# Phenomenology of warped dimensions

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# Introduction

- Proposed in 1999 by Randall and Sundrum (RS)

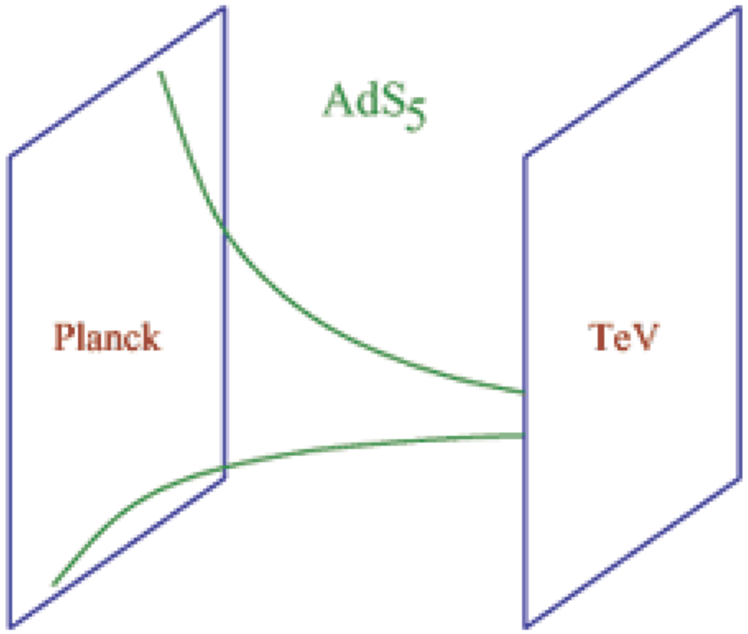
*L. Randall, R. Sundrum, 9905221*

- 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 toward the IR brane (composite):
- Heavy (light) fermions are mainly localized @ the IR (UV) brane: composite (elementary)
- Zero mode gauge bosons are flat
- KK modes are mainly localized toward 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

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

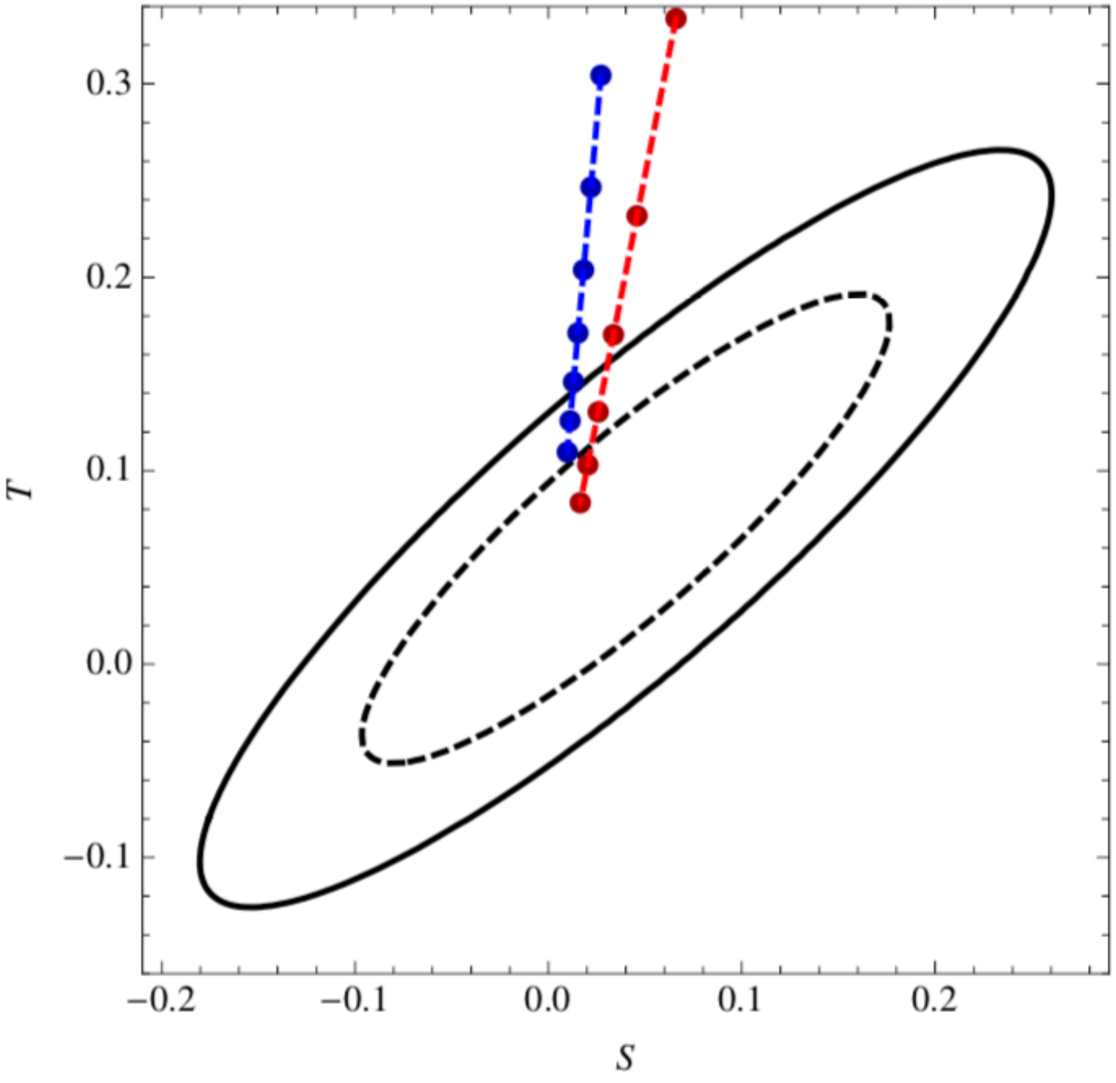
$$c_{KK} = \frac{m_{KK}}{k} e^{k y_1}, \quad k y_1 \simeq 35$$

Using the PDG 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*

# *ONE POSSIBLE WAY OUT: AAdS*

- One possibility is to have large back reaction on the metric such as to create a singularity
- Typical example is the metric

