Electroweak symmetry breaking and holography

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Amsterdam, November 7, 2011

Outline

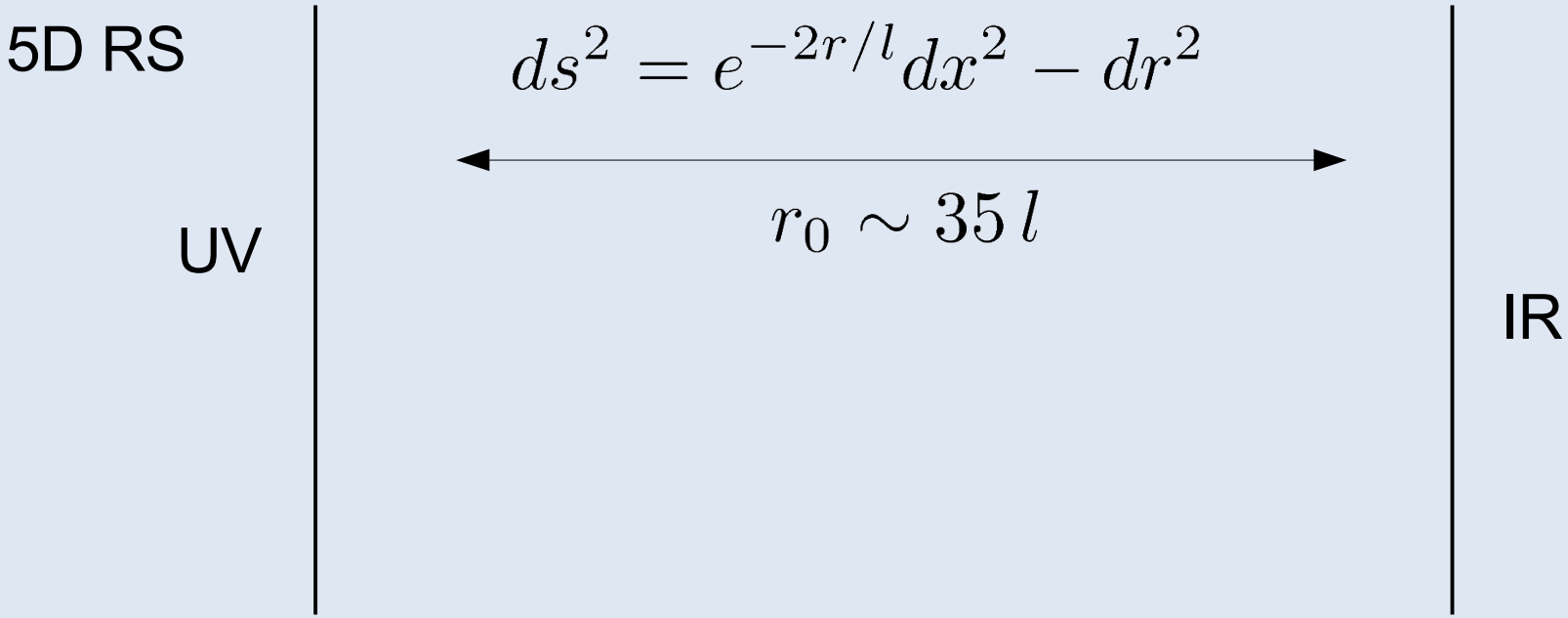
Stabilization and phase transition in 5D

Electroweak baryogenesis

Goldberger-Wise mechanism

Warped extra dimensions provide one possible solution to the hierarchy problem

$$\mathcal{L} \ni -M_5^3 \int d^5x \sqrt{g} \left[R + \frac{12}{l^2} \right]$$



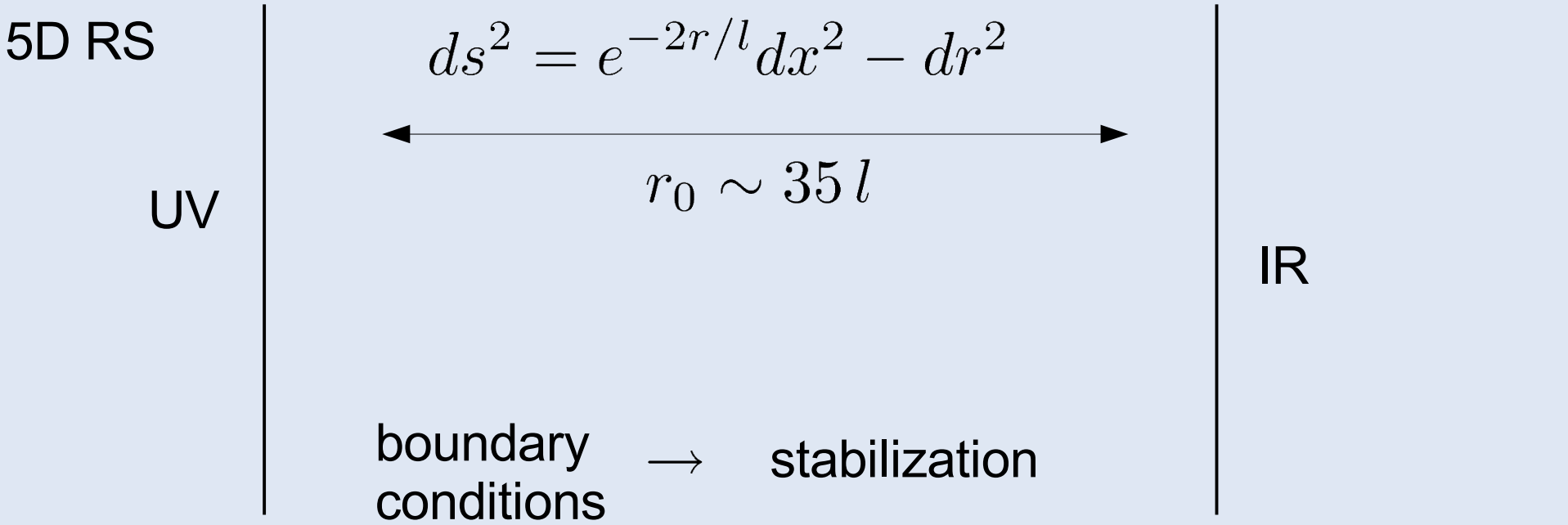
[Randall&Sundrum '99]

Goldberger-Wise mechanism

Warped extra dimensions provide one possible solution to the hierarchy problem

$$\mathcal{L} \ni -M_5^3 \int d^5x \sqrt{g} \left[R + \frac{12}{l^2} \right] + \int d^5x \sqrt{g} \frac{1}{2} \left[(\partial\phi)^2 + m^2\phi^2 \right]$$

$$\epsilon = (ml)^2/4 \sim 1/30$$



[Randall&Sundrum '99], [Goldberger&Wise '99]

