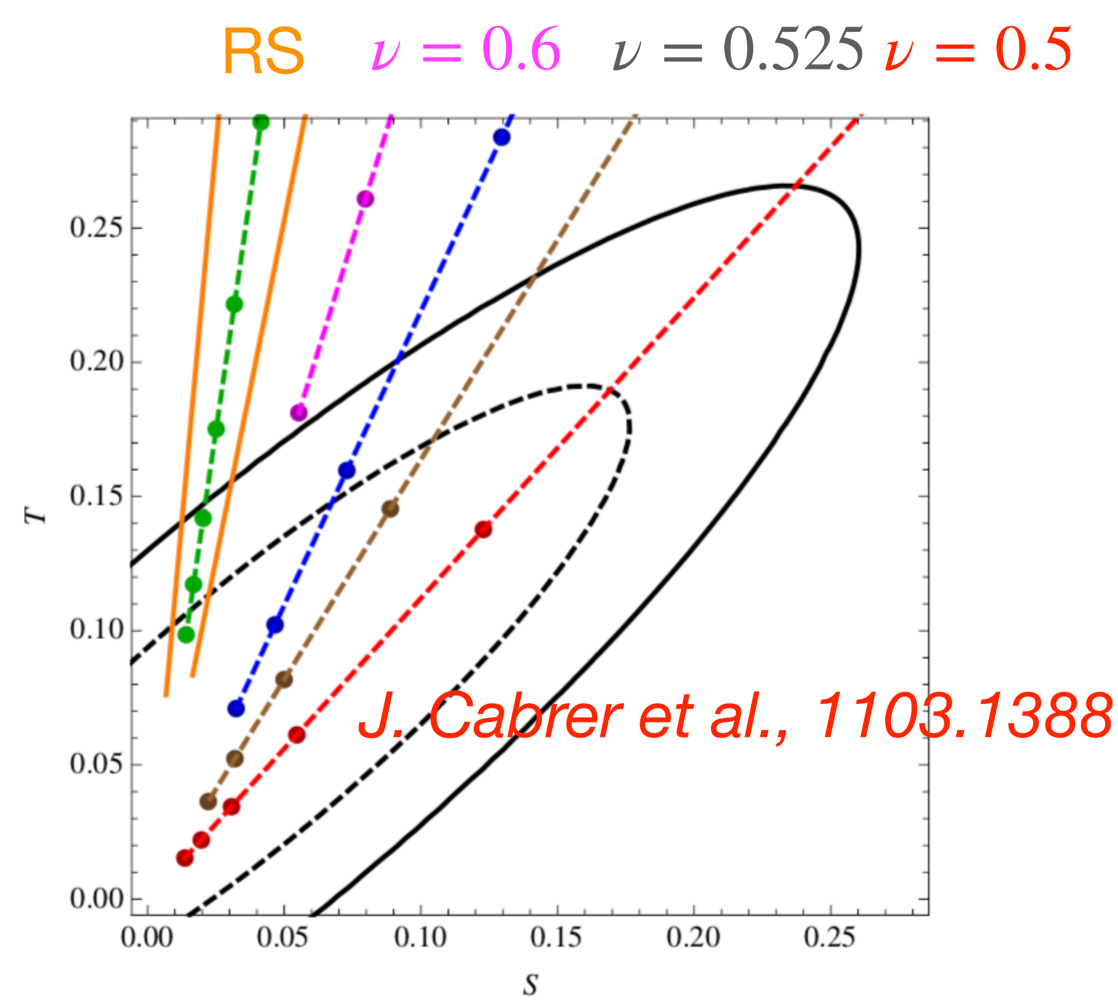
*S. Gubser, 0002160*

- The improvement in EWPD comes from the fact that the Higgs profile in flat coordinates is $f_{hA}^{(0)}(y) \propto e^{-A}h(y) \to 0,\ (y \to y_s)$

- Then the Higgs profile has a maximum away from the IR brane




A. Carmona et al., 1107.1500




$\nu = 0.55,\ m_{KK} \leq 3\ TeV, \Delta m_{KK} = 0.5\ TeV$

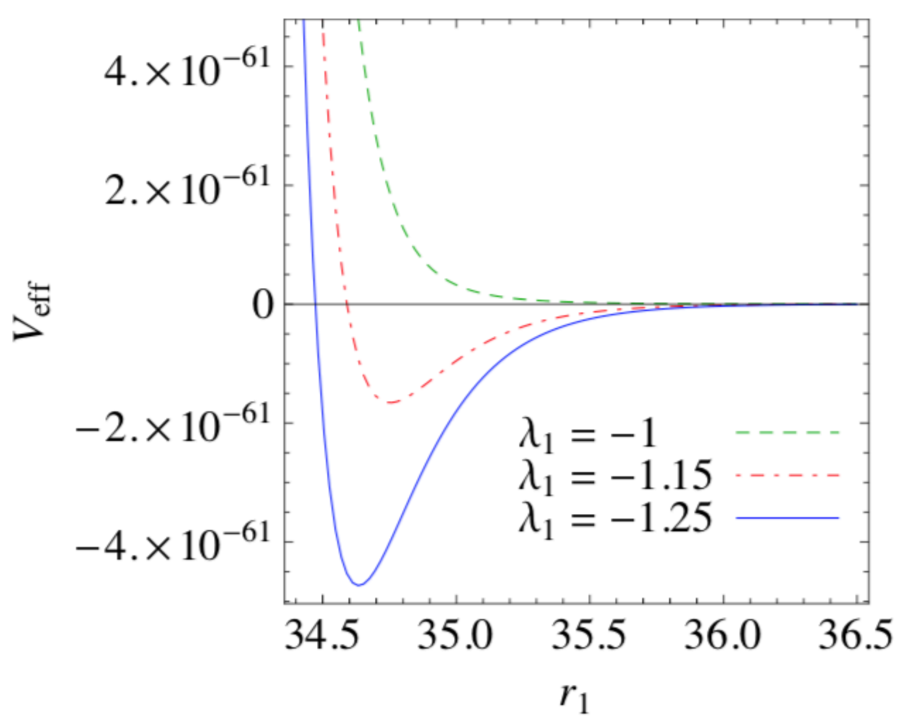
$\nu = 5,\ m_{KK} \leq 12\ TeV, \Delta m_{KK} = 1\ TeV$