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

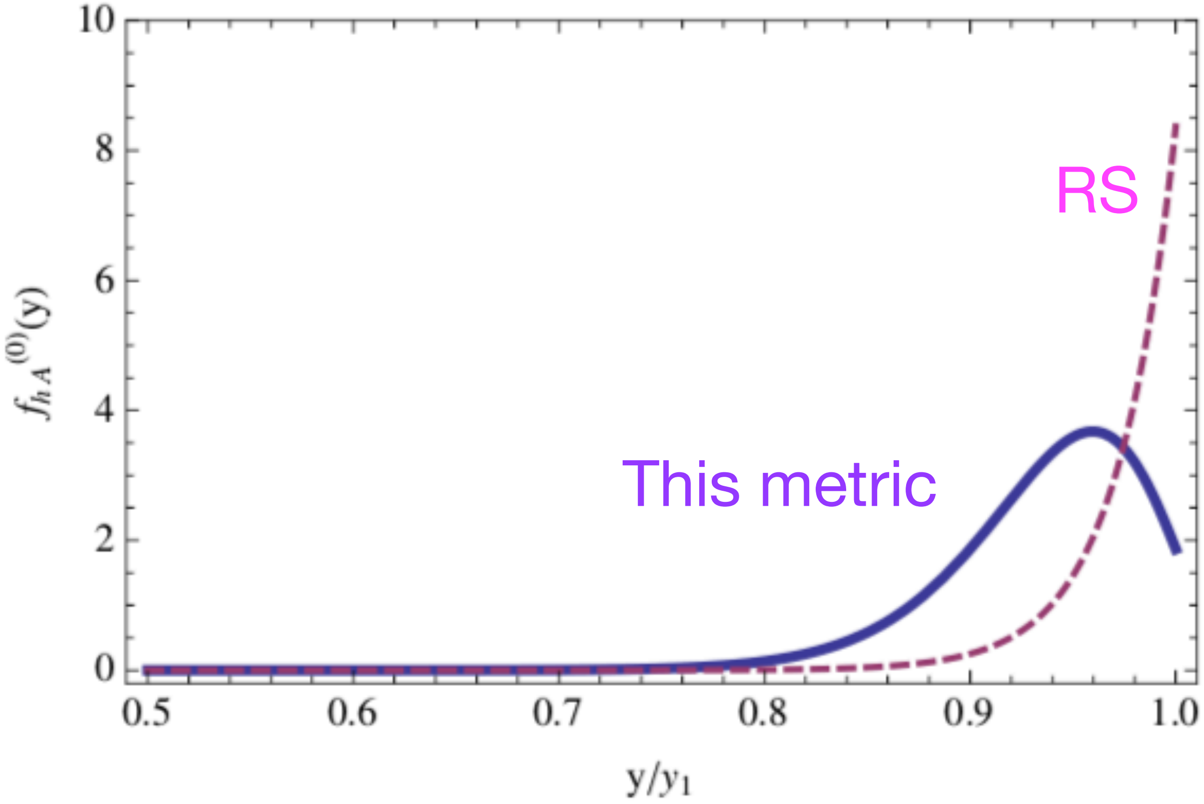
- Which is AdS on the UV: y=0

*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

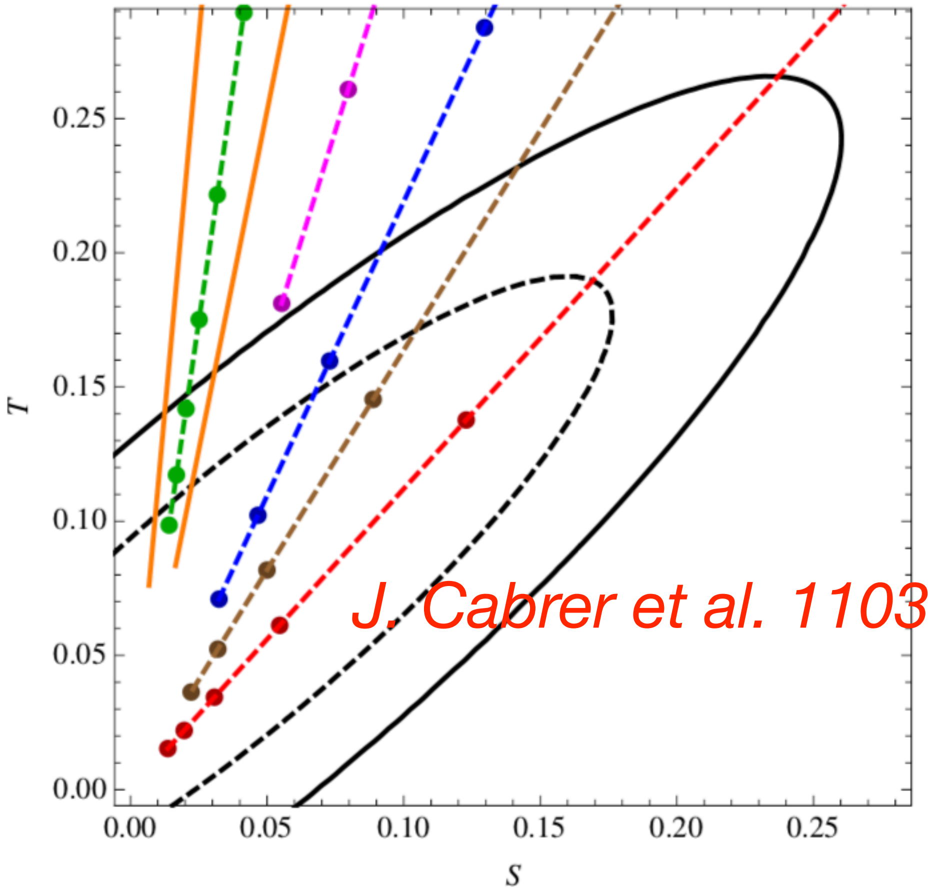
*S. Gubser, 0002160*

- 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

RS $\nu = 0.6$ $\nu = 0.525$ $\nu = 0.5$



J. Cabrer et al. 1103.1388

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

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

# Confinement/deconfinement PhT

- In these theories there is a confinement/deconfinement phase transition

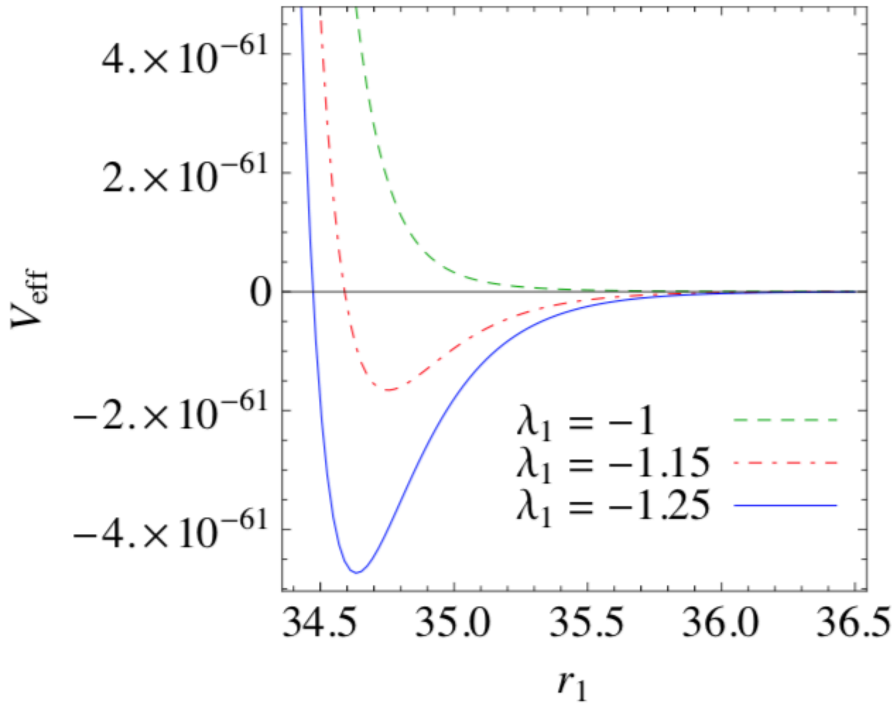
P. Creminelli et al. 0107141

A. Pomarol @ this conference

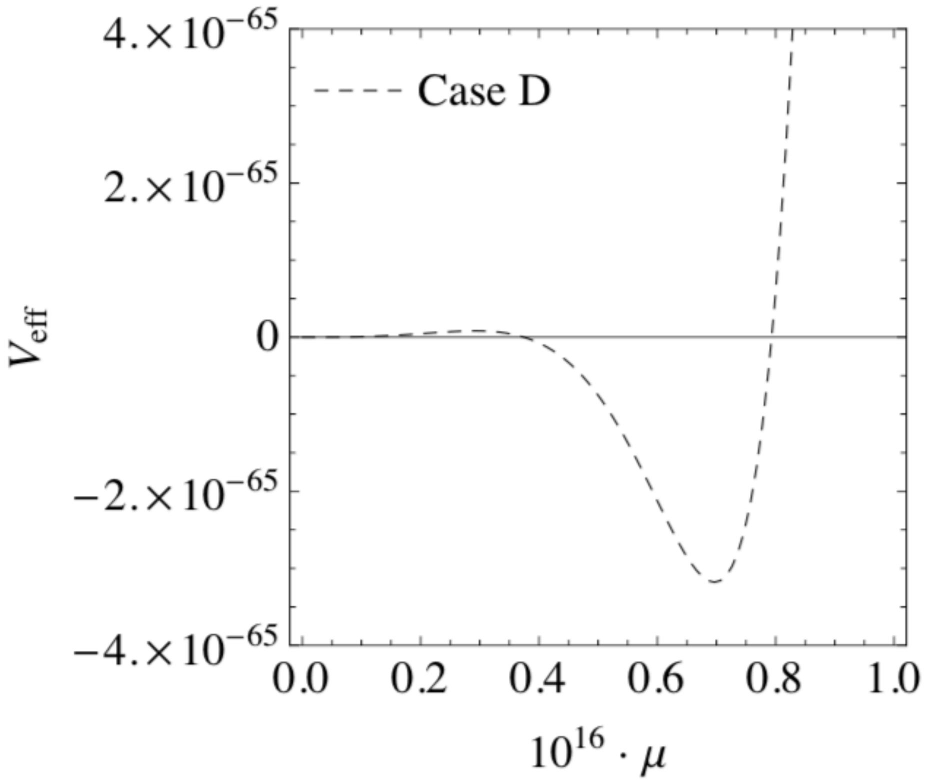
- We have to introduce the notion of effective potential as a function of the radion field