Goldberger-Wise

$$ds^2 = e^{-2A(r)} dx^2 - dr^2$$

$$\phi'' + 4A'\phi' = \frac{\partial V}{\partial \phi} + \text{branes} \qquad A'^2 = -\frac{\kappa^2}{6} V + \frac{\kappa^2}{12} \phi'^2 \simeq \frac{1}{l^2}$$

$$V(\phi) = -\frac{12M^3}{l^2} + \frac{1}{2} m^2 \phi^2 \qquad \epsilon = (ml)^2/4 \sim 1/30$$

[Goldberger&Wise '99]

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Neglecting backreactions $\qquad ds^2 = e^{-2r/l}dx^2 - dr^2$

$$\phi \sim \alpha e^{-\epsilon r/l} + \beta e^{(4+\epsilon)r/l}$$

$v_{1,2} = \phi$ on the branes

[Goldberger&Wise '99]

Goldberger-Wise

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Potential $V(\mu) \simeq \mu^4 P(\mu^\epsilon) \qquad \mu = \frac{1}{l}\exp(-r/l)$

Minimum of the potential $\mu_- = \frac{1}{l}\exp\left(-\frac{1}{\epsilon}\log\frac{v_1}{v_2}\right) \qquad m_{rad}^2 \simeq \epsilon^{3/2}\mu_-^2$

[Goldberger&Wise '99]

Superpotential

$$\phi'' + 4A'\phi' = \frac{\partial V}{\partial \phi} + \text{branes} \qquad A'^2 = -\frac{\kappa^2}{6}V + \frac{\kappa^2}{12}\phi'^2$$

Including backreactions

$$V(\phi) = m^2\phi^2 = \frac{1}{8}\left(\frac{\partial W}{\partial \phi}\right)^2 - \frac{\kappa^2}{6}W(\phi)^2$$

$$\phi' = \frac{1}{2}\frac{\partial W}{\partial \phi}\ , \quad A' = -\frac{\kappa^2}{6}W$$

W is typically called superpotential

Again $\mu_- = \exp\left(-\frac{1}{\epsilon}\log\frac{v_1}{v_2}\right)$

But $m^2_{rad} \simeq \epsilon^2\mu^2_-$ GW: $m^2_{rad} \simeq \epsilon^{3/2}\mu^2_-$

[DeWolfe, Freedman, Gubser, Karch '99]

Problems

- There is obviously a discrepancy between the radion masses in the GW and superpotential schemes
- The GW setup neglects backreactions on the metric
- The superpotential method cannot be used to determine the radion potential (different brane separations would correspond to different superpotentials)

Including backreactions

Idea: Still assume $\phi^2 \ll M^3$ and include the backreactions on the metric in leading order.

For consistency this requires the inclusion of cosmological expansion

$$dS_4: \quad \bar{g}_{\mu\nu}dx^\mu dx^\nu = dt^2 - e^{2\sqrt{\Lambda}t}(dx_1^2 + dx_2^2 + dx_3^2)$$

And also a detuning on the branes. Parametrized by ξ

We find the radion mass $m_{rad}^2 \simeq \epsilon(\xi - 1 + \xi\epsilon/4)\mu_-^2$

the potential $V(\mu) = \mu^4 P(\mu^\epsilon)$

and the special cases $\xi = 1$ (superpotential)
$\xi = 1 + \sqrt{\epsilon}/2$ (GW)

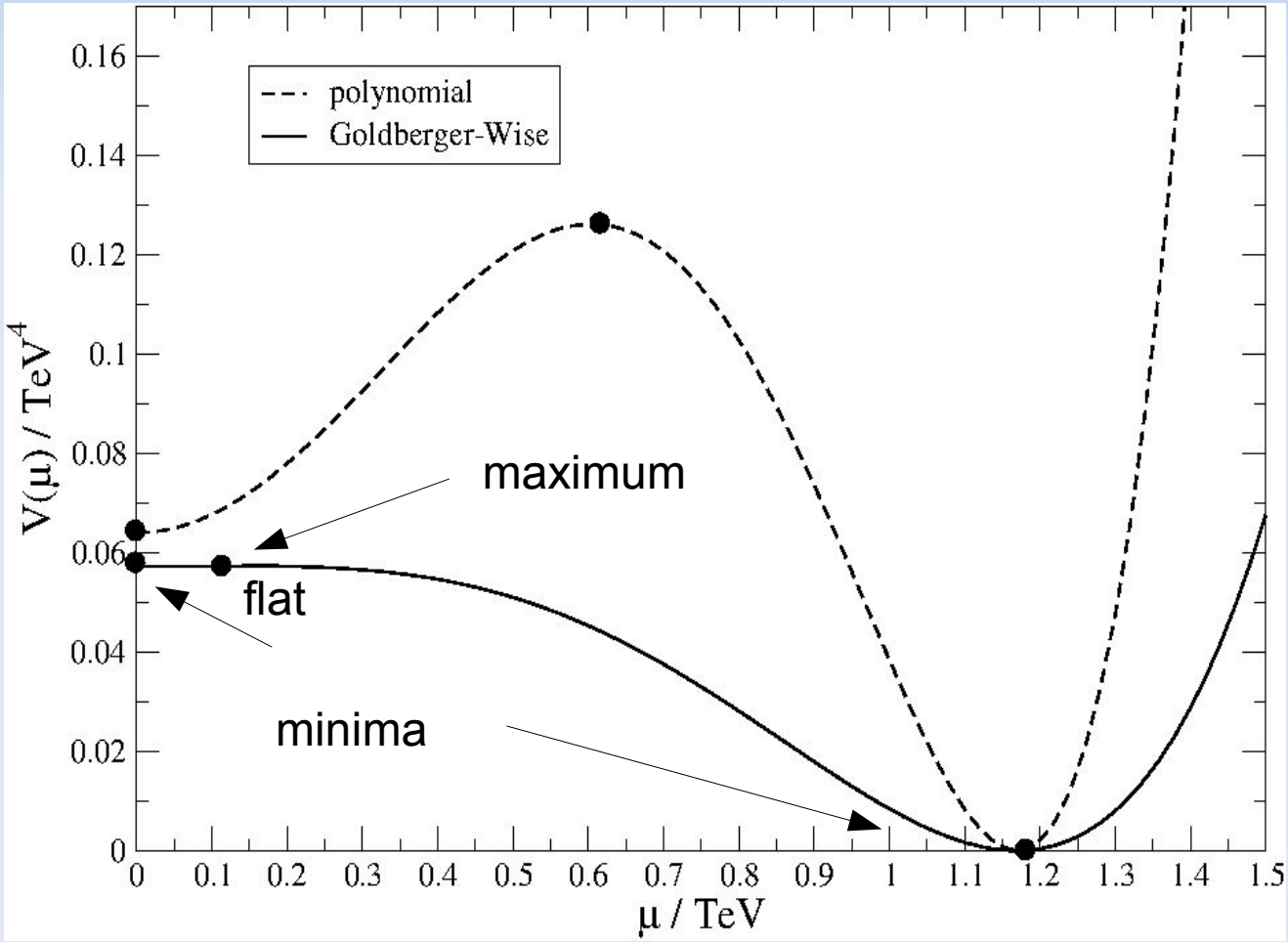
→ better control of backreactions

[TK, G Nardini, M Quiros '10]

Radion potential

The resulting radion potential is quite peculiar. $V(\mu) = \mu^4 P(\mu^\epsilon)$

In particular, there is a hierarchy between the maximum and the EW minimum.