# First order phase transitions

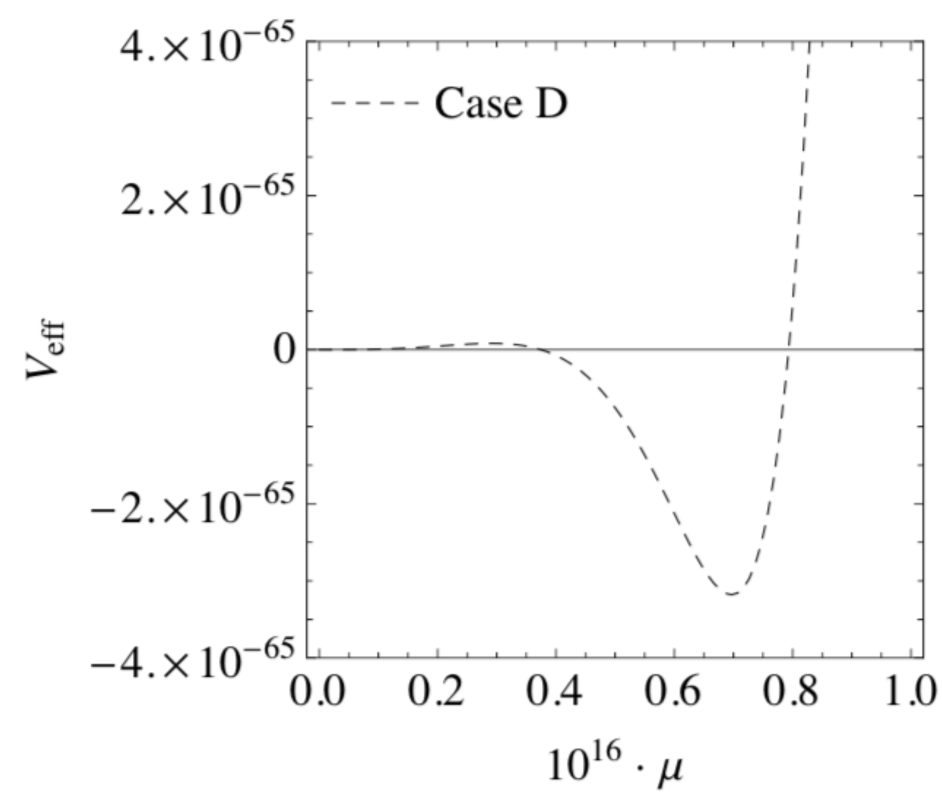
- In this theories there is the confinement/deconfinement phase transition *P. Creminelli et al., 0107141*

- We have to introduce the notion of effective potential as a function of the radion field *E. Megias et al., 1806.04877*

$$ds^2 = -[1 + 2F(x,y)]^2 dy^2 + e^{-2[A+F(x,y)]}\eta_{\mu\nu}dx^\mu dx^\nu, \quad F(x,y) = F(y)r_1(x)$$




*Units of k*




$$r_1(x) \to \mu(x)$$

- At finite temperature the system allows for an additional 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

