Cosmological implications of hidden scale invariance

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This talk is based on arXiv: 1701.04927, 701.04927, 1710.091032 + work in progress, with Neil Barrie, Shelley Liang, Suntharan Arunasalam, Cyril Lagger and Albert Zhou.

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Higgs and naturalness

- Why is the Higgs mass light relative to a UV scale,

$$m_h/\Lambda << 1$$

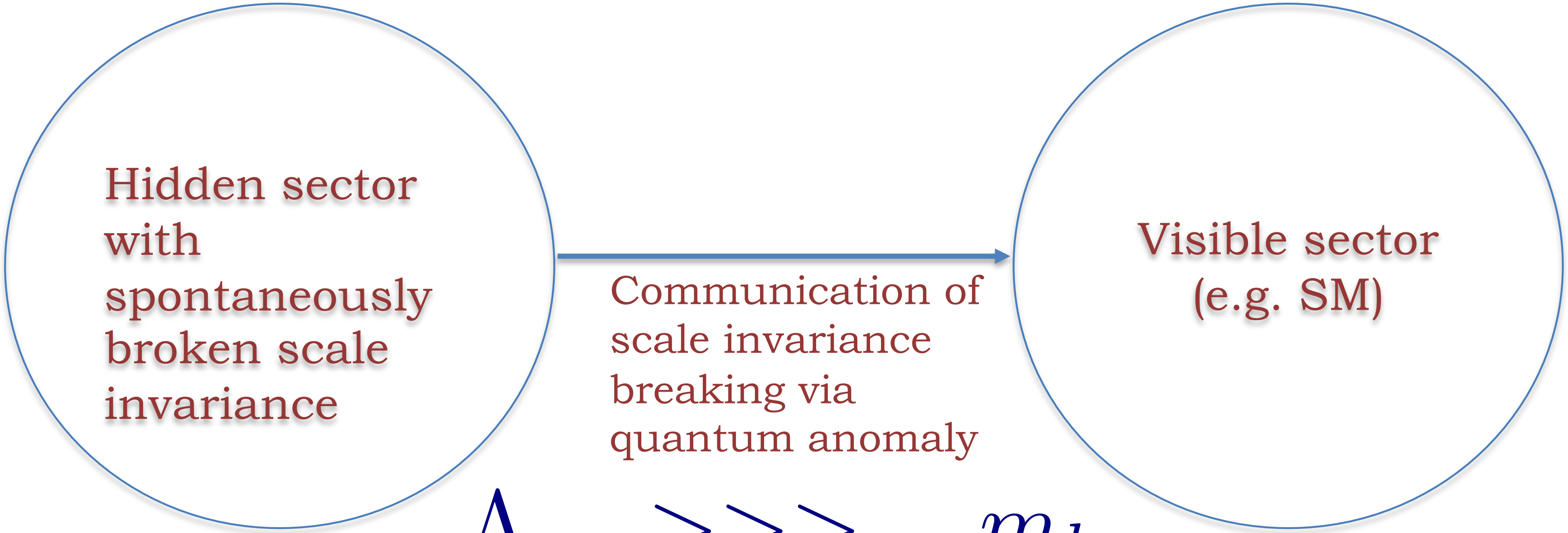
- New dynamics (supersymmetry, composite Higgs, extra dimensions) at ‘radiative distance’,

$$\Lambda \sim m_h/\alpha \sim \text{ few TeV}$$

- Higgs with $m_h \approx 125$ GeV is somewhat heavy than in typical supersymmetric models and somewhat light than typical prediction of technicolour models.

- No sign of new physics at LHC or elsewhere

Scale invariant paradigm



$$\Lambda \quad >>> \quad m_h$$

- There is only one scale generated via dimensional transmutation
- Hierarchy of scales emerge only though the hierarchy of dimensionless couplings
- The hierarchy is natural if the relevant beta-functions (aka anomaly) are small in the infrared [Wetterich 84'; Bardeen 95'; Meissner, Nicolai; Foot, AK, McDonald, Volkas, 07']

Scale invariant SM with light dilaton

- Consider SM as an effective Wilsonian theory with 'physical' cut-off Λ.