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

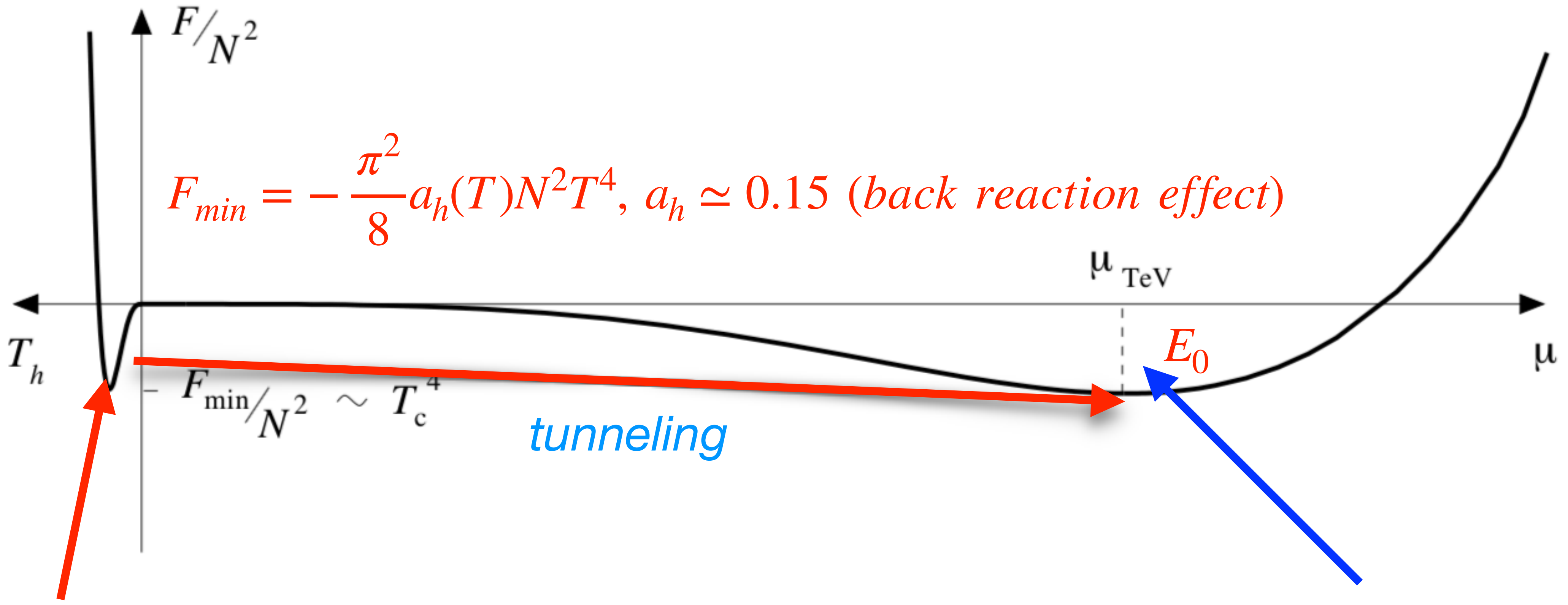
$$F_d(T) = E_0 + F_{min} - \frac{\pi^2}{90} g_d^{eff} T^4 \qquad F_c(T) = -\frac{\pi^2}{90} g_c^{eff} T^4$$

Potential depth

Depth in the BH phase

# Cartoon potential

*P. Creminelli et al. 0107141*



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

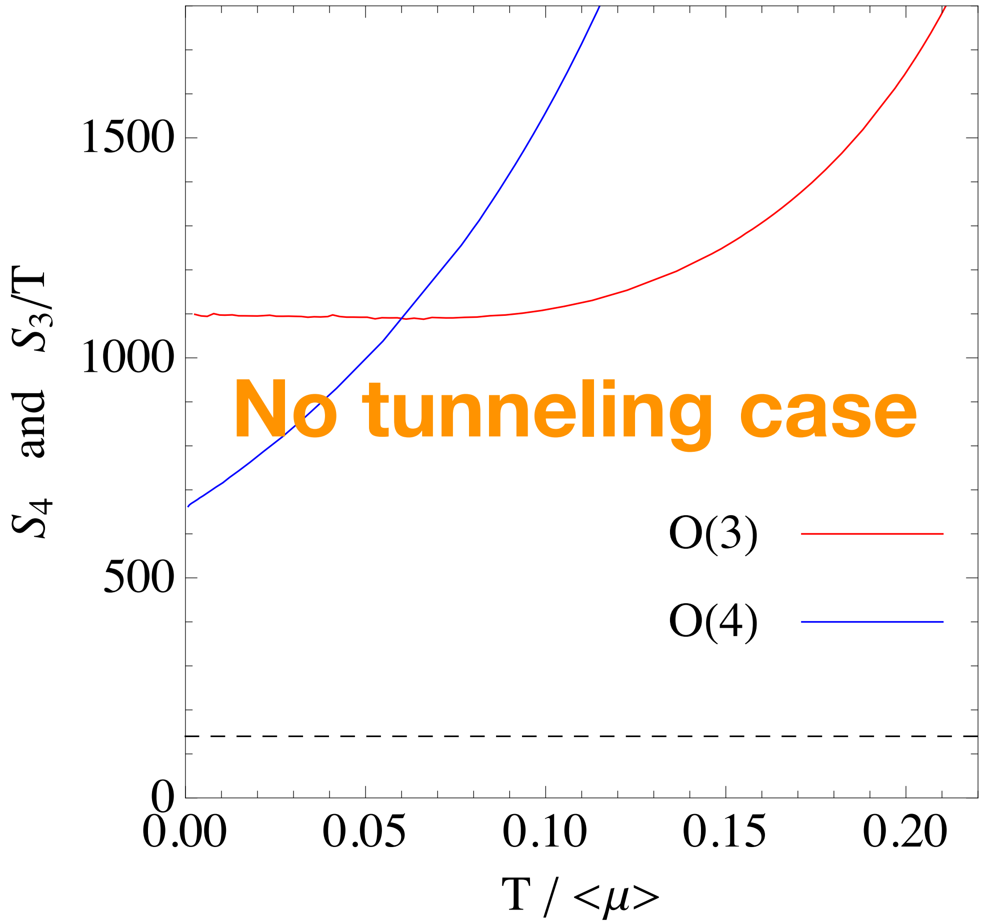
*tunneling*

Depth in the BH phase

Potential depth

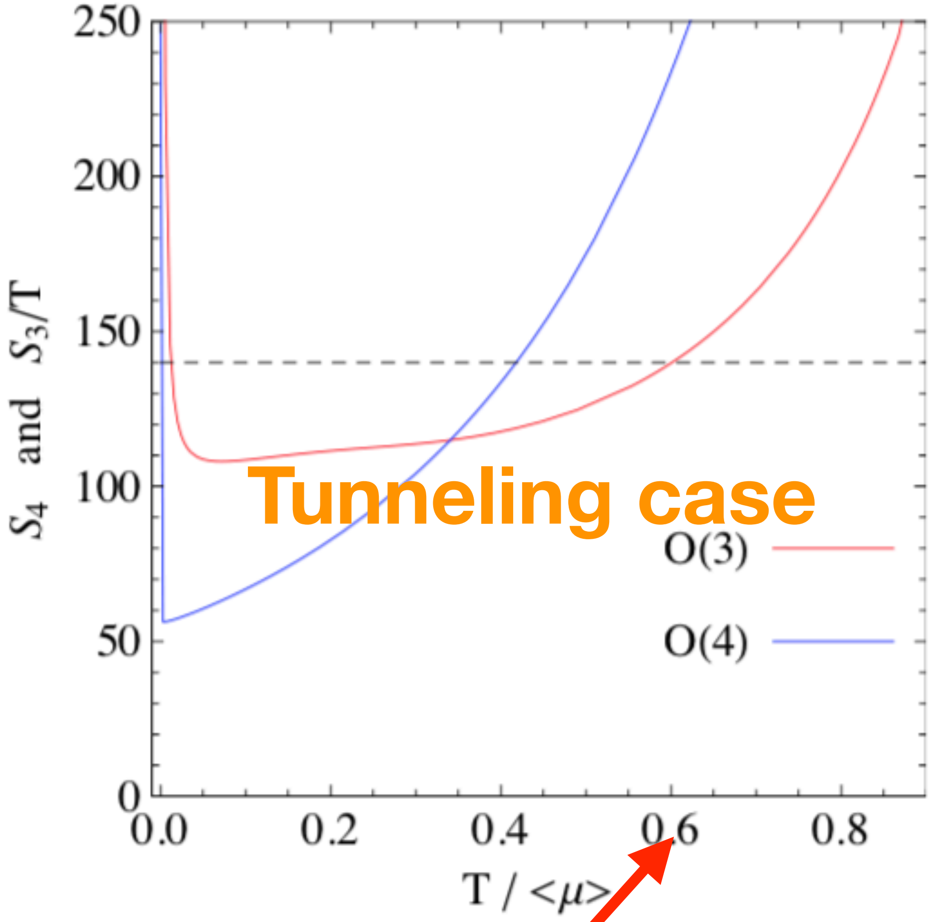
## Two typical examples

**Small back reaction: Dilaton trapped in supercooled phase**



No tunneling case

**Large back reaction: Phase transition at TeV**



Tunneling case

*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 very 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 TeV