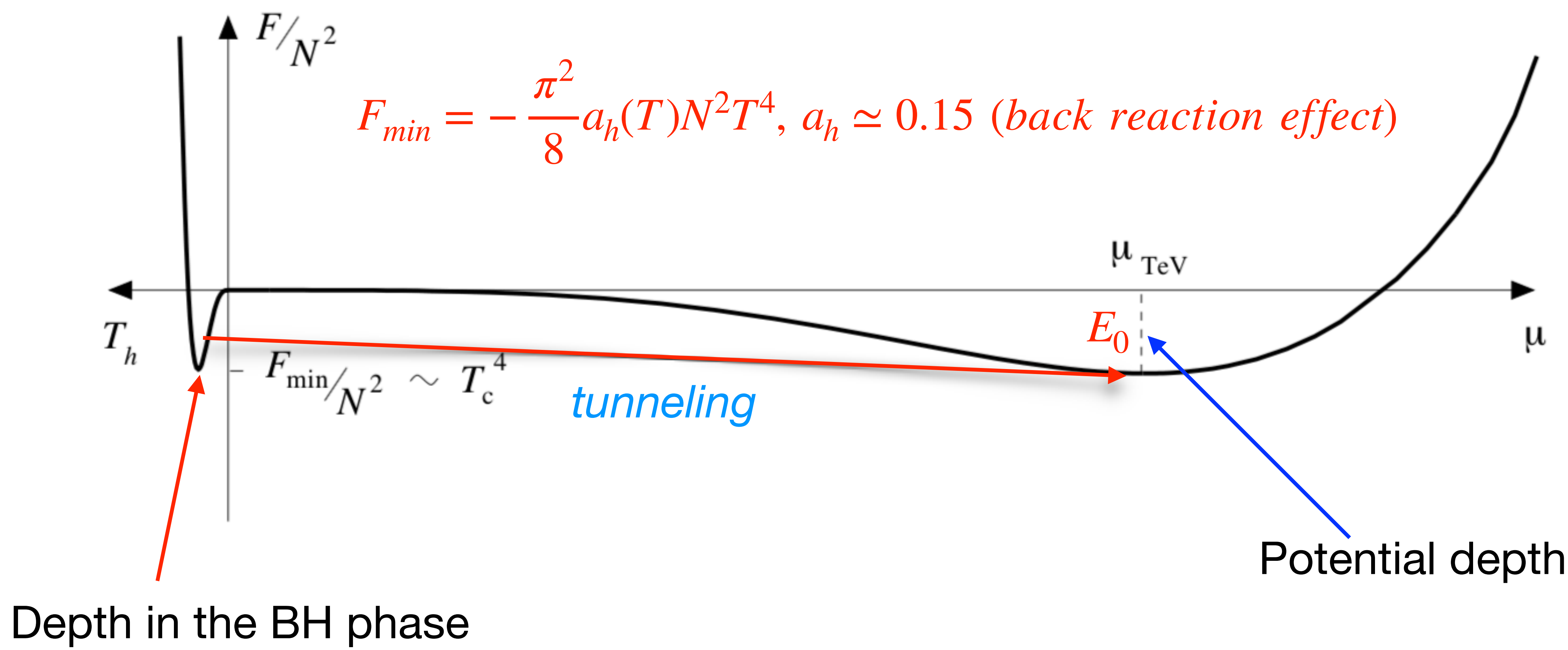
Depth in the BH phase

# Deconfinement/confinement phase transition

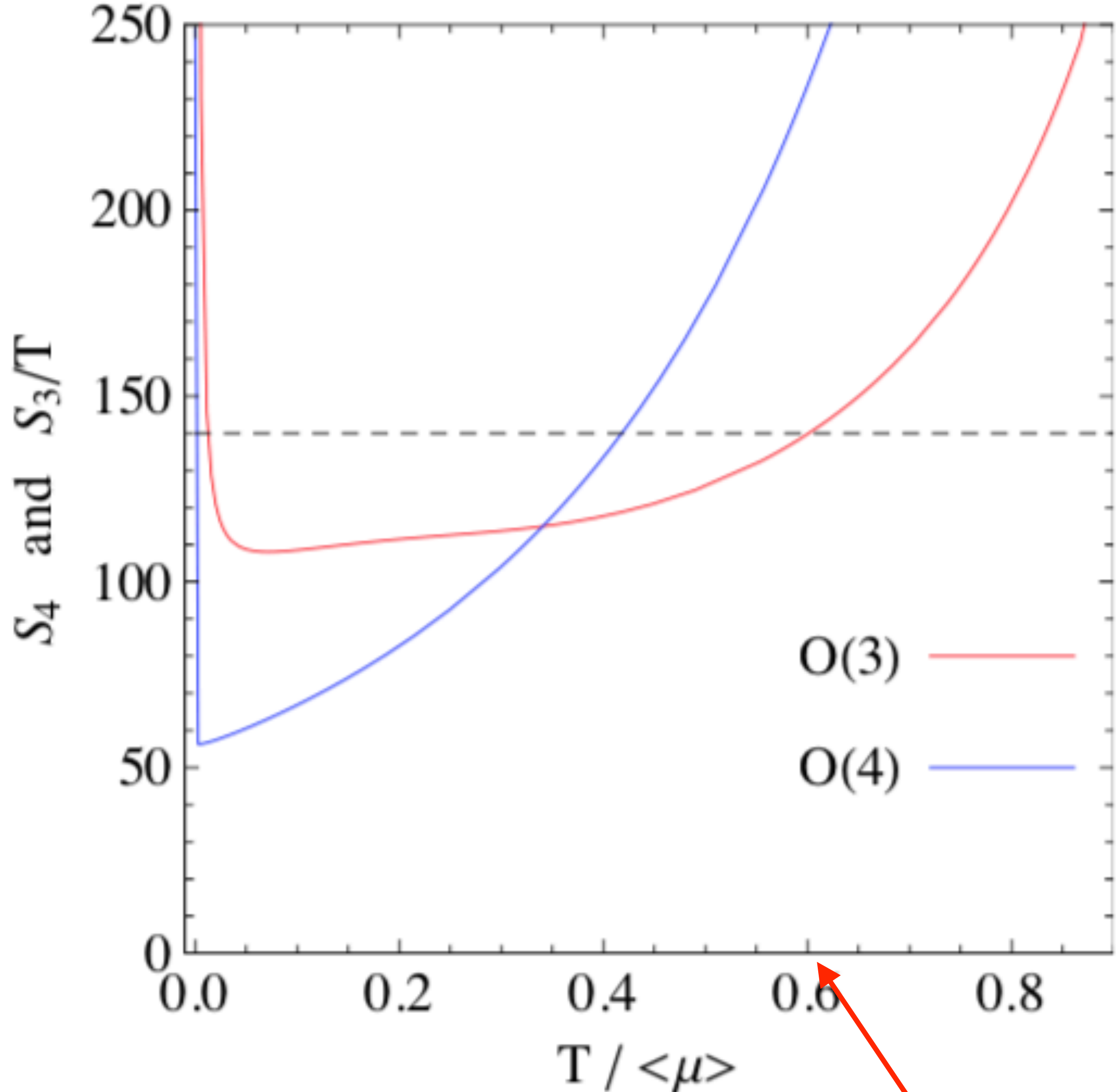
**Cartoon**

*P. Creminelli et al., 0107141*

$$F_{min} = -\frac{\pi^2}{8} a_h(T) N^2 T^4,\ a_h \simeq 0.15\ (back\ reaction\ effect)$$



O(4) bounce O(3) bounce




*E. Megias et al., 1806.04877*

$T_n$ *(tunneling temperature)*

- When the radion phase transition happens the nucleation temperature is smaller than the VEV: then $\langle \mu \rangle / T_n \gg 1$ and the phase transition is very strong first order

- The cooling triggers a brief period of cosmological inflation with few e-folds of inflation

- During the phase transition the energy density is approximately conserved

- 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 TeV

# The electroweak phase transition

- The confinement/deconfinement phase transition is tightly connected to the electroweak phase transition

- This is the case e.g. when the Higgs, radion and right-handed top are localized toward the IR brane (only exist in the confined phase)

- In this case the nucleation temperature of the radion phase transition is essentially unaffected by the SM degrees of freedom

- When the BH horizon moves beyond the IR brane during the radion phase transition the Higgs potential appears as

$$V(\mu, \mathscr{H}) = V_{eff}(\mu) + \left(\frac{\mu}{\langle\mu\rangle}\right)^4 V_{\rm SM}(\mathscr{H}, T)$$

- The minimum of the SM Higgs potential is at

$$v(T) = v\sqrt{1 - T^2/T_{EW}^2}, \quad T_{EW} \simeq m_{\mathscr{H}}/\left(m_W^2/v^2 + m_Z^2/2v^2 + m_t^2/v^2\right)^{1/2} \simeq 150\ GeV$$

- Depending on the relationship between the tunneling and reheat temperatures, and the EW temperature the EWBG scenario will be different.

- Two cases: $T_R > T_{EW}$ and $T_R < T_{EW}$

- Of course one or another case depends on the choice of the model parameters

## Sequential phase transitions

$T_R > T_{EW}$

- Generic prediction in most models
- Even if $T_n < T_{EW}$ the reheat temperature can be large
- Electroweak symmetry is restored after reheating
- Electroweak baryogenesis should proceed as in the SM case

## Simultaneous phase transitions

$T_R < T_{EW}$

- The reheating does not restore EW symmetry and the Higgs lies at the minimum of the potential $V(\mathscr{H}, T_R)$
- The EW phase transition is strong enough if $T_R < T_{\mathscr{H}} \simeq 140\ GeV$
- In the window $T_{\mathscr{H}} < T_R < T_{EW}$ the EWPT is too weak for EWBG