Deconfining phase transition

confined phase

$$ds^2 = e^{-2r/l} dx^2 - dr^2$$ + bulk scalar

deconfined phase

$$ds^2 = \left(\frac{\rho^2}{l^2} - \frac{\rho_h^4}{\rho^2 l^2} \right) dt^2 + \left(\frac{\rho^2}{l^2} - \frac{\rho_h^4}{\rho^2 l^2} \right)^{-1} dx^2 + \frac{\rho^2}{l^2} dr^2$$

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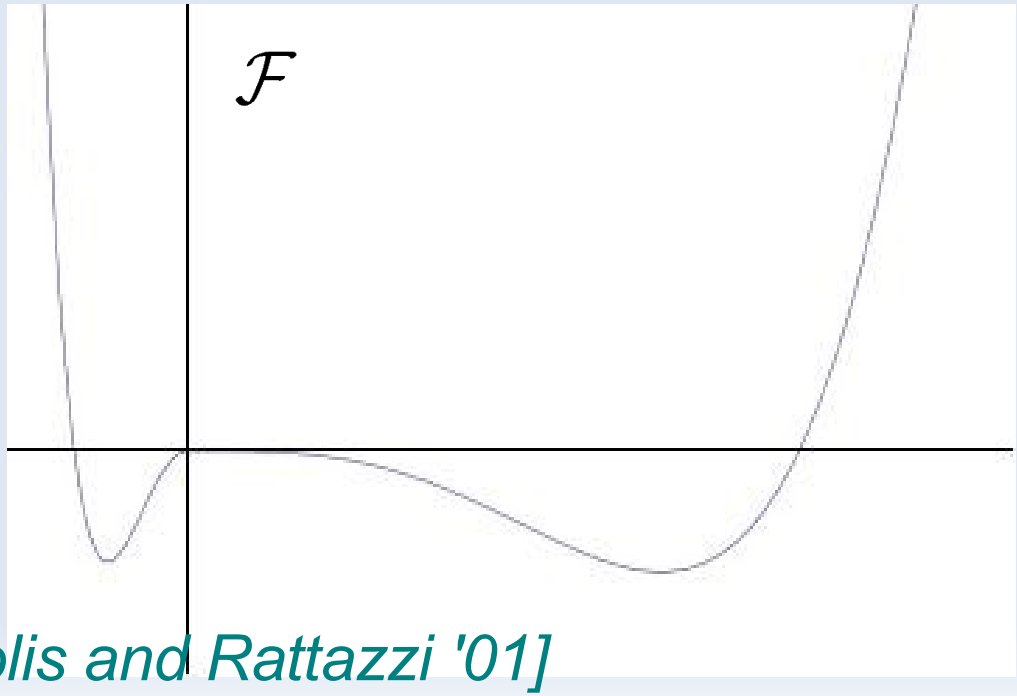
temperature

$$T_h = \frac{\rho_h}{\pi l^2}$$



radion

$$\mu = \frac{1}{l} e^{-r/l}$$

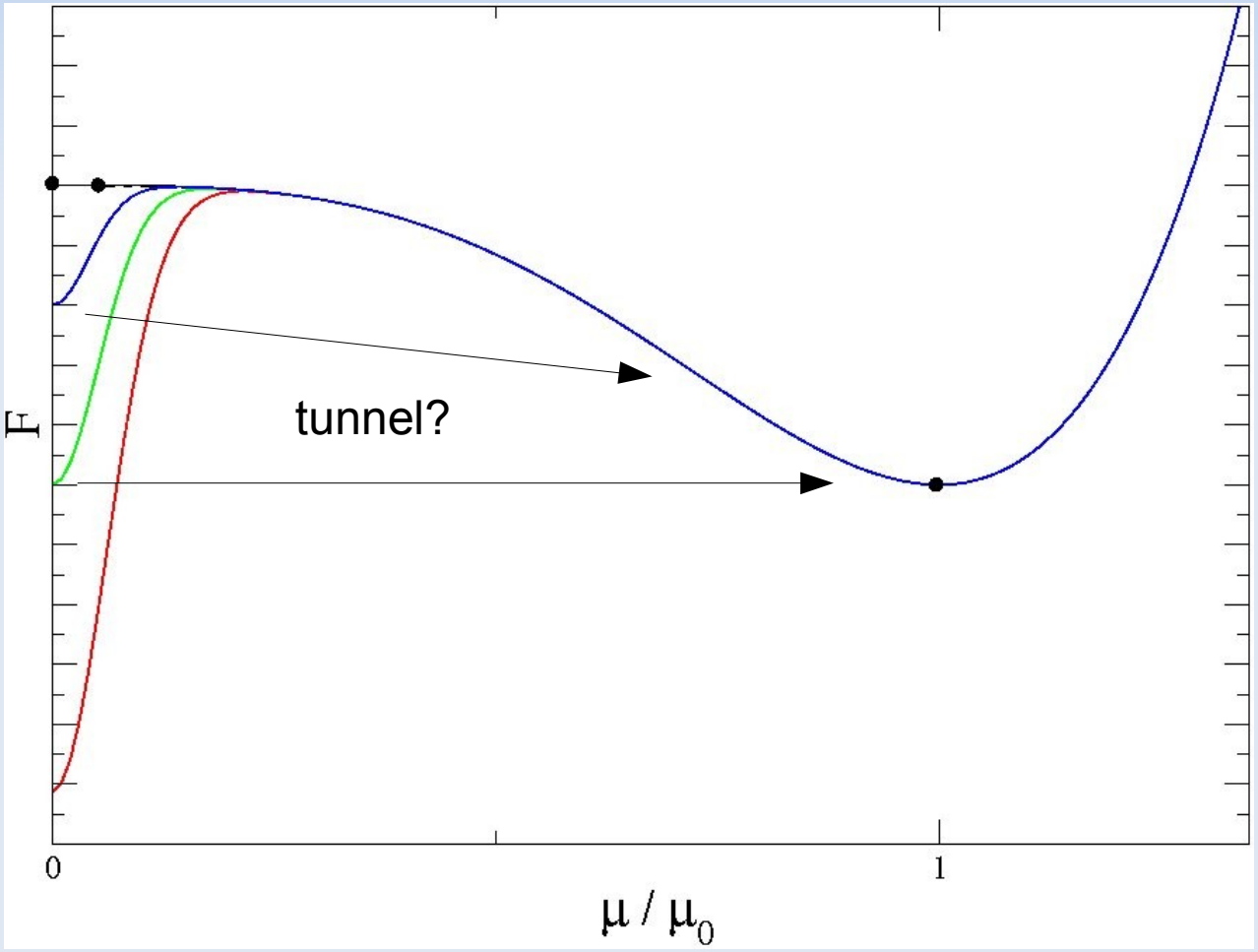
[Creminelli, Nicolis and Rattazzi '01]

Free energy - 4D

In a thermal system a phase transition will connect the two stable phases of the system.