# The electroweak PhT

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

- For instance assuming that only the Higgs, radion and right-handed top are localized toward the IR brane (only exist in the confined phase) 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

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

G. Nardini et al. 0706.3388

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

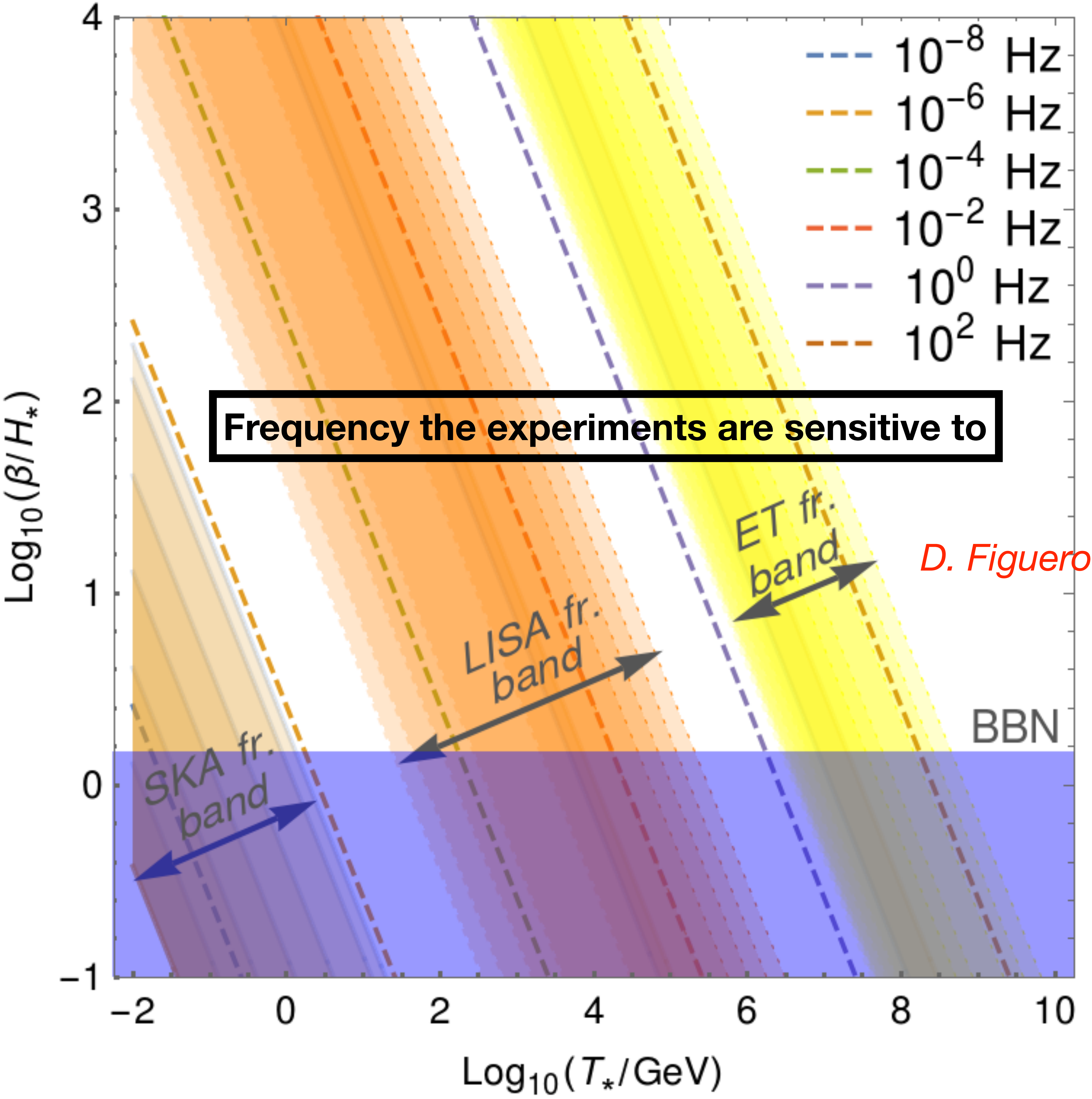
- The power spectrum depends on phase transition quantities

*M. Spannowsky @ this conference*

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

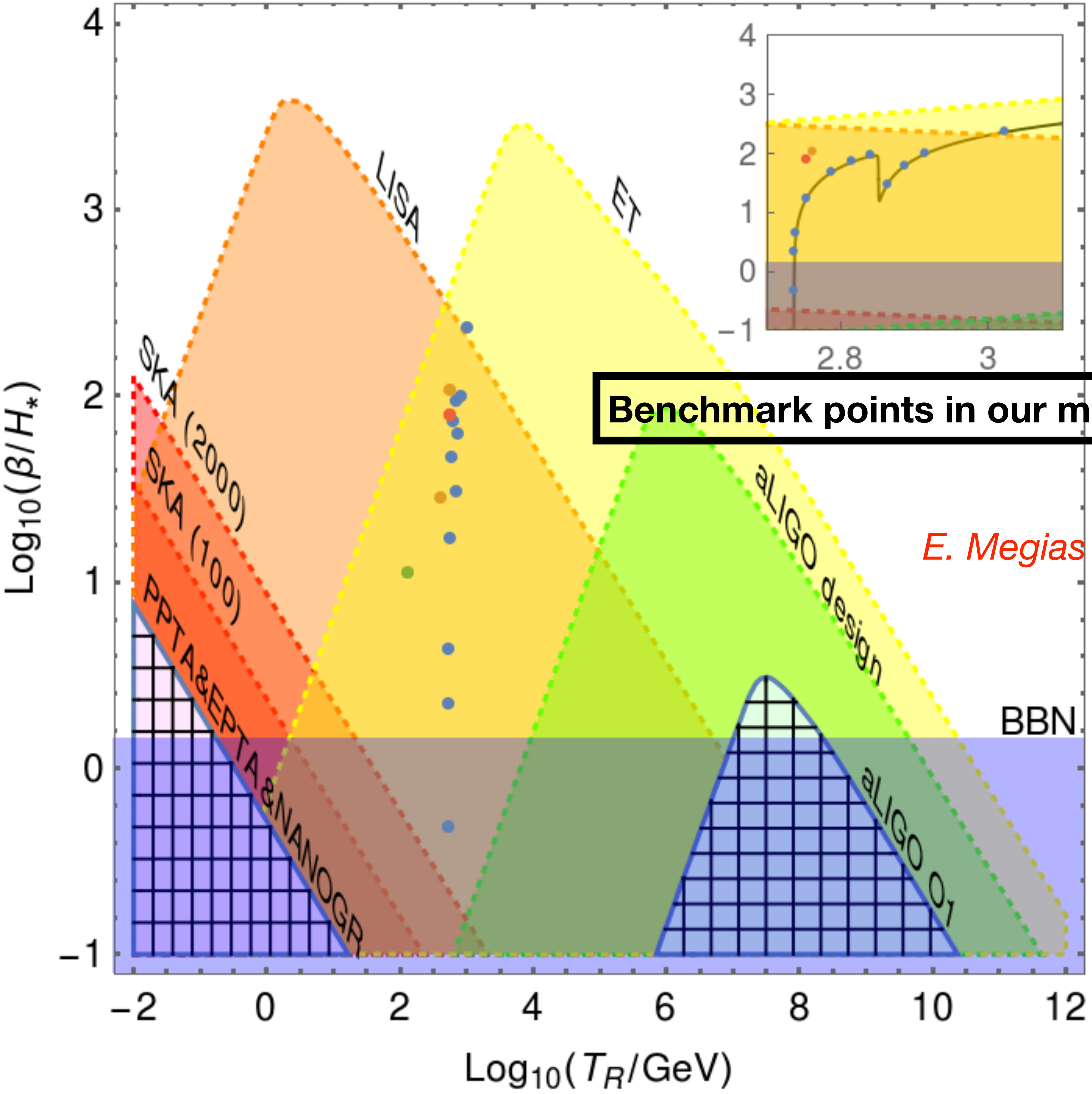
- In the next two decades several GW observatories will have the potential to observe, or constrain, the SGWB produced in our benchmark models