G. Nardini et al., 0706.3388

- If $T_R < T_{\mathscr{H}}$ EWPT is strong enough for EWBG

# Gravitational waves

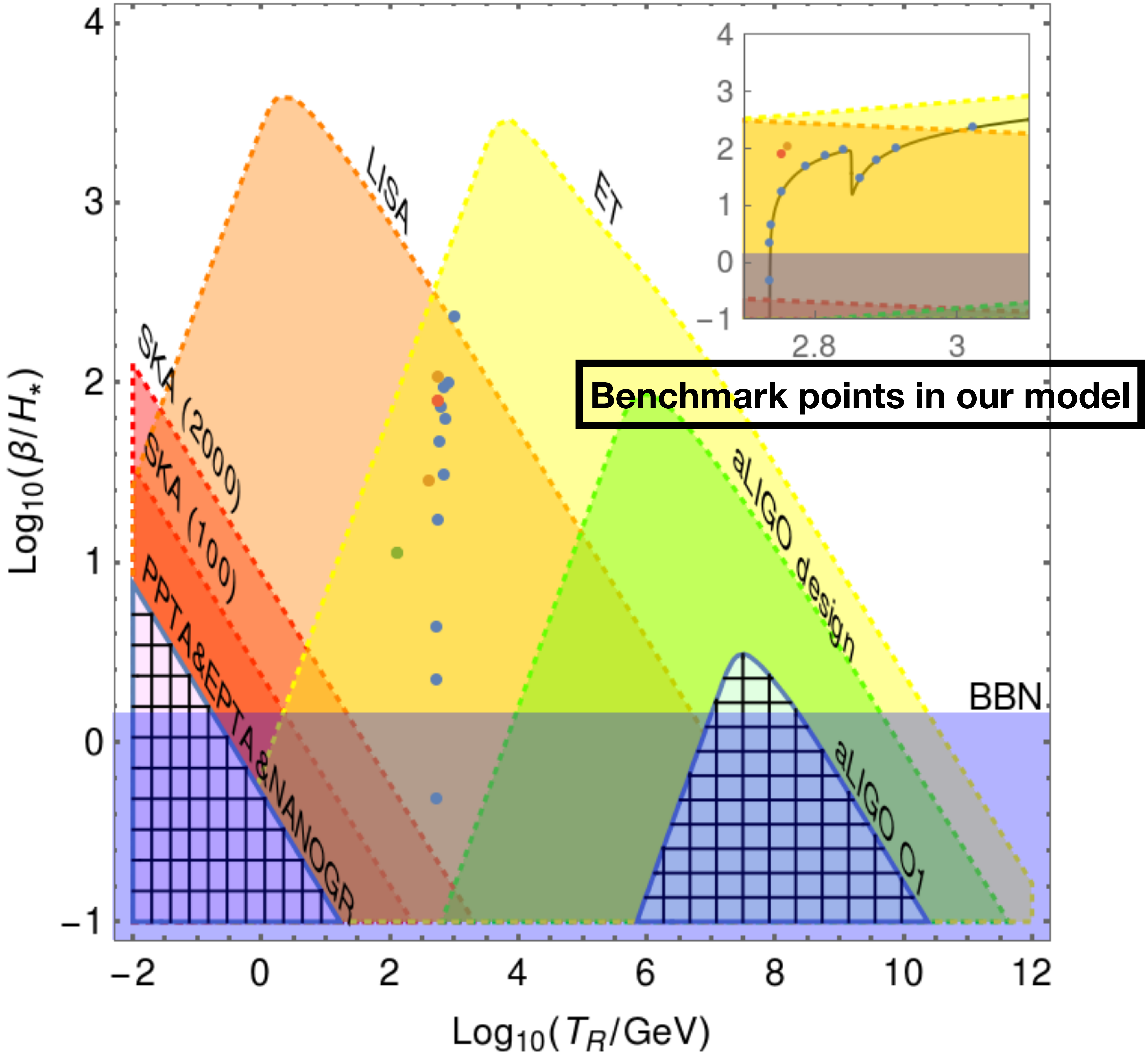
A. Zimmerman talk @ this conference Friday 15:50

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

- The power spectrum depends on phase transition quantities

$$\alpha \simeq \frac{E_0}{3(\pi^2 N^2/8)a_h(T_n)T_n^4} \qquad \frac{\beta}{H_\star} \simeq T_n \frac{dS_E}{dT}\bigg|_{T=T_n}$$

- In the next two decades several GW observatories will have the potential to observe, or constrain, the SGWB produced in our benchmark models



LISA
ET
SKA (2000)
SKA (100)
PPTA&EPTA&NANOGRAV
aLIGO design
aLIGO O1
BBN
Benchmark points in our model
$\mathrm{Log}_{10}(\beta/H_*)$
$\mathrm{Log}_{10}(T_R/\mathrm{GeV})$

# Collider phenomenology

- The lightest BSM state is the radion

- Radion couples to the SM fields X as the Higgs with a reduction coefficient which is model dependent

$$\mathscr{L}_{\mathscr{R}XX} = c_X \mathscr{L}_{HXX}, \quad X = \gamma_\mu, g_\mu, f, Z_\mu, W_\mu, \mathscr{H}$$

- The coefficients are model dependent and less than 1

| Scen. | $m_{\rm rad}/\text{TeV}$ | $m_G/\text{TeV}$ | $c_\gamma$ | $c_g$ | $c_V$ | $c_{\mathcal{H}}$ | $c_f$ |
|---|---|---|---|---|---|---|---|
| $B_2$ | 0.915 | 4.80 | 0.472 | 0.164 | 0.0649 | 0.259 | 0.259 |
| $B_8$ | 0.745 | 4.19 | 0.542 | 0.146 | 0.0744 | 0.298 | 0.298 |
| $C_1$ | 0.890 | 3.08 | 0.532 | 0.179 | 0.0904 | 0.362 | 0.362 |
| $C_2$ | 0.751 | 2.77 | 0.595 | 0.162 | 0.101 | 0.404 | 0.404 |
| $D_1$ | 0.477 | 4.50 | 3.791 | 0.475 | 0.397 | 1.586 | 1.586 |
| $E_1$ | 0.643 | 4.16 | 0.562 | 0.124 | 0.0746 | 0.298 | 0.298 |

**Some benchmark points**

- The radion is a heavy narrow weakly coupled resonance

| Scen. | $\Gamma_{\mathcal{R}\to WW}$ | $\Gamma_{\mathcal{R}\to ZZ}$ | $\Gamma_{\mathcal{R}\to hh}$ | $\Gamma_{\mathcal{R}\to t\bar{t}}$ | $\Gamma_{\mathcal{R}\to b\bar{b}}$ | $\Gamma_{\mathcal{R}\to \tau\bar{\tau}}$ | $\Gamma_{\mathcal{R}\to \gamma\gamma}$ |
|---|---|---|---|---|---|---|---|
| $B_2$ | 1220 | 610 | 5.70 | 2670 | 0.825 | 0.129 | 0.0385 |
| $B_8$ | 786 | 389 | 9.01 | 2680 | 0.917 | 0.138 | 0.0143 |
| $D_1$ | 4960 | 2350 | 362 | 28000 | 17.73 | 2.49 | 0.378 |