Quarks/gluons that are confined in the broken phase induce a difference in free energy between the two phases

$$\Delta F = \frac{\pi^2}{90} \Delta g \, T^4$$



Tunnel probability

[Coleman '77]

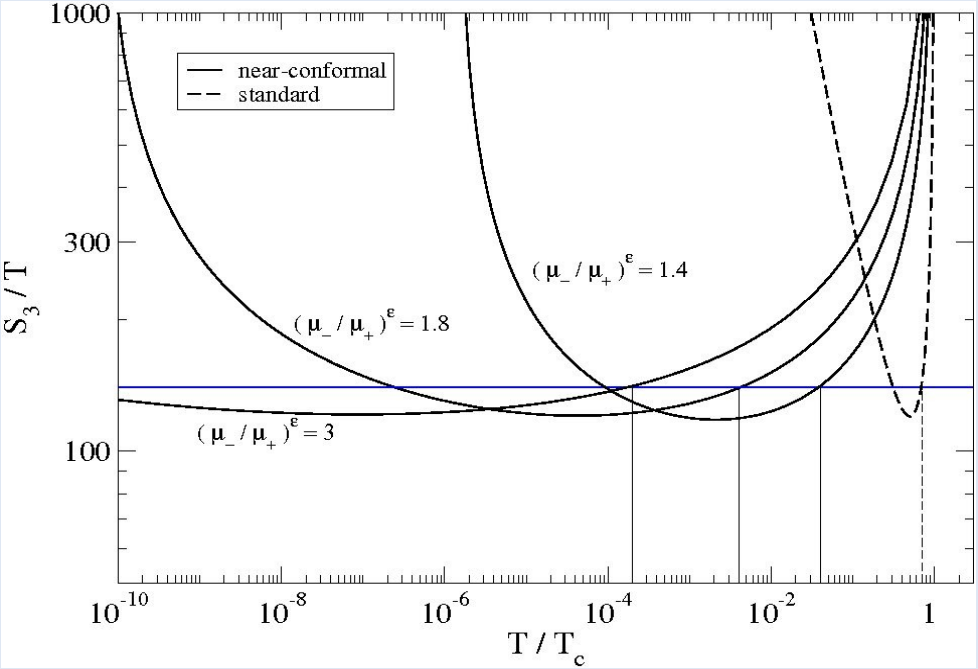
The semi-classical tunnel probability is given by the Euclidean action

$$p \sim \frac{T^4}{H^4} e^{-S_3/T}$$

The tunnel action inherits the nearly conformal behavior of the scalar potential

$$S_3/T \sim 4 \log T/H \sim 140$$

$$S_3/T \sim \text{polynomial}((T/T_c)^\epsilon)$$

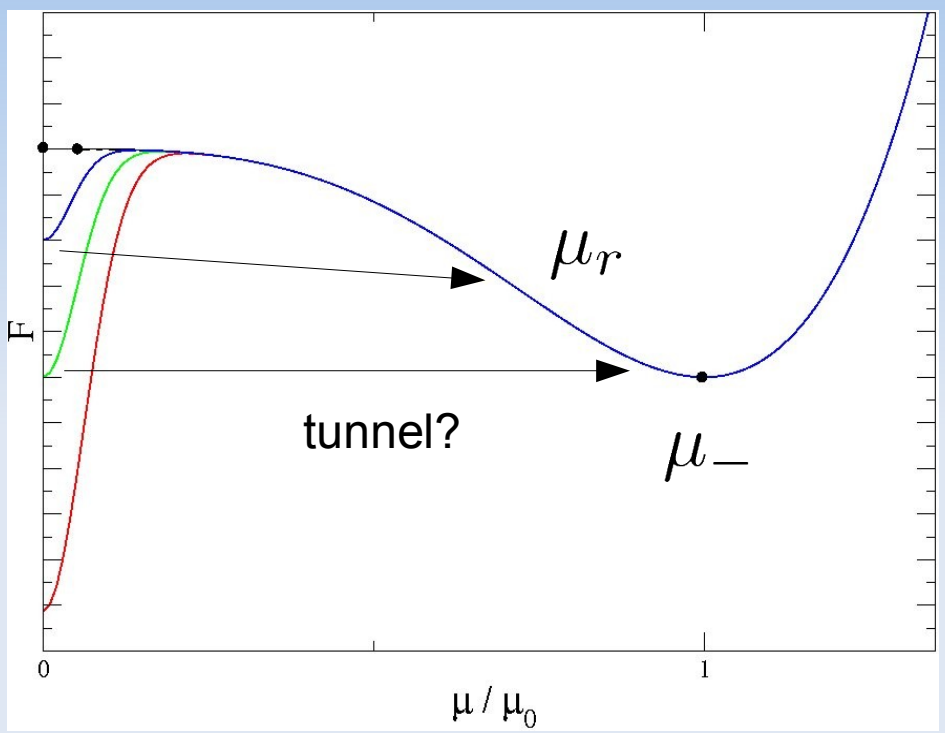


→ large supercooling and extremely strong phase transitions generic

The nearly conformal potential evades the graceful exit problem of old inflation, but only ~ 15 efolds of inflation possible.