*C. Caprini et al. 1512.06239*



**Frequency the experiments are sensitive to**

*D. Figueroa et al. 1806.06463*



**Benchmark points in our model**

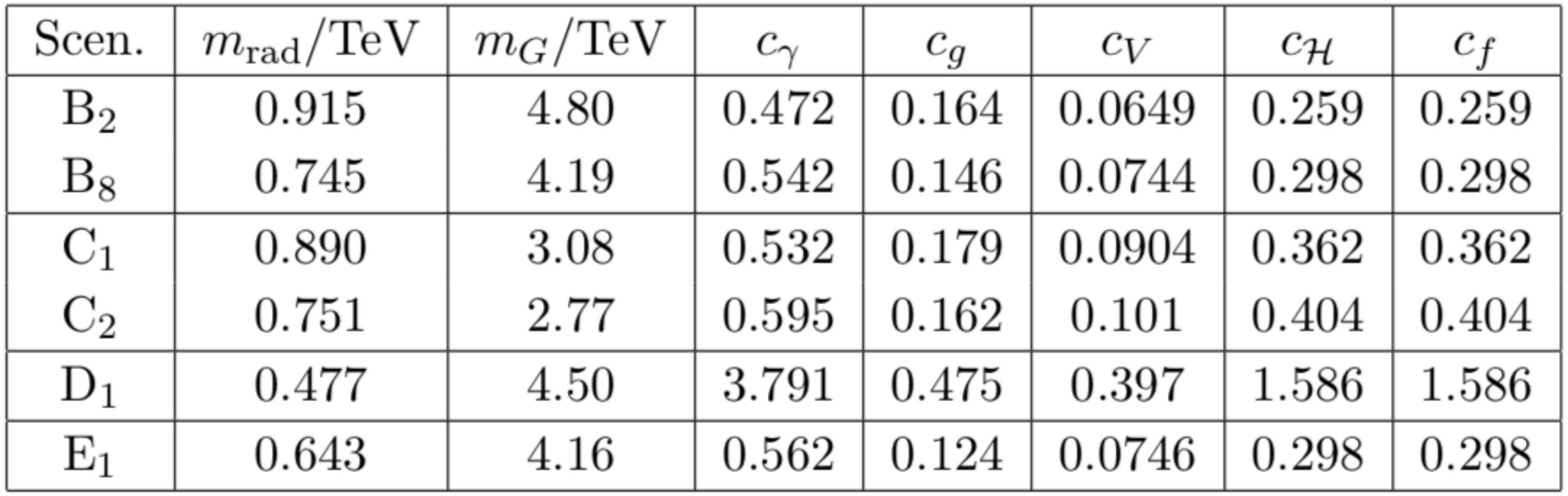
*E. Megias et al. 1806.04877*

# 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

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

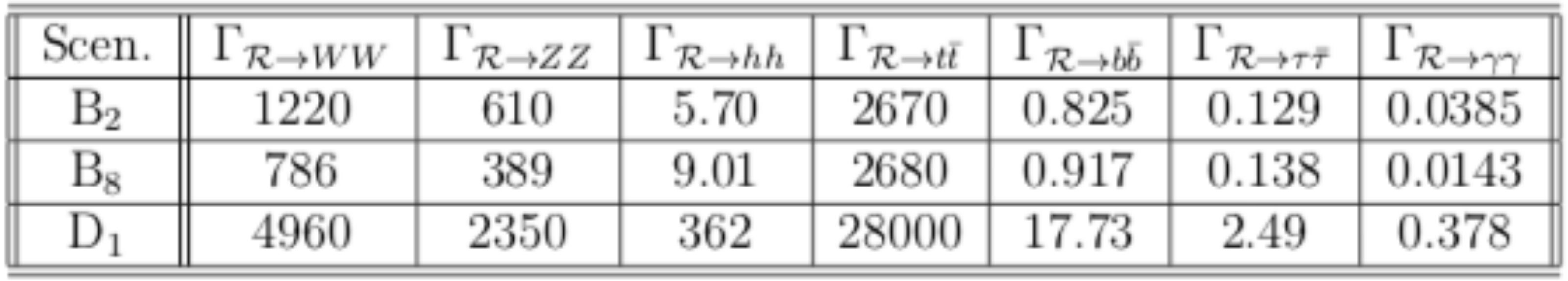
- The coefficients are model dependent and less than 1



| Scen. | $m_{\rm rad}$/TeV | $m_G$/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 |