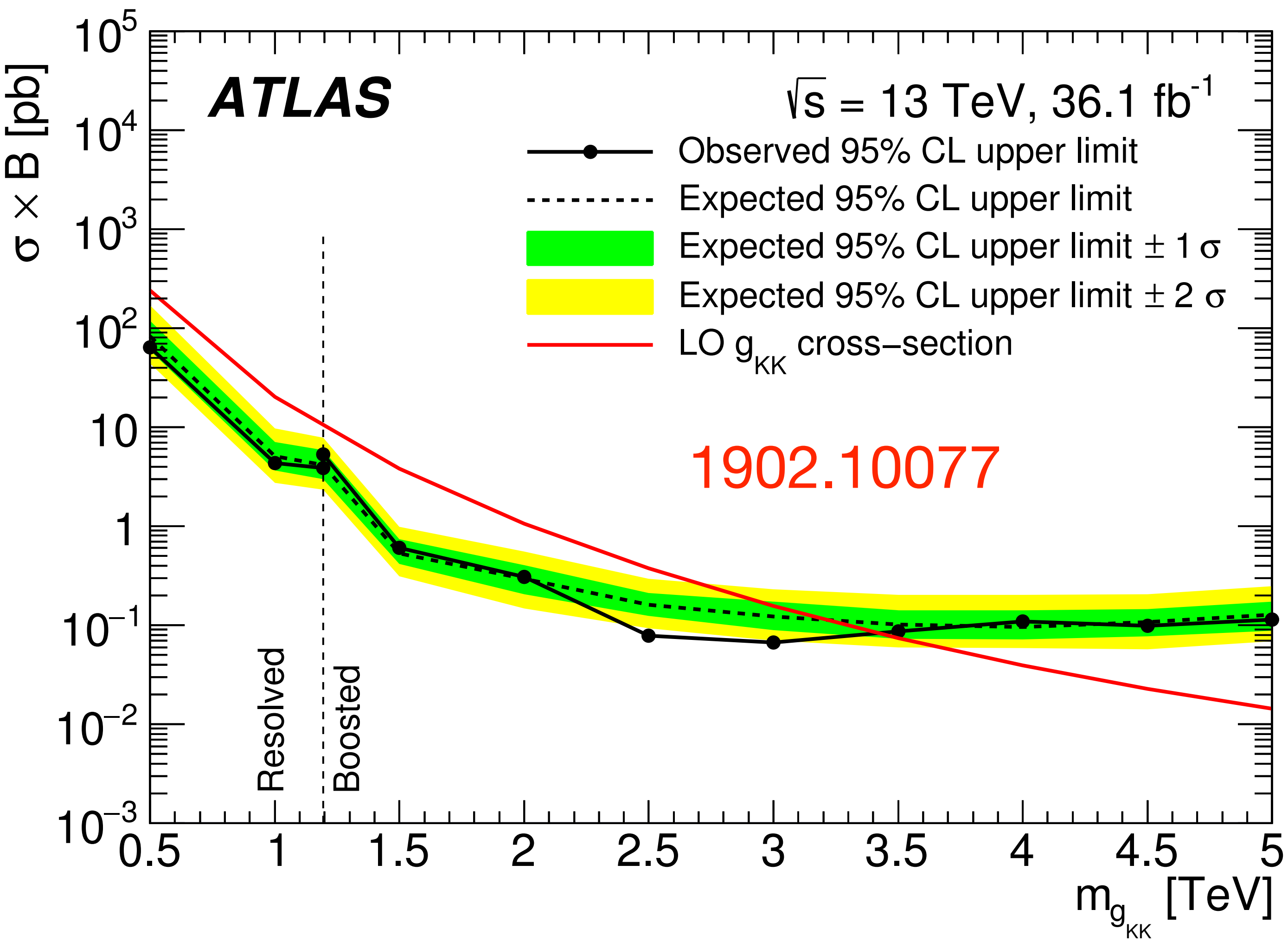
all widths are in MeV

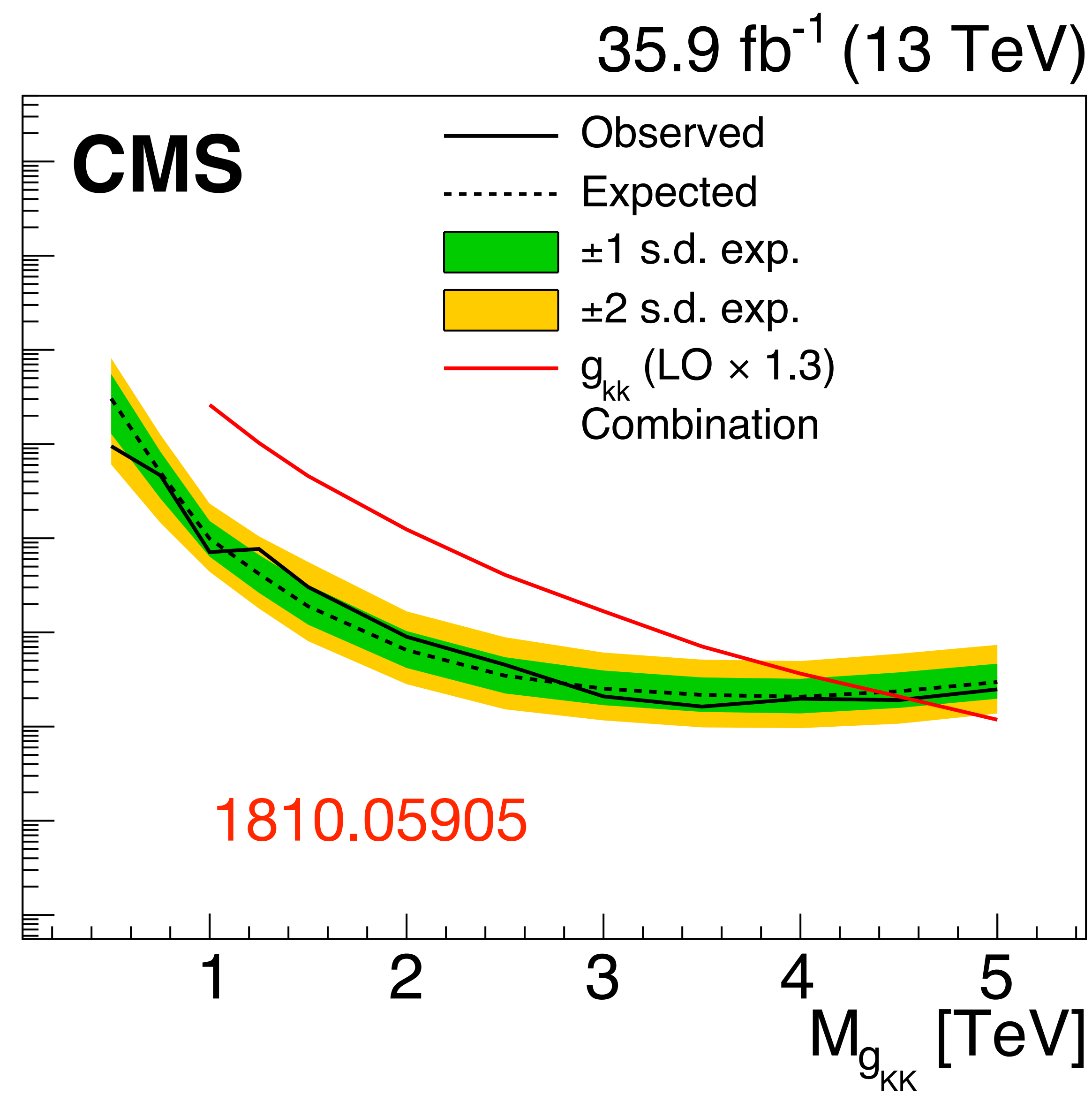
- Mainly coupled to W and Z gauge bosons and top quark

- The heavy radion phenomenology is very model dependent and it is in general easy to avoid the present bounds as we have found in our benchmark points

- Still the bounds on KK modes start to be very demanding

Bounds from ATLAS & CMS start to be very strong




$$g_{g_{KK}qq} = -0.2 g_s,\ g_{g_{KK}t_L t_L} = g_s,\ \Gamma_{g_{KK}} = 30\,\%$$

# Gapped continuum KK modes

- Experimental searches normally assume that new particles are isolated (narrow) resonances that can be produced on-shell

- A possible "explanation" for elusiveness: KK states are a TeV gapped continuum of states instead of isolated particles

C. Csaki et al., 1811.06019

- A theory in that direction is the clockwork mechanism, or its 5D version, where TeV is the fundamental scale, and Planck is a derived scale. The KK modes have a TeV mass gap and a (quasi continuum) spacing of 30 GeV