$$V(\Phi^\dagger\Phi) = V_0(\Lambda) + \lambda(\Lambda)\left[\Phi^\dagger\Phi - v_{ew}^2(\Lambda)\right]^2 + \ldots,$$

- Assume, the 'fundamental' theory exhibits scale invariance. Scale invariance implies the full conformal invariance [Komorgodski, Schwimmer 11'] which is spontaneously broken down to the Poincare invariance,

$$SO(2,4) \to ISO(1,3)$$

- Only one scalar (pseudo)Goldstone is relevant in the low energy theory, the dilaton, $\chi(x)$

Scale invariant SM with light dilaton

- This symmetry is non-linearly realized in the low-energy effective theory. Promote all dimensionfull parameters in the low energy action to $\chi(x)$ [Coleman, 85']:

$$\Lambda \to \Lambda \frac{\chi}{f_\chi} \equiv \alpha\chi, \quad v_{ew}^2(\Lambda) \to \frac{v_{ew}^2(\alpha\chi)}{f_\chi^2}\chi^2 \equiv \frac{\xi(\alpha\chi)}{2}\chi^2, \quad V_0(\Lambda) \to \frac{V_0(\alpha\chi)}{f_\chi^4}\chi^4 \equiv \frac{\rho(\alpha\chi)}{4}\chi^4$$

- Theory becomes manifestly scale invariant (up to quantum anomaly):

$$V(\Phi^\dagger\Phi, \chi) = \lambda(\alpha\chi)\left[\Phi^\dagger\Phi - \frac{\xi(\alpha\chi)}{2}\chi^2\right]^2 + \frac{\rho(\alpha\chi)}{4}\chi^4$$

Scale invariant SM with light dilaton

- The dilaton dependence of couplings is determined through the relevant RG beta-functions

$$\lambda^{(i)}(\alpha\chi) = \lambda^{(i)}(\mu) + \beta_{\lambda^{(i)}}(\mu)\ln(\alpha\chi/\mu) + \beta'_{\lambda^{(i)}}(\mu)\ln^2(\alpha\chi/\mu) + ...,$$

$$\beta_{\lambda^{(i)}}(\mu) = \left.\frac{\partial\lambda^{(i)}}{\partial\ln\chi}\right|_{\alpha\chi=\mu} \sim \mathcal{O}(\hbar)\ , \quad \beta'_{\lambda^{(i)}}(\mu) = \left.\frac{\partial^2\lambda^{(i)}}{\partial(\ln\chi)^2}\right|_{\alpha\chi=\mu} \sim \mathcal{O}(\hbar^2)\ , ...$$

- At leading order, dilaton-SM interactions are given by:

$$\mathcal{L}_{\chi-SM} \propto \frac{\chi}{f_\chi} T^{\mu}_{\mu} \text{ (SM anomaly)}$$

- The model can incorporate e.g. neutrino masses, various DM candidates, axion physics…

Scale invariant SM with light dilaton

- Find vacuum configuration + impose cancelation condition on vacuum energy:

$$\left.\frac{dV}{d\chi}\right|_{\Phi=\langle\Phi\rangle,\chi=\langle\chi\rangle}=0$$

$$\left.\frac{dV}{d\Phi}\right|_{\Phi=\langle\Phi\rangle,\chi=\langle\chi\rangle}=0 \quad \Longrightarrow$$

$$V(v_{ew},v_\chi)=0$$

$$\rho(\Lambda)=0\ ,$$

$$\beta_\rho(\Lambda)=0\ ,$$

$$\xi(\Lambda)=\frac{v_{ew}^2}{v_\chi^2}\ .$$

- Scalar mass spectrum:

$$m_h^2\simeq 2\lambda(\Lambda)v_{ew}^2\ ,$$

$$m_\chi^2\simeq\frac{\beta'_\rho(\Lambda)}{4\xi(\Lambda)}v_{ew}^2\propto m_h^2\xi\ ,$$ (@ 2-loop!)

$$\sin\alpha\sim\sqrt{\xi}$$

Foot, AK, Volkas, 11'
AK, Liang, 17'