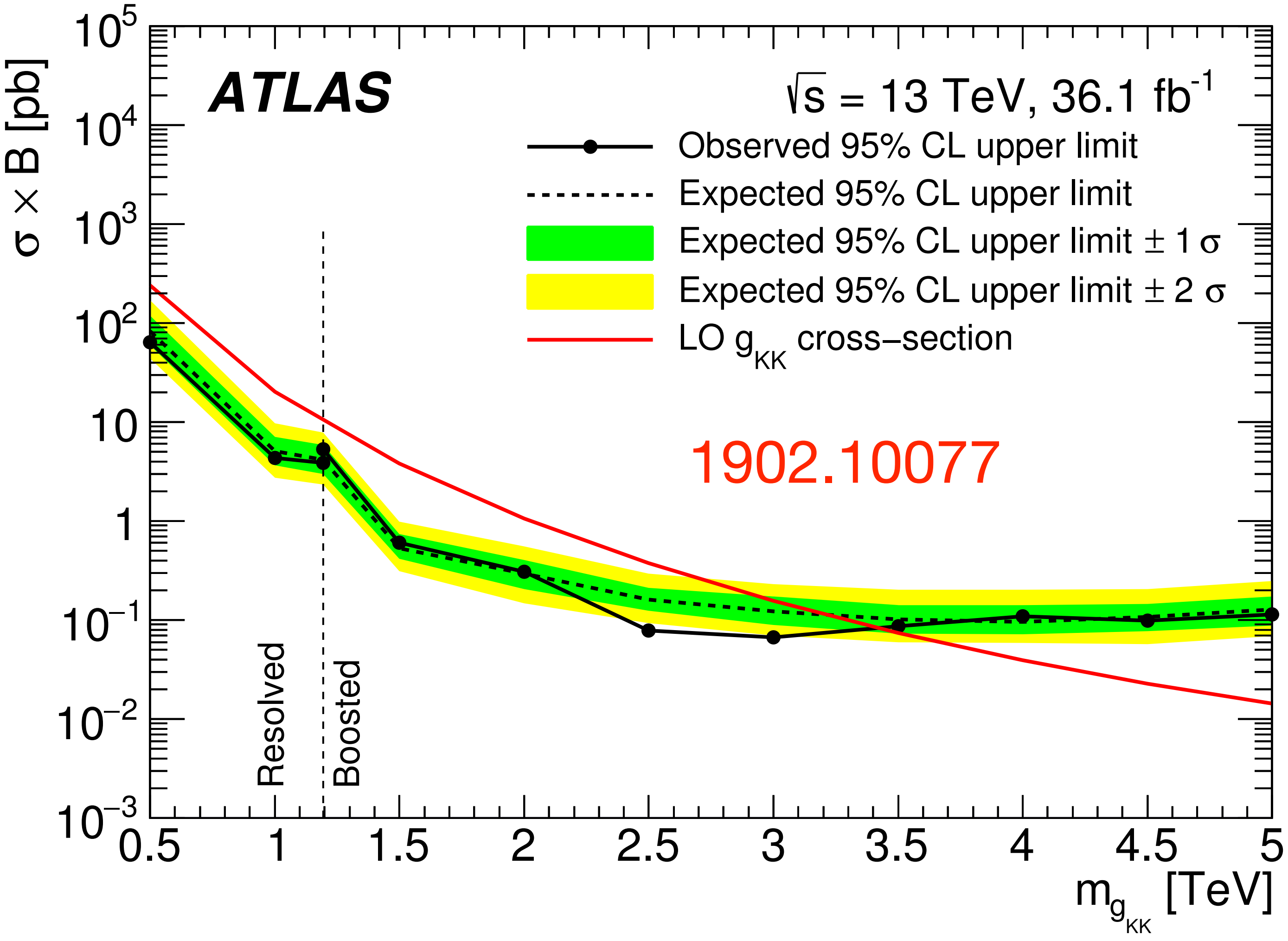
all widths are in MeV

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

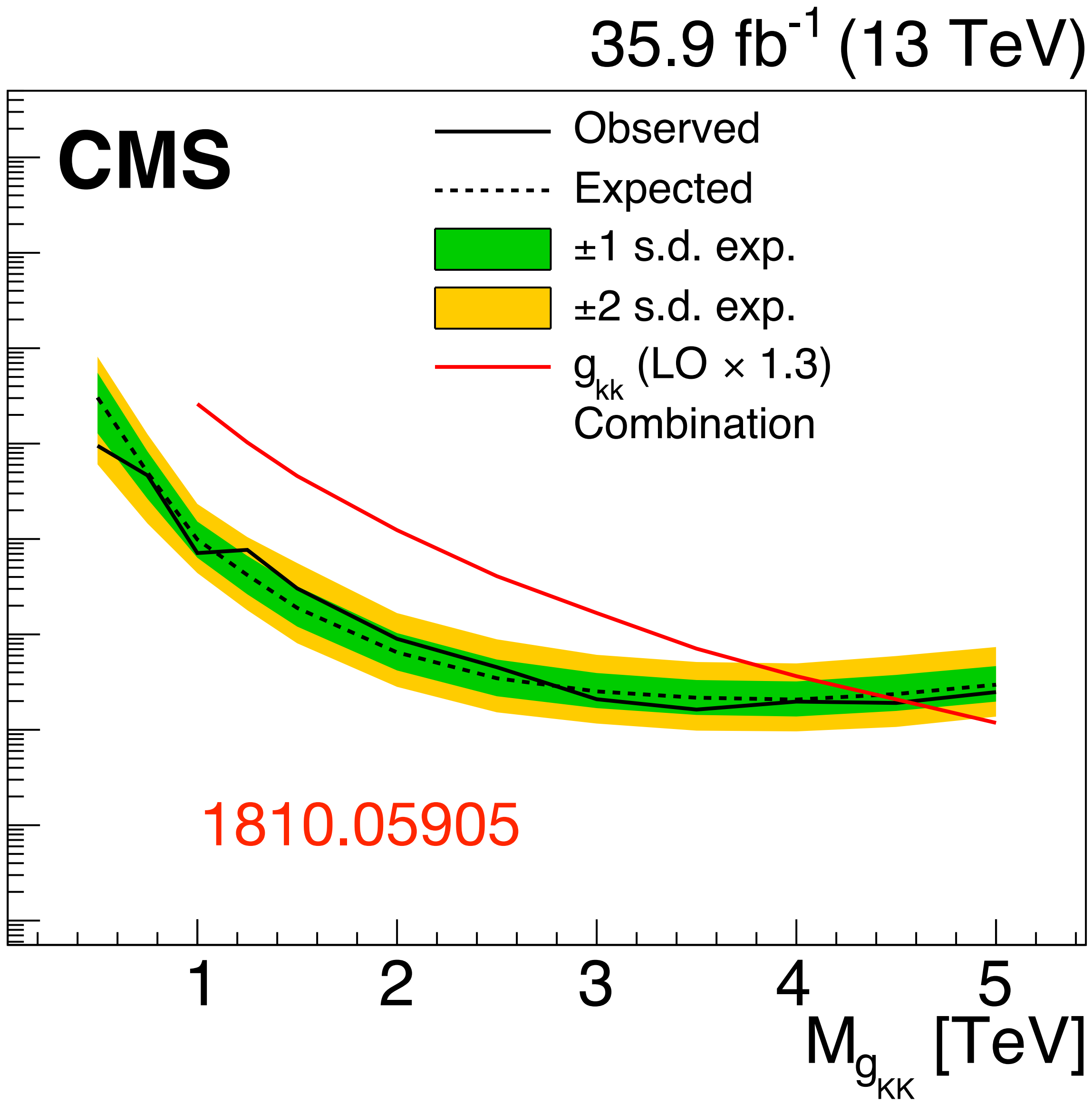
- The heavy radion phenomenology is very model dependent and it is in general easy to avoid the present bounds as we have found in our benchmark points

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

# Bounds from ATLAS & CMS start to be very strong



1902.10077



1810.05905

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

# Gapped continuum KK modes

E. Megías and MQ, 1905.07364

*E. Megías @ this conference*

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

D. Stancato, J. Terning, 0807.3961;
A. Falkowski, M. Perez-Victoria, 0810.4940

C. Csaki et al. 1811.06019

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

*M. Olechowski @ this conference*

G. Giudice et al. 1711.08437

- Similar in the IR to Linear Dilaton scenarios, dual to Little String theories

I. Antoniadis et al. 1102.4043

- The class of models we have considered show some properties

UV AdS IR deformation

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

1. They reproduce RS in the UV and therefore they can conventionally explain 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.
   Modelization of Unhiggs

   D. Stancato, J. Terning, 0807.3961;
   A. Falkowski, M. Perez-Victoria, 0810.4940

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

$$G_A(p^2, m^2) = \Re G_A(p^2, m^2) + i\,\Im G_A(p^2, m^2)\theta(p^2 - m^2)$$

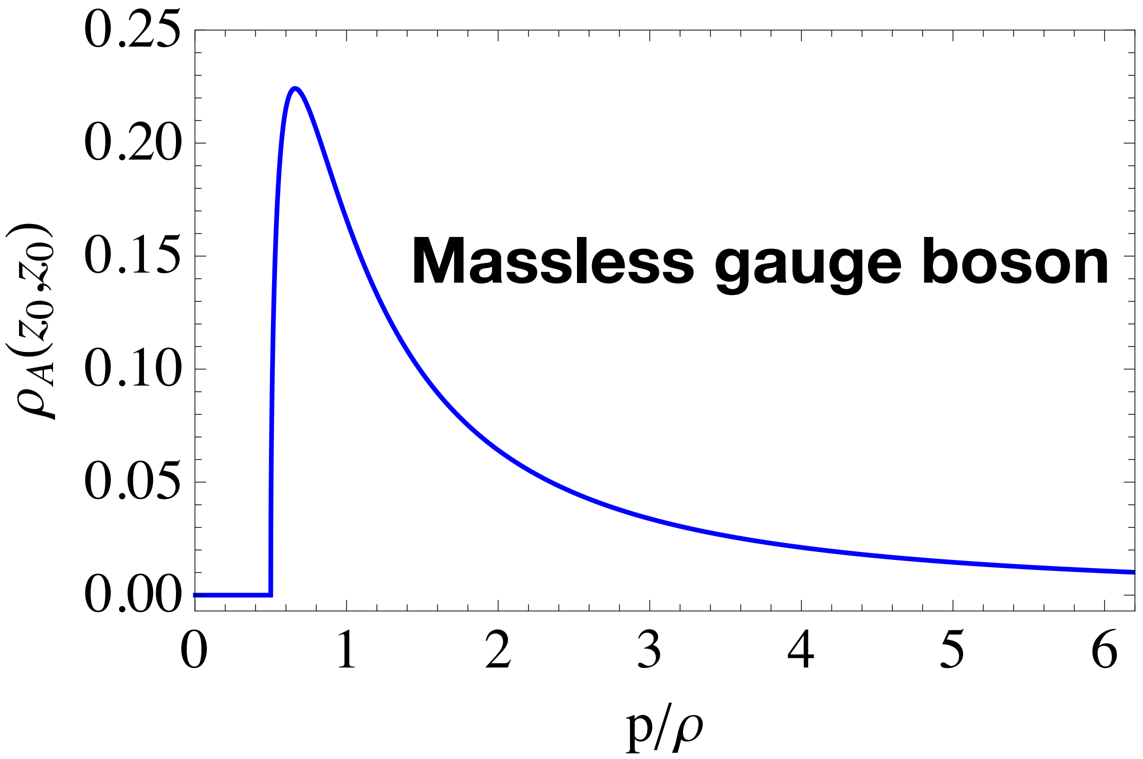
- This is the behavior of gapped unparticles where the gap was usually produced by EW breaking