G. Giudice et al., 1711.08437

S. Chan Park talk @ this conference Friday 15:00

- Similar to Linear Dilaton scenarios, dual to Little String theories

I. Antoniadis et al., 1102.4043

- The class of models we have considered here share some properties

$$A(y) = ky - \frac{1}{\nu^2}\log(1 - y/y_s)$$

**UV AdS** **IR deformation**

1. They reproduce RS in the UV and therefore they can explain conventionally the hierarchy with a fundamental Planck scale and a warped TeV scale

2. For $\nu > 1$ they yield discrete KK spectra with TeV spacing

3. For $\nu < 1$ they yield ungapped continuum spectra similar to unparticles

   H. Georgi, 0703260

4. For $\nu = 1$ they yield gapped continuum spectra

A. Falkowski et al., 0806.1737 J.A. Cabrer et al., 0907.5361

- Their Green functions generalize from particle propagator with isolated poles

$$\frac{1}{p^2 - m^2 + i\epsilon} = \mathscr{P}\frac{1}{p^2 - m^2} + i\,\pi\,\delta(p^2 - m^2)$$

- … to Green functions with an isolated pole (the zero mode) and a continuum of states, instead of a discrete sum of KK modes, with a mass gap m

$$G_A(p^2, m^2) = ReG_A(p^2, m^2) + i\,ImG_A(p^2, m^2)\theta(p^2 - m^2)$$

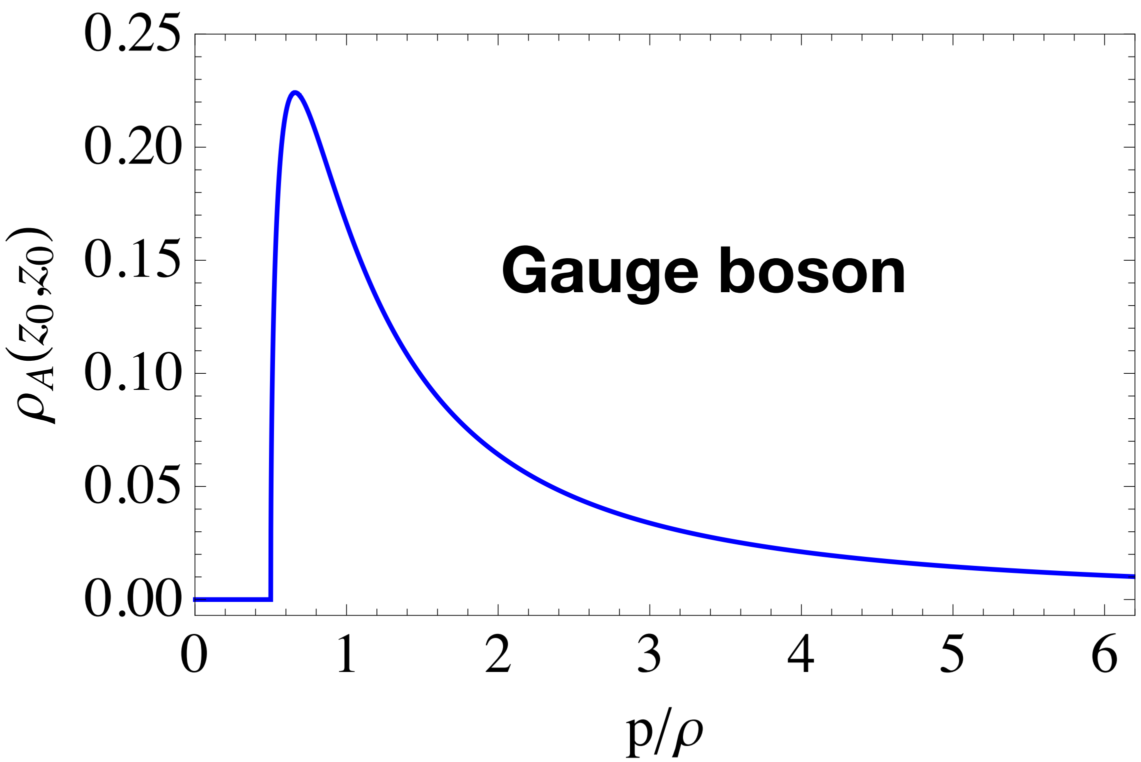
- This is the behavior of gapped unparticles where the gap was usually produced by EW breaking

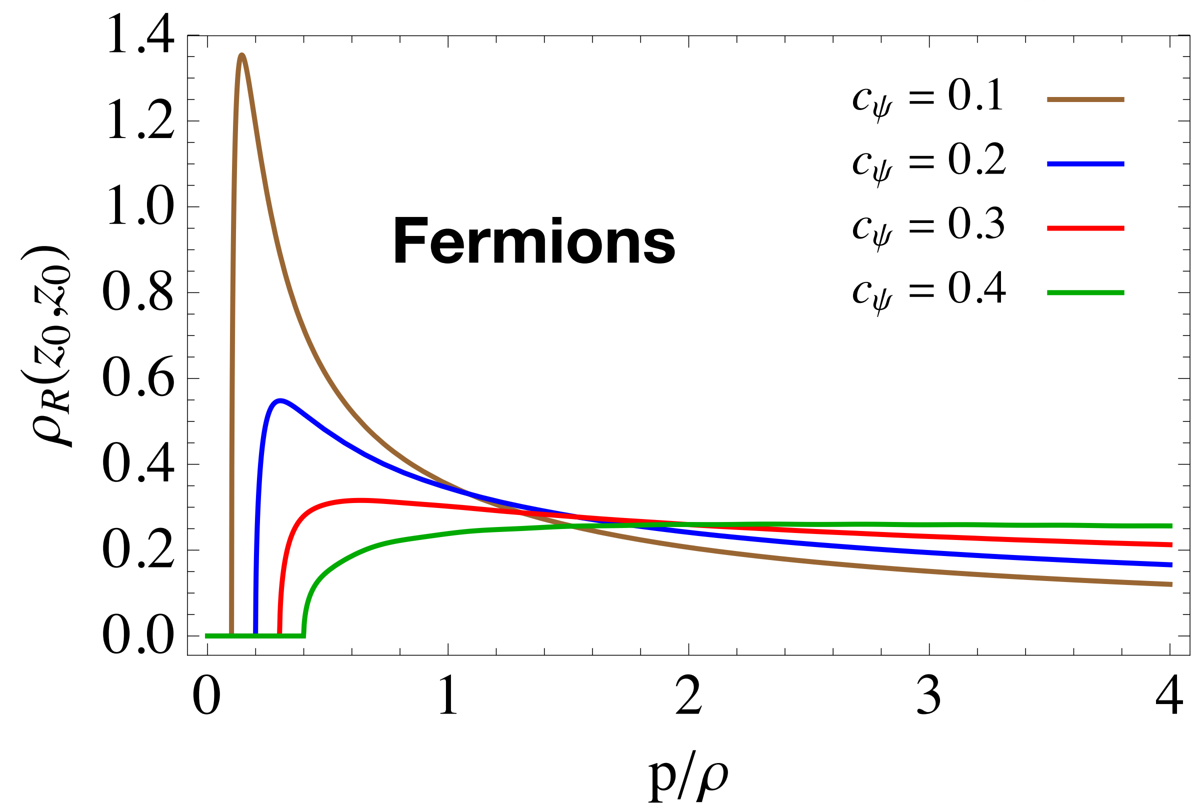
- Here the gap is TeV, and is linked to the solution of the hierarchy problem