Scale invariant SM with light dilaton

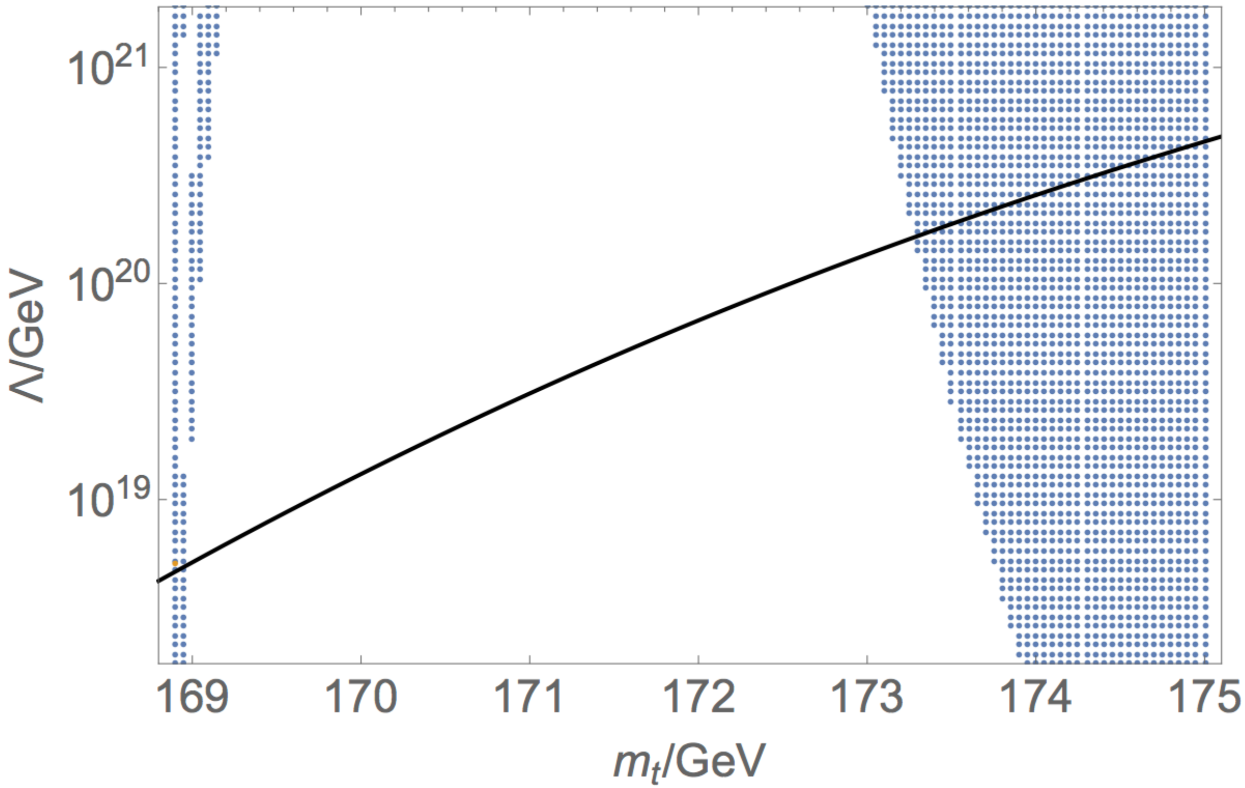


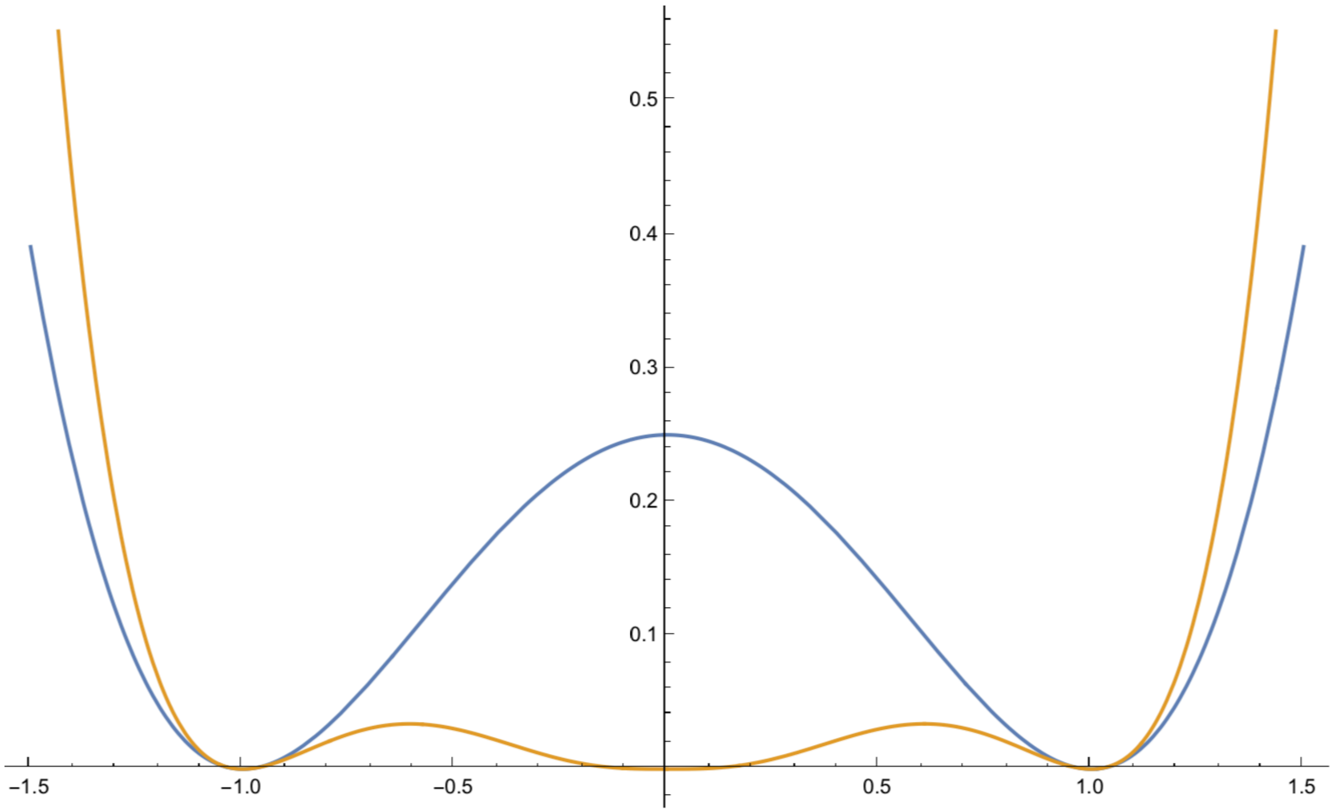
Figure 1: Plot of the allowed range of parameters (shaded region) with $m_\chi^2(v_{ew}) > 0$, i.e., the electroweak vacuum being a minimum. The solid line displays the cut-off scale Λ as function of the top-quark mass m_t for which the conditions in Eq. (6) are satisfied.

- If $\Lambda \sim 10^{19}$ GeV, $m_\chi \sim 10^{-8}$ eV!

Cosmological electroweak phase transition

[Arunasalam, AK, Lagger, Liang, Zhou, 17']

- Higgs-dilaton potential: the energy densities at the origin and at the electroweak vev are degenerate and are separated by a small barrier (flat direction lifted by 2-loop quantum corrections).



Cosmological electroweak phase transition

- In cosmological setting a thermal barrier is also generated which implies that the critical temperature of the transition is $T_c=0$.

- QCD condensates drive the electroweak phase transition! [Witten 81']

Cosmological electroweak phase transition

$$V_T(h,\chi) = \frac{\lambda(\Lambda)}{4}\left[h^2 - \frac{v_{ew}^2}{v_\chi^2}\chi^2\right]^2 + \sum_i n_i(-1)^{2s_i+1}\left[\frac{m_i^4}{32\pi^2}\log\frac{\alpha\chi}{m_i} - \frac{1}{2\pi^2}T^4 J_i(m_i^2/T^2)\right]$$

- High temperature/small field expansion:

$$V_T(h,\chi) = \frac{\lambda(\Lambda)}{4}\left[h^2 - \frac{v_{ew}^2}{v_\chi^2}\chi^2\right]^2 + c(h)\pi^2 T^4 - \frac{\lambda(\Lambda)}{24}\frac{v_{ew}^2}{v_\chi^2}\chi^2 T^2 + \frac{1}{48}\left[6\lambda(\Lambda) + 6y_t^2(\Lambda) + \frac{9}{2}g^2(\Lambda) + \frac{3}{2}g'^2(\Lambda)\right]h^2 T^2$$