[Nardini, Wulzer, Quiros '07] [TK, Nardini, Quiros '10] [TK, Servant '11]

Nearly conformal approximation



$$V(\mu) = \mu^4 P(\mu^\epsilon) \simeq \mu^4 P(\mu_r^\epsilon)$$

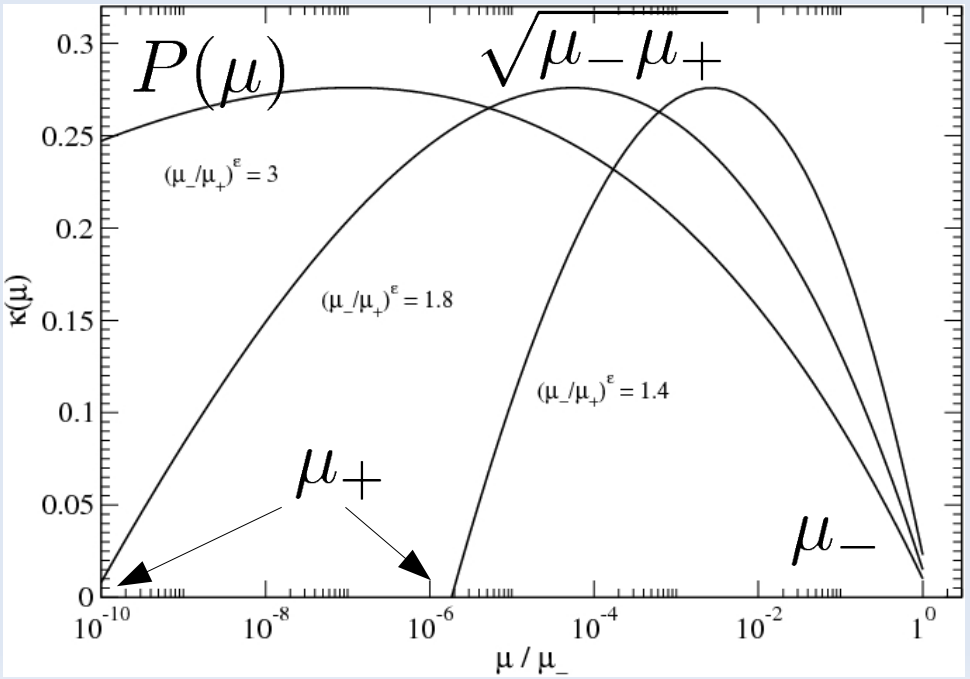
$$T \propto P^{1/4} \mu_r$$

$$S_3/T \propto P^{-3/4}$$

$$\mu_r > \sqrt{\mu_+ \mu_-}$$

$$\frac{\mu_+}{\mu_-} > \frac{\mu_-}{l^{-1}}$$

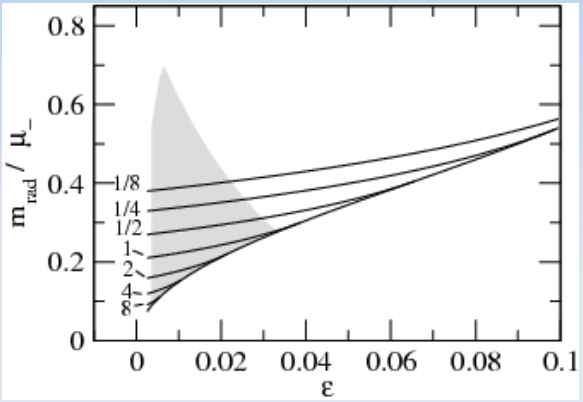
$$\rightarrow \quad N_e < 18$$

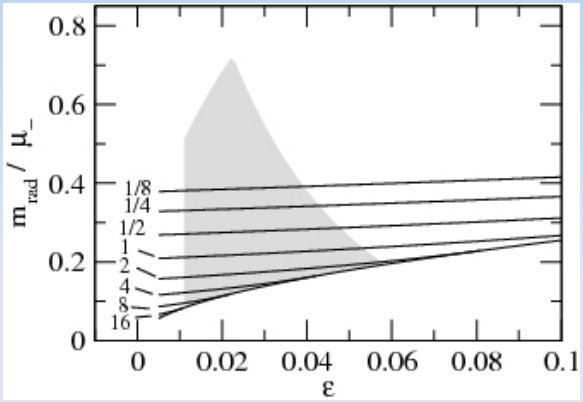


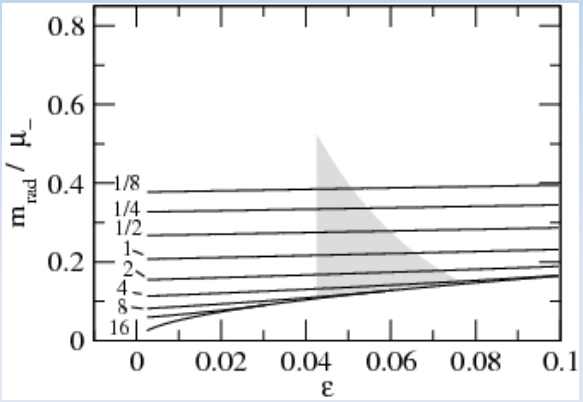
Contours of e-folds

Imposing conditions from backreactions