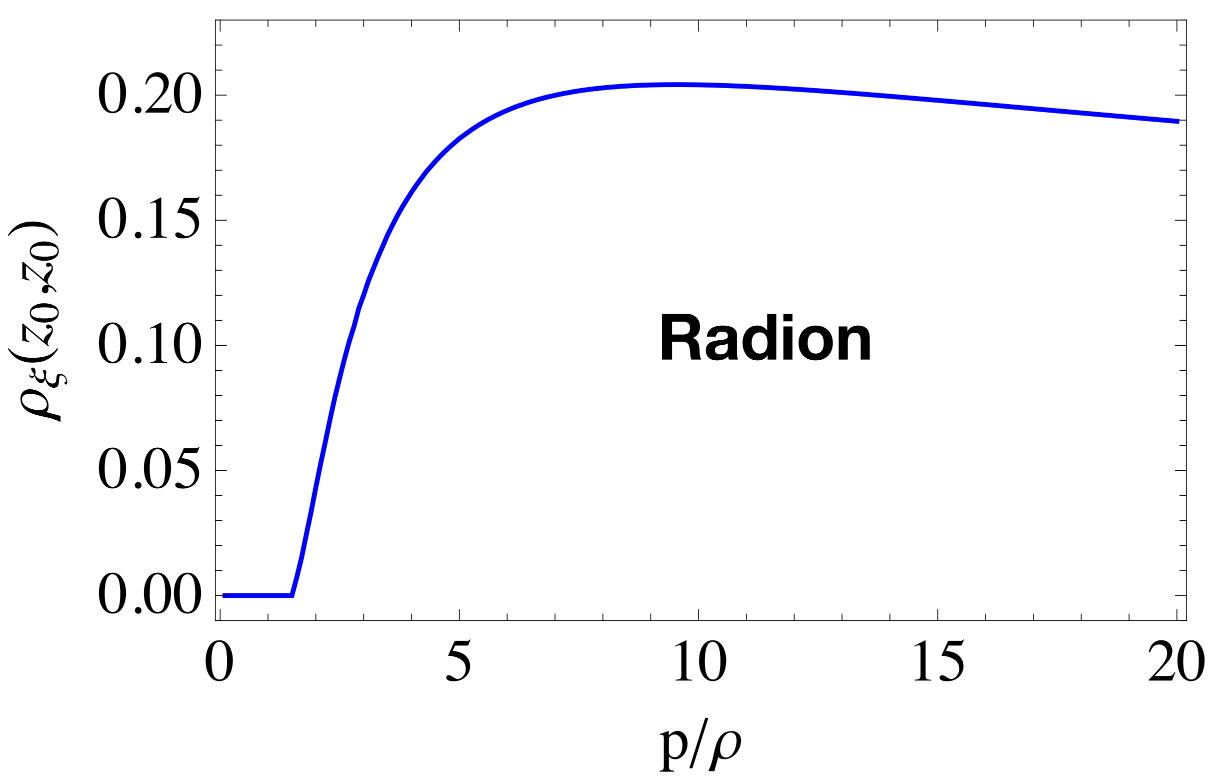
# The continuum spectrum shows up in the spectral density function