- Solve for the dilaton field:

$$\chi^2 = \frac{v_\chi^2}{v_{ew}^2}h^2 + \frac{v_\chi^2}{v_{ew}^2}T^2$$

Cosmological electroweak phase transition

- The Higgs potential becomes:

$$V_T(h,\chi(h)) = \left[c(h)\pi^2 - \frac{\lambda(\Lambda)}{576}\frac{v_{ew}^2}{v_\chi^2}(2+v_{ew}^2/v_\chi^2)\right]T^4 + \frac{1}{48}\left[4\lambda(\Lambda)+6y_t^2(\Lambda)+\frac{9}{2}g^2(\Lambda)+\frac{3}{2}g'^2(\Lambda)\right]h^2T^2$$

$4\lambda(\Lambda)+6y_t^2(\Lambda)+\frac{9}{2}g^2(\Lambda)+\frac{3}{2}g'^2(\Lambda) > 0 \implies$ *h=0* is a local minimum for any T.

- If so, the universe would be trapped in symmetric vacuum *h=0*.

Cosmological electroweak phase transition

- In *h=0* vacuum all quarks are massless. *SU(6)xSU(6)* chiral symmetry is broken at T_c~132 MeV. The quark condensate break the electroweak symmetry as well.

$$\langle\bar{q}q\rangle_T = \langle\bar{q}q\rangle\left[1-(N^2-1)\frac{T^2}{12Nf_\pi^2}-\frac{1}{2}(N^2-1)\left(\frac{T^2}{12Nf_\pi^2}\right)^2+\mathcal{O}\left((T^2/12Nf_\pi^2)^3\right)\right]$$

$$\langle\bar{q}q\rangle \approx -(250\ \mathrm{MeV})^3$$

[Gasser & Leutwyler, 86']

- Higgs-quark Yukawa interactions: $y_q\langle\bar{q}q\rangle_T h/\sqrt{2}$
- $y_q\langle\bar{q}q\rangle_T/\sqrt{2}+\frac{\partial V_T}{\partial h}=0 \rightarrow$ *h=0* is no more an extremum

Cosmological electroweak phase transition

- Quark condensate tips the Higgs field from the origin, which 'runs down' classically towards the electroweak minimum, smoothly and quickly completing the transition