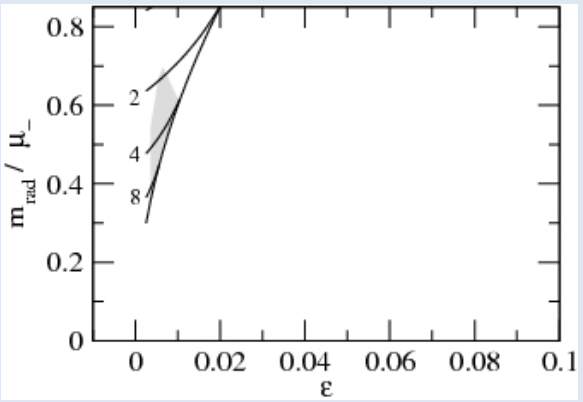
$N = 2$

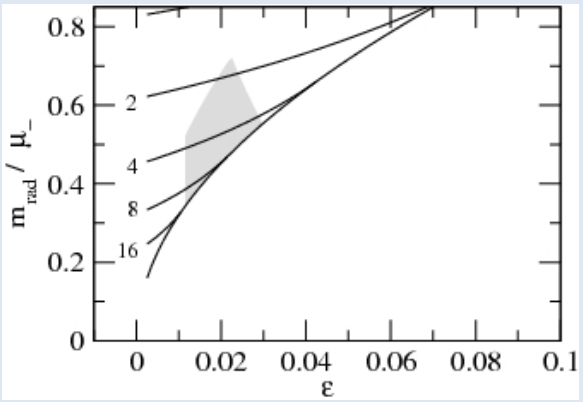


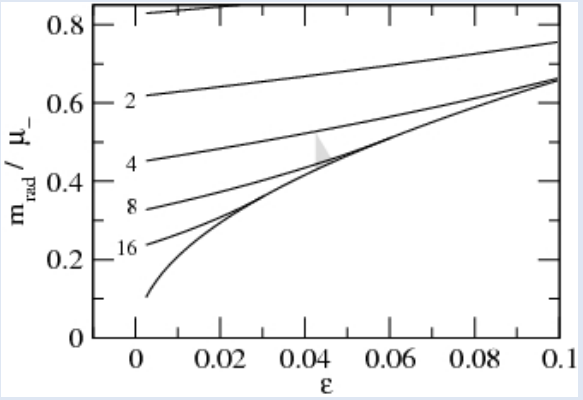




$N = 5$







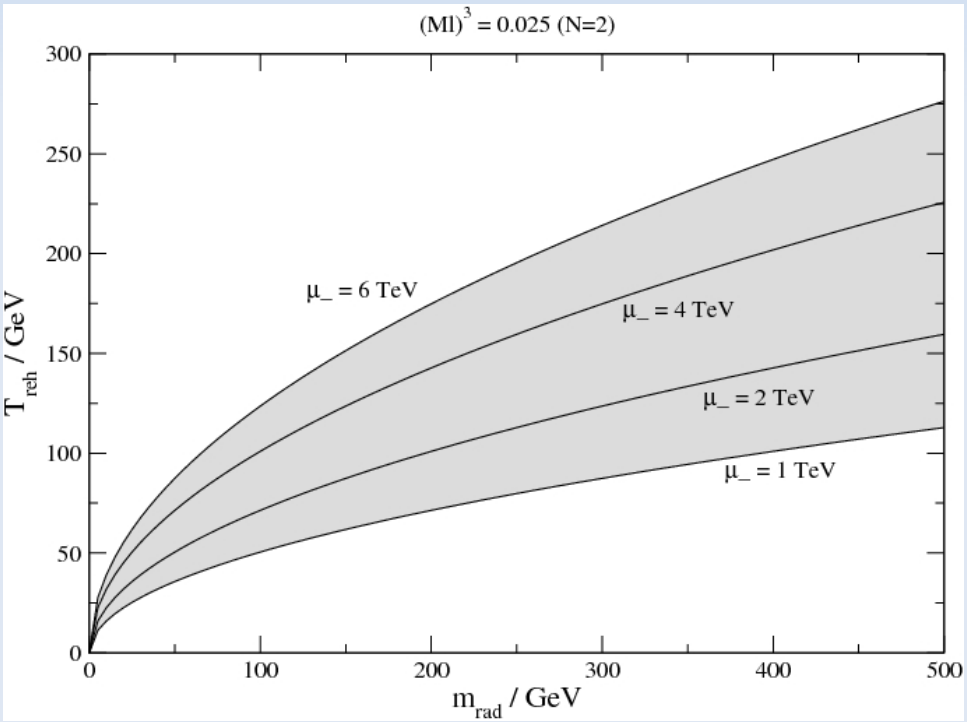
$\xi = 1.05$ $\xi = 1.2$ $\xi = 1.65$

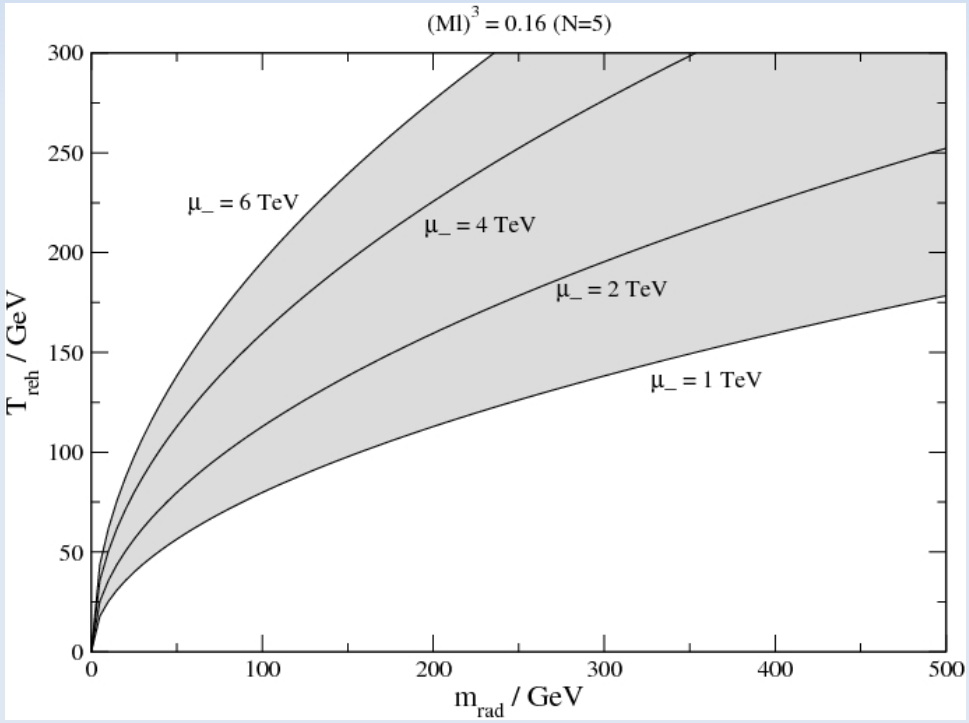
There is a stress between large N and metastability!

Reheating

The reheating temperature depends on the vacuum energy of the radion

$$T_{\rm reh} = \left(\frac{45}{2\pi^2 g_*}\right)^{1/4} (Ml)^{3/4} \sqrt{m_{\rm rad}\mu_-}$$





Whether the electroweak symmetry is restored depends in addition on the Higgs mass.