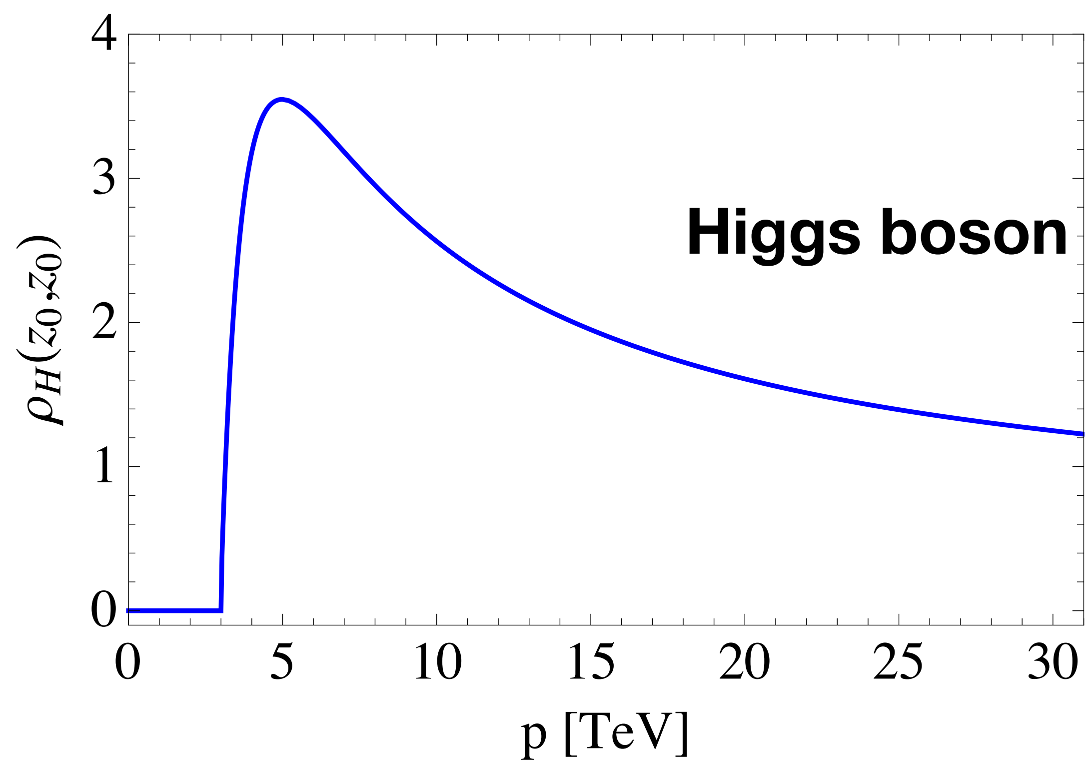
E. Megías and MQ, 1905.07364

$p \equiv \sqrt{s}, \quad \rho =$ **mass gap**



# Phenomenology of continuum KK modes

- The mass gap is different for different states

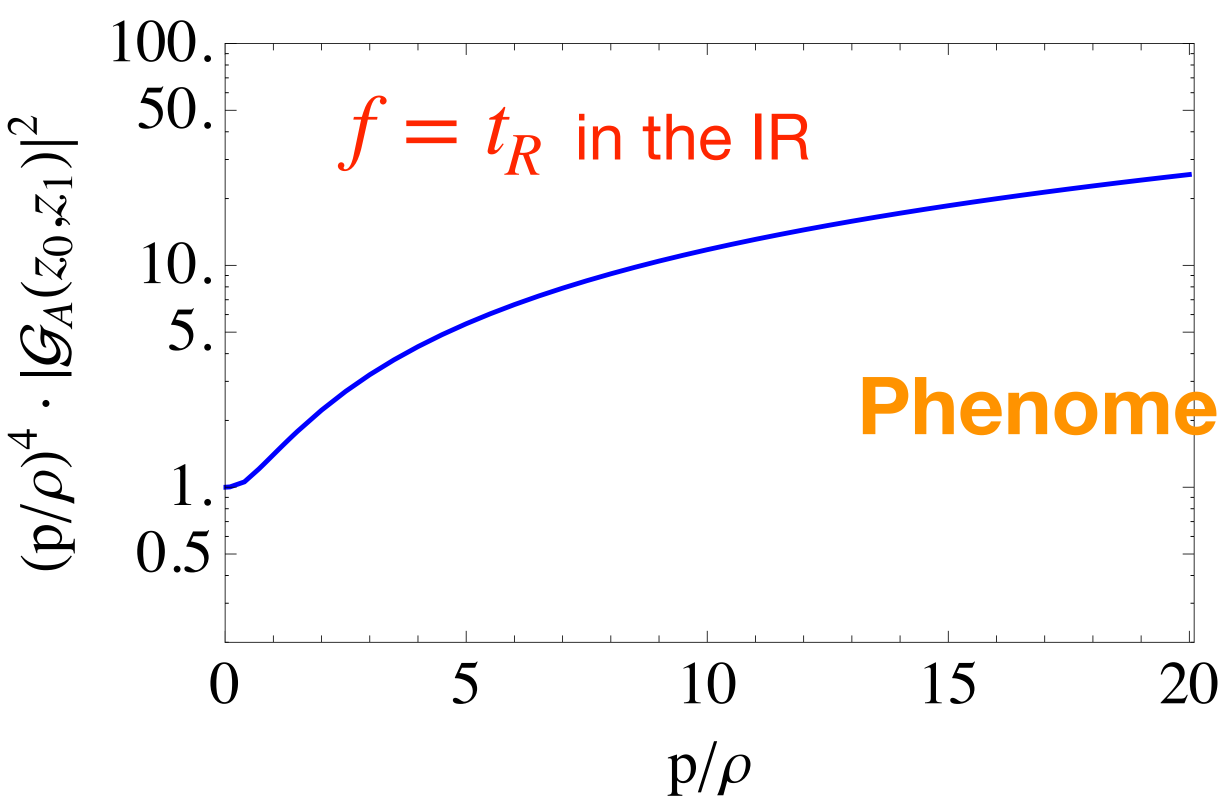
| field | gauge boson | fermion | graviton radion Higgs |
|---|---|---|---|
| mass gap | $\frac{1}{2}\rho$ | $\lvert c_f \rvert \rho$ | $\frac{3}{2}\rho$ |

*As for light fermions* $c_f > 1/2,$ *the easiest produced continuum is for gauge bosons*

- Normal searches at LHC are based on bumps in the invariant mass of final state

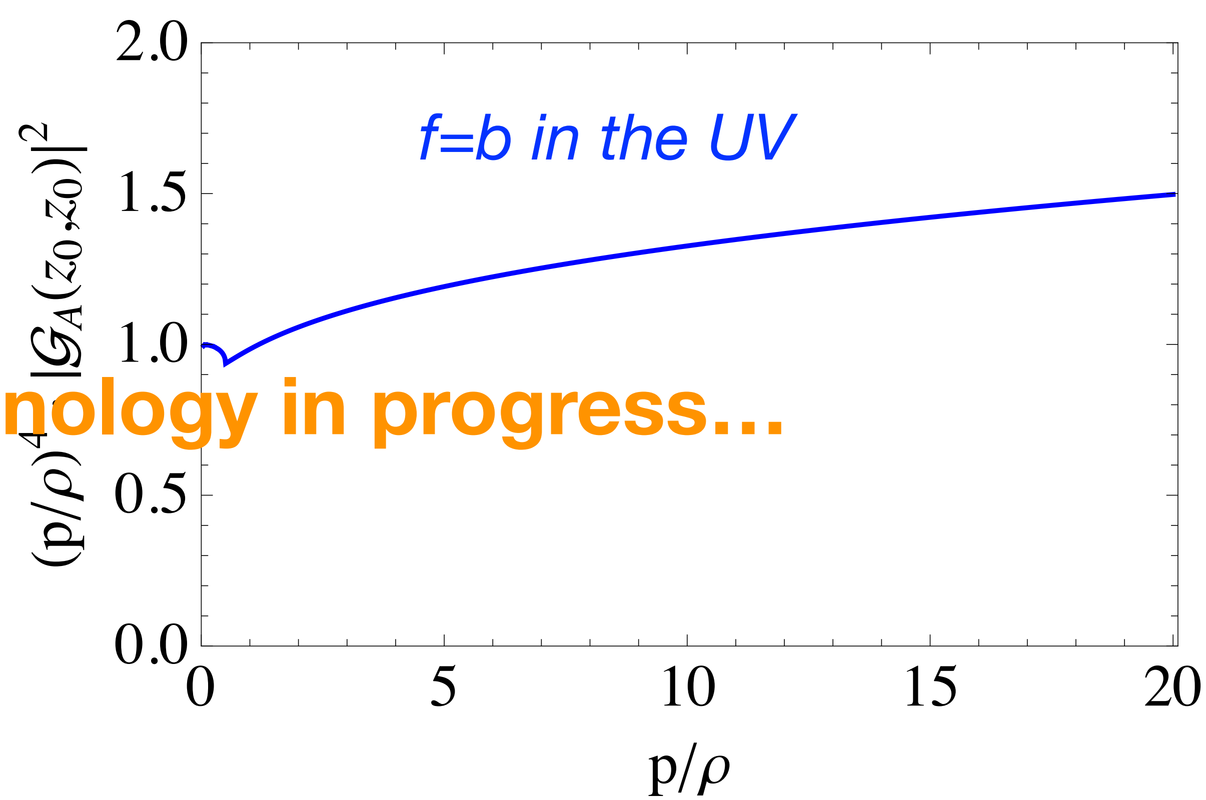
- However here, in production of fermions from DY processes via gluon KK continuum, there is just an increase in the cross section: $\sigma(q\bar{q} \to g^* \to f\bar{f}), \quad p = \sqrt{\hat{s}}$

$$\sigma/\sigma_{SM}(q\bar{q} \to f_{IR}\bar{f}_{IR})$$




**Strong increase with energy**

$$\sigma/\sigma_{SM}(q\bar{q} \to f_{UV}\bar{f}_{UV})$$




**Little increase with energy**

**Phenomenology in progress…**

# Conclusions

- Warped extra dimensions is an interesting alternative to solve the hierarchy problem (dual to CFT,…)
- It triggers a confinement/deconfinement first order phase transition, and possibly a first order EW phase transition
- Gravitational waves are useful tools to detect the existence of first order phase transitions, and thus of new physics
- An exploring possibility to solve the elusiveness of signals at LHC is a continuum of KK states (related to CFT, unparticles,..)