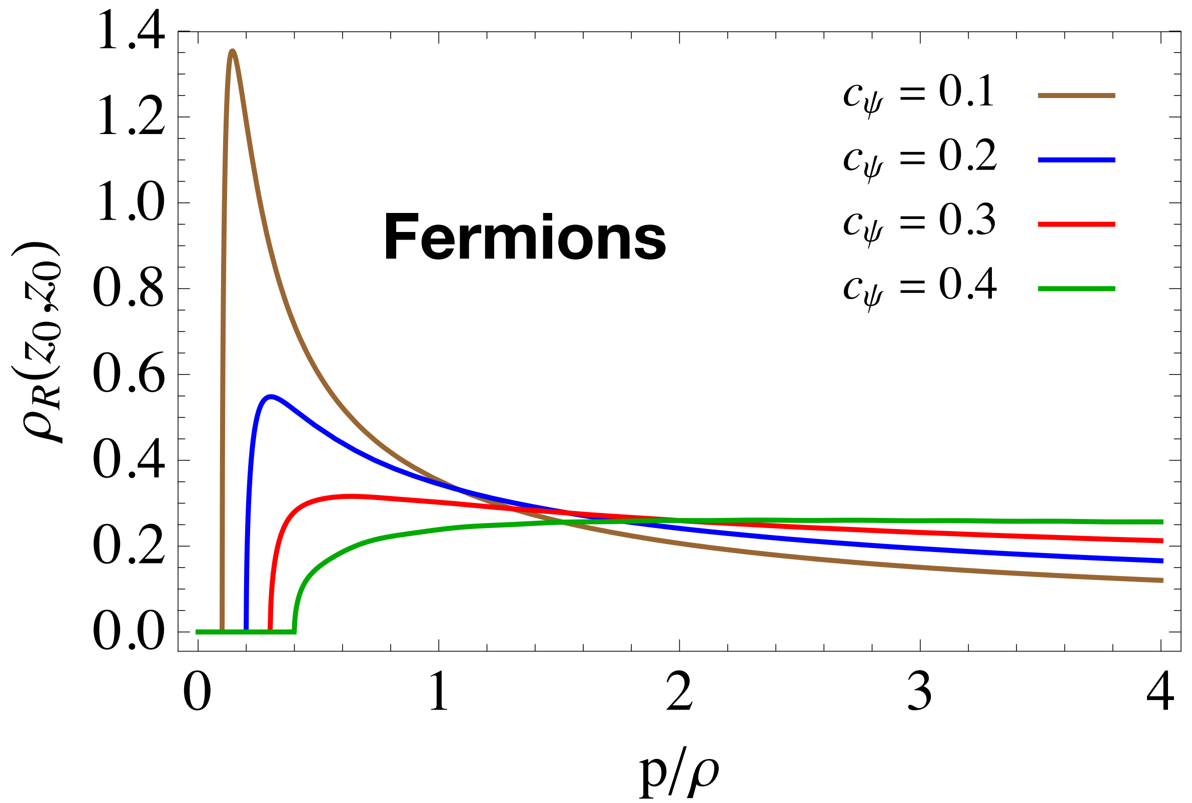
- Here the gap is TeV, and is linked to the solution of the hierarchy problem

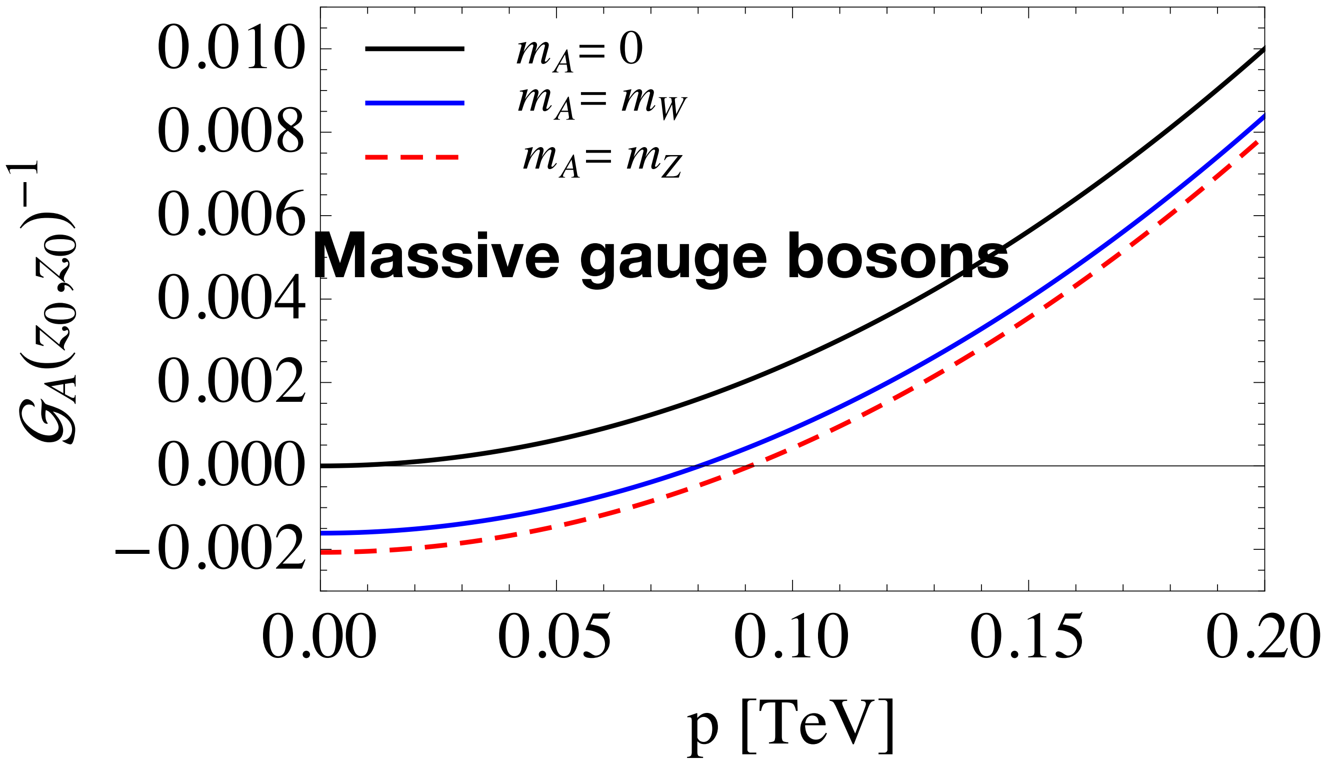
# The continuum spectrum shows up in the spectral density function