Gravitational Waves

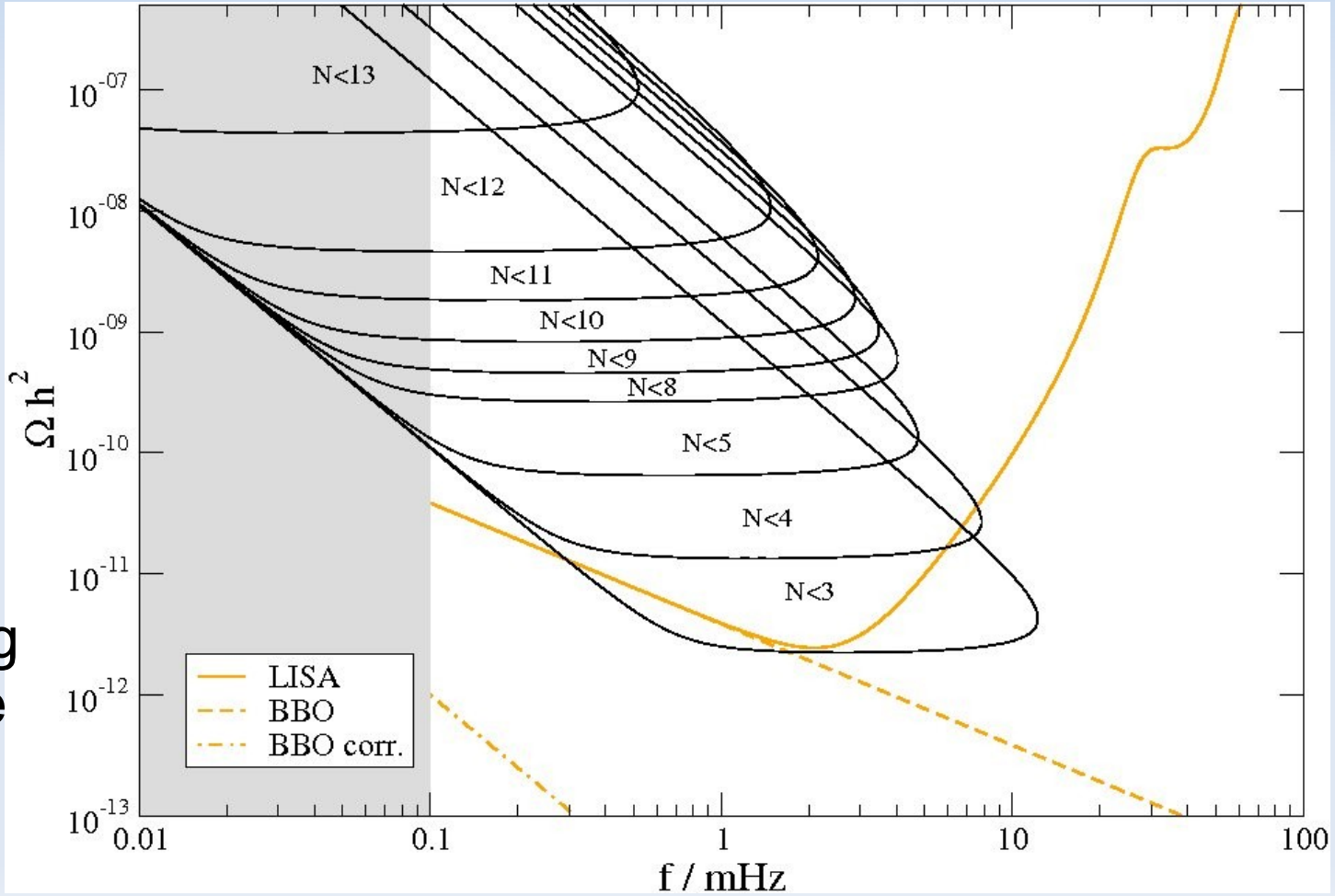
Sizable supercooling is the optimal condition for large gravitational wave production.

[TK, Nardini, Quiros '10]

$$\alpha = \frac{\rho_{vac}}{\rho_{rad}} \gg 1$$

$$\tau^{-1} \gtrsim \text{a few} H$$

Once the scale of strong coupling is found, the reheating temperature can be cross-checked with the radion mass



Cosmology

Several efolds of inflation at the electroweak scale would have far-reaching implications for cosmology.

Pre-exisiting baryon asymmetries and dark matter abundances are heavily diluted.

Which baryogenesis mechanisms are possible during/after reheating depends on the radion mass and the Higgs potential.

	$T_{reh} > T_{EW}$		$T_{reh} < T_{EW}$	
	EWPT 1st order	2nd order crossover	$\left.\frac{\phi}{T}\right\|_{T_{reh}} > 1$	$\left.\frac{\phi}{T}\right\|_{T_{reh}} < 1$
cold EWBG	-	-	+	-
non-local EWBG	if $\phi/T\|_{T_{EW}} > 1$	-	-	-
low-scale leptogenesis	+	+	-	+
asymmetric dark matter	+	+	+	+

Outline

Stabilization and phase transition in 5D

Electroweak baryogenesis

Composite Higgs models

The Higgs could be a Pseudo-Goldstone boson of a broken global symmetry

QCD: $$\frac{SU(2)_L \times SU(2)_R}{SU(2)_V} \to 3\pi$$

The broken symmetry will determine the light degrees of freedom and their quantum numbers

$$\frac{SO(5)}{SO(4)} \to H$$

but also

$$\frac{SO(6)}{SO(5)} \to H + S \qquad \frac{SO(6)}{SO(4) \times SO(2)} \to 2H$$

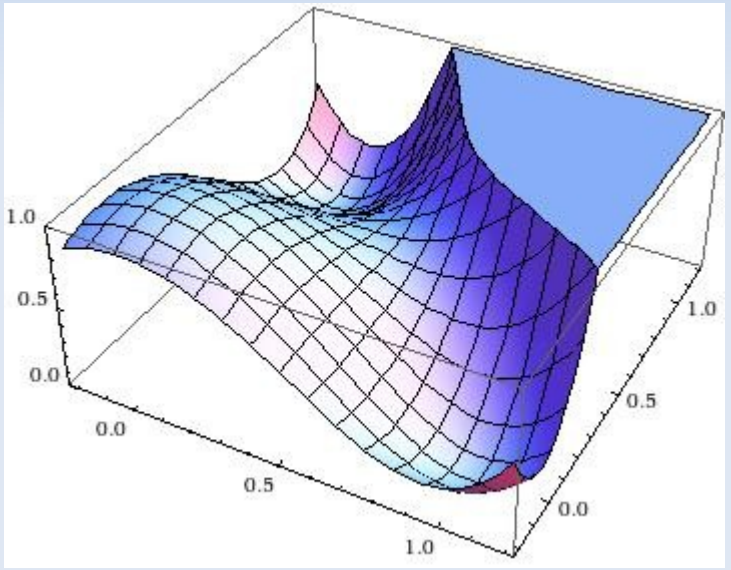
Ingredients

Two ingredients of baryogenesis are missing in the Standard Model. These are provided in models that have an additional singlet in the low energy effective description

1) Strong first-order electroweak phase transition

$$V(h,s) = \frac{\lambda}{4}(h^2 - v^2)^2$$

$$+m_s^2 s^2 + \lambda_s s^4 + \lambda_m h^2 s^2$$

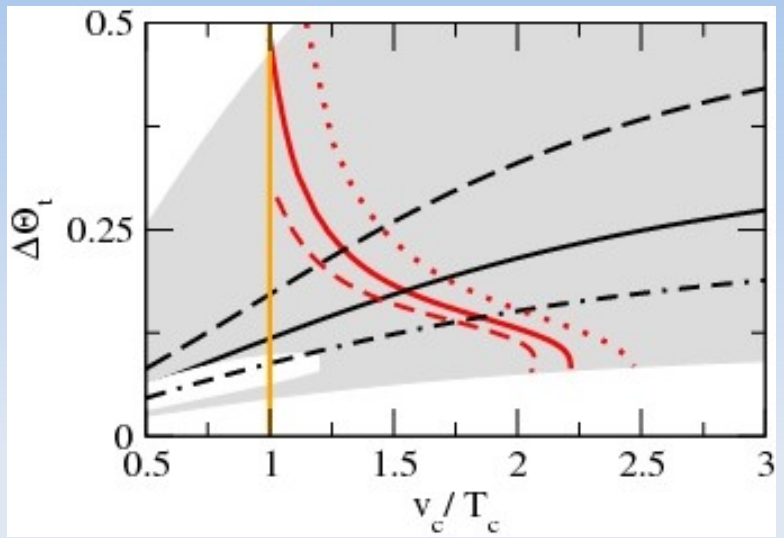


2) CP violation

$$\mathcal{L} \ni y_t \bar{\psi}_t H \psi_t + \frac{\tilde{y}_t}{f} S y_t \bar{\psi}_t H \psi_t$$