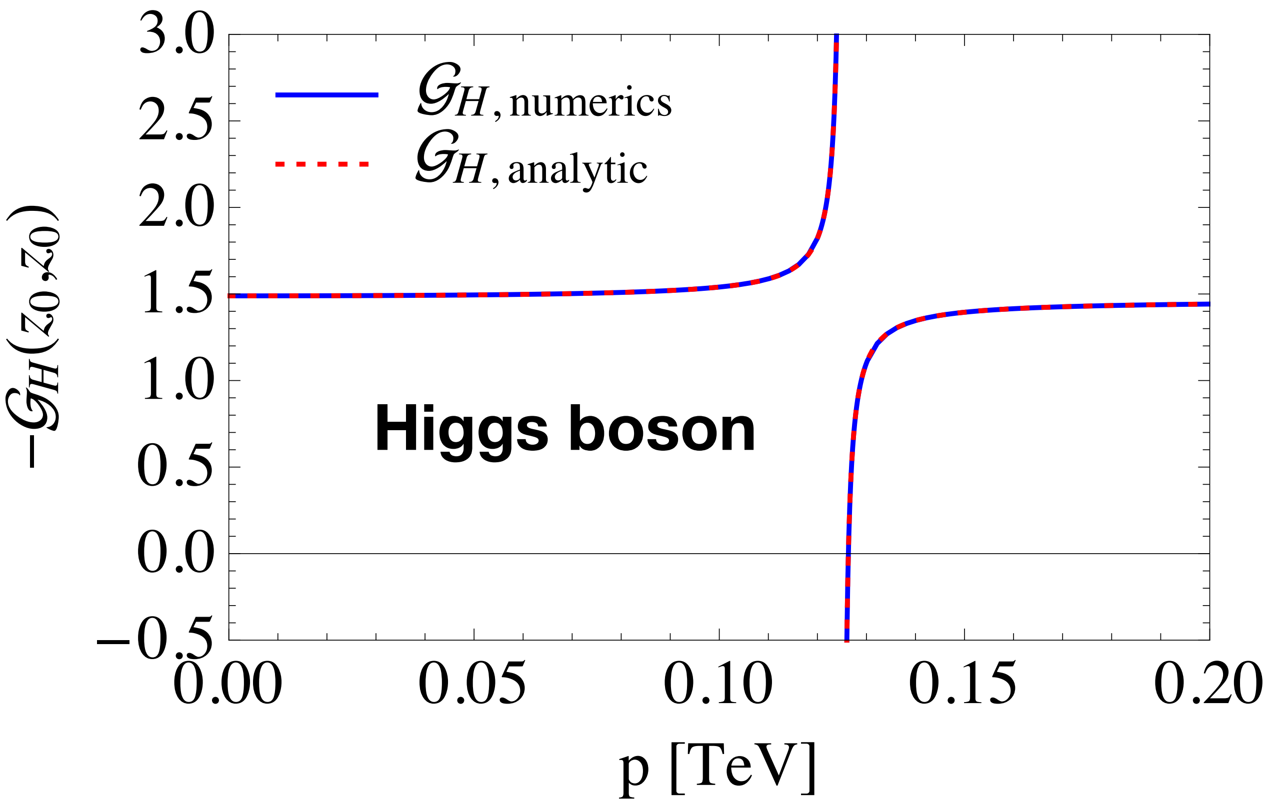
$p \equiv \sqrt{s}, \quad \rho =$ **mass gap**

E. Megías and MQ, 1905.07364









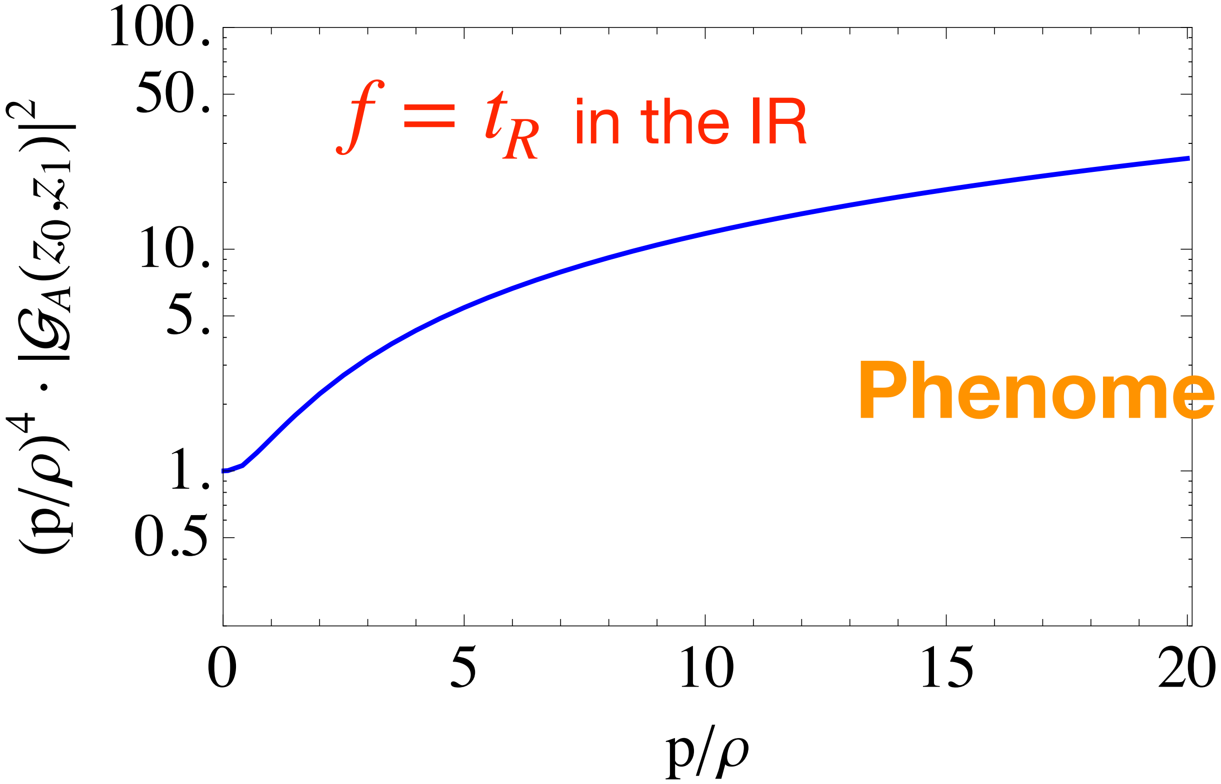
# Phenomenology of continuum KK modes

- The mass gap is different for different states

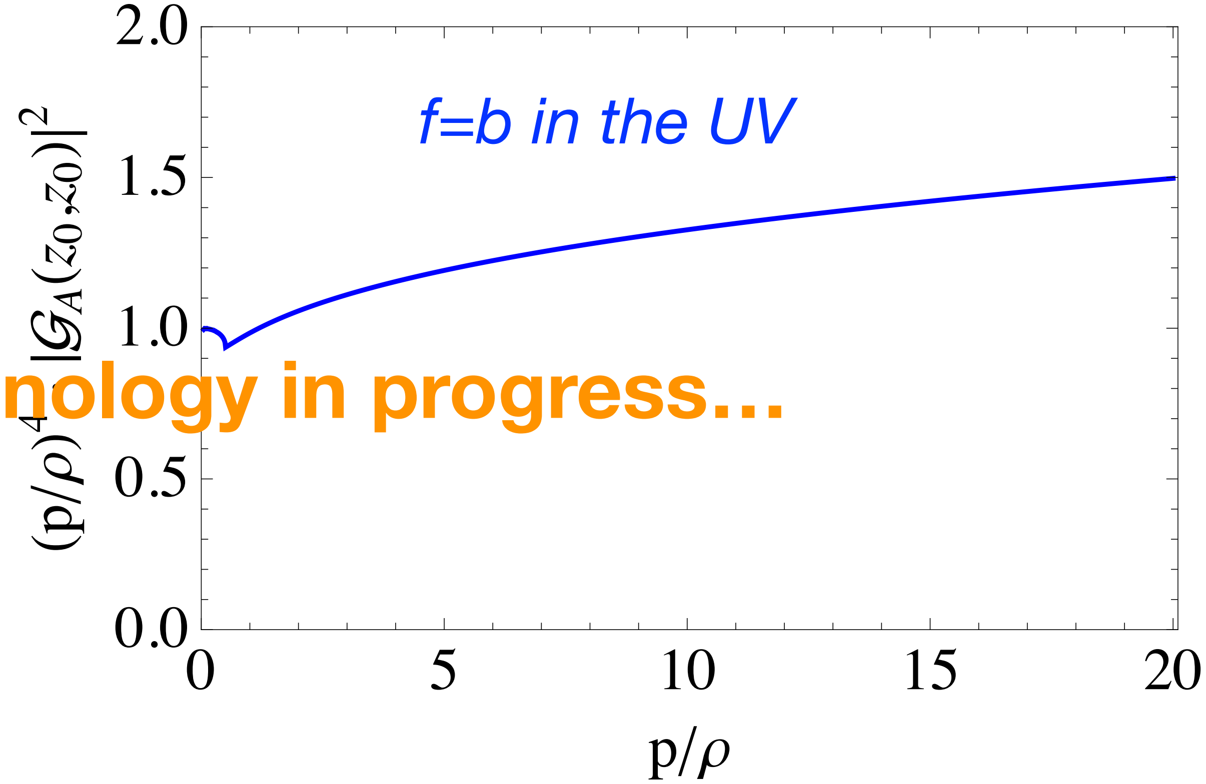
| field | gauge boson | fermion | graviton<br>radion<br>Higgs |
|---|---|---|---|
| mass gap | $\frac{1}{2}\rho$ | $\lvert c_f \rvert \rho$ | $\frac{3}{2}\rho$ |

*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 the production of fermions from DY processes via gluon KK continuum, there is 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

- A warped extra dimension 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 here
- An exploring possibility to cope with elusiveness of signals is a continuum of KK states (related to CFT, unparticles,..)