$$\Im(y_t \tilde{y}_t^*) \neq 0$$

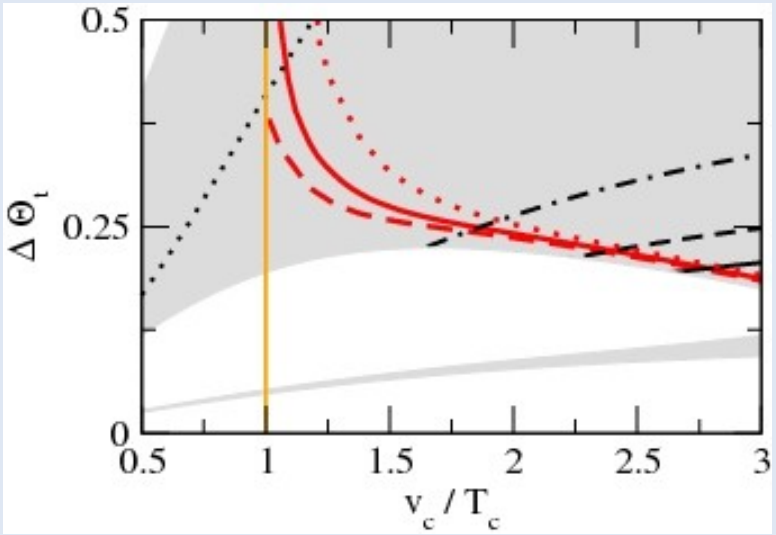
Baryogenesis



$m_s = 130\,\mathrm{GeV}$

strength of
CP violation

strength of the phase transition

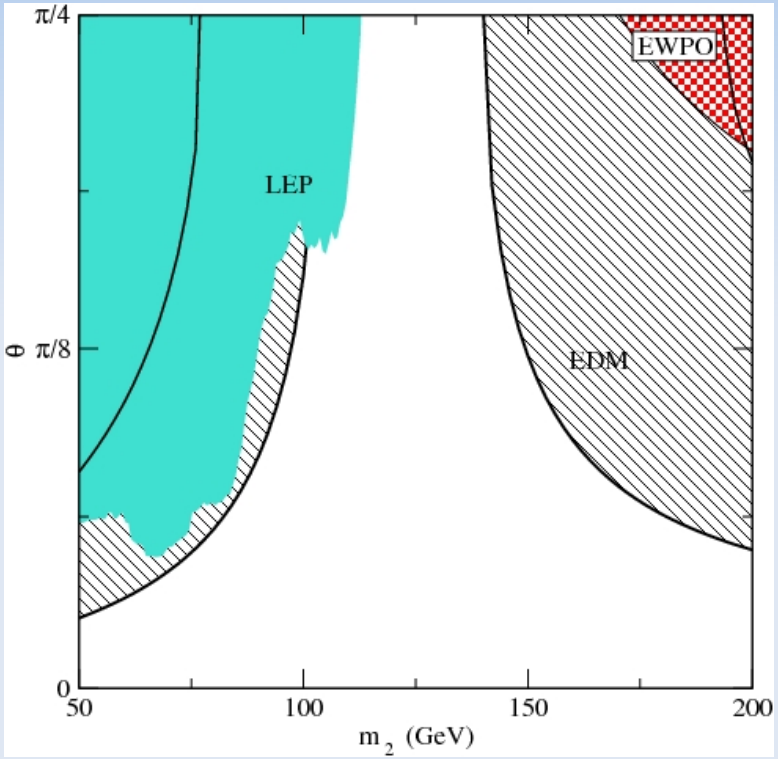


$m_s = 80\,\mathrm{GeV}$

[Espinosa, Gripaios, TK, Riva '11]

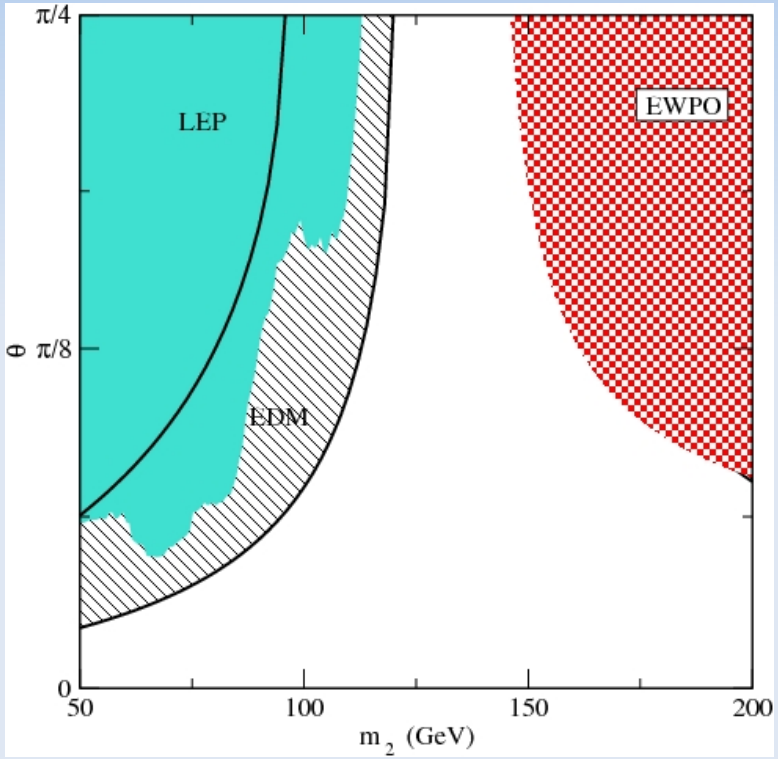
Signals

$m_h = 120\,\mathrm{GeV}$



Higgs-singlet mixing ~
strength of the CP violation

$m_h = 140\,\mathrm{GeV}$



singlet mass ~
strength of the phase transition

[Espinosa, Gripaios, TK, Riva '11]

Conclusions

Holography can serve a playground for strongly-coupled (composite Higgs) scenarios to EWSB and solutions to the hierarchy problem.

Quite generally the confinement phase transition is very strong what implies observational signals in terms of gravitational waves.

The large super-cooling of this phase transition puts some cosmological problems in a different light

- Baryogenesis
- Dark matter