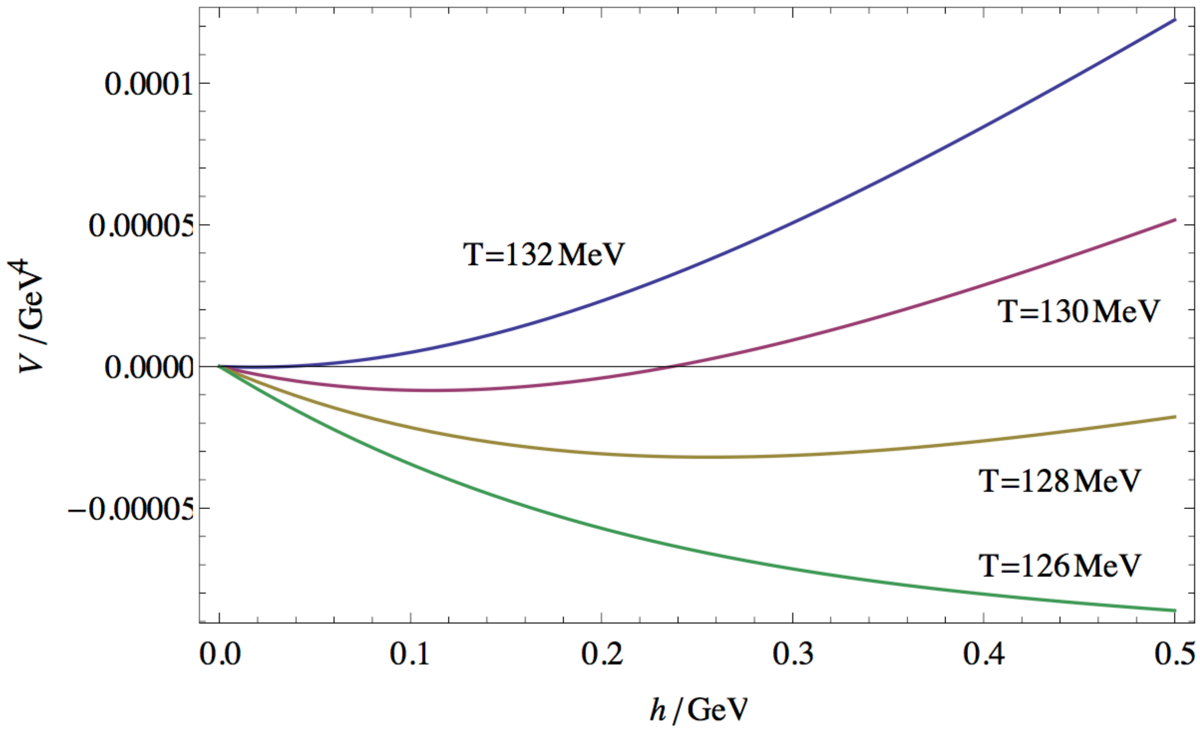


Figure 2: $V_T(h) - V_T(0)$ for different temperatures below the chiral phase transition.

Cosmological electroweak phase transition

- QCD with N=6 quarks undergoes first-order phase transition, unlike the standard case with N=3 [Pisarski, Wilczek 84'].

- Formation of 6 flavour quark matter nuggets of mass ~10^7 kg and size ~1 mm [Bai, Long 17', Witten 84']. Can constitute 100% dark matter.

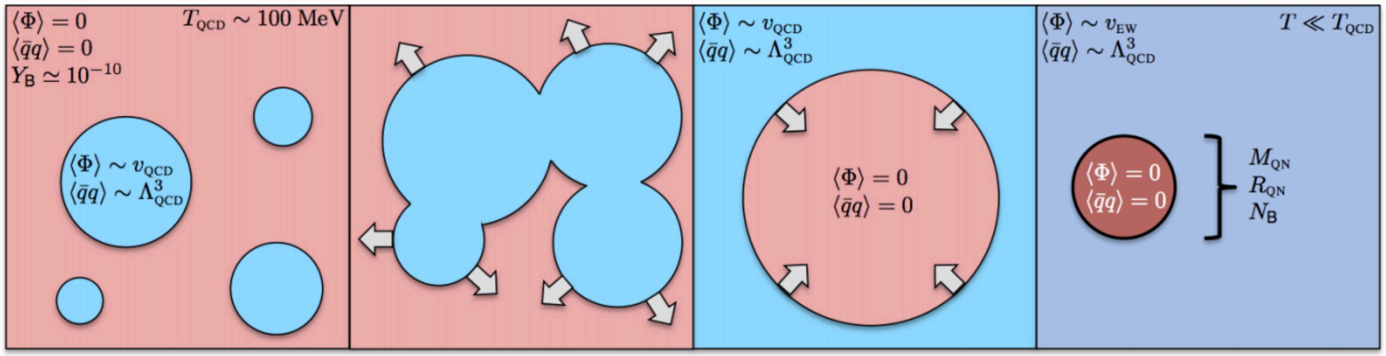


Figure 2: A cartoon illustrating the cosmological dynamics leading to the formation of nuggets of six-flavor quark matter. A first-order QCD phase transition causes the baryon number to accumulate into pockets of quark gluon plasma, which eventually cool to form 6FQM nuggets.

Taken from arXiv:1804.10249

Cosmological electroweak phase transition

- Gravitational waves with peak frequency ~10^{-8} Hz, potentially detectable by means of pulsar timing (EPTA, SKA…)

$$f_{\rm GW} \sim H_{\rm QCD}(T_0/T_{\rm QCR}) \sim 10^{-8}{\rm Hz}$$

- Production of primordial black holes with mass M_{bh}~$M_{\odot}$

$$R \sim 1/H_{\rm QCD} \sim M_P/T^2_{\rm QCD},$$
$$M_{bh} = R/2G \sim M_P^3/T^2_{QCD} \sim 10^{30} \text{ kg}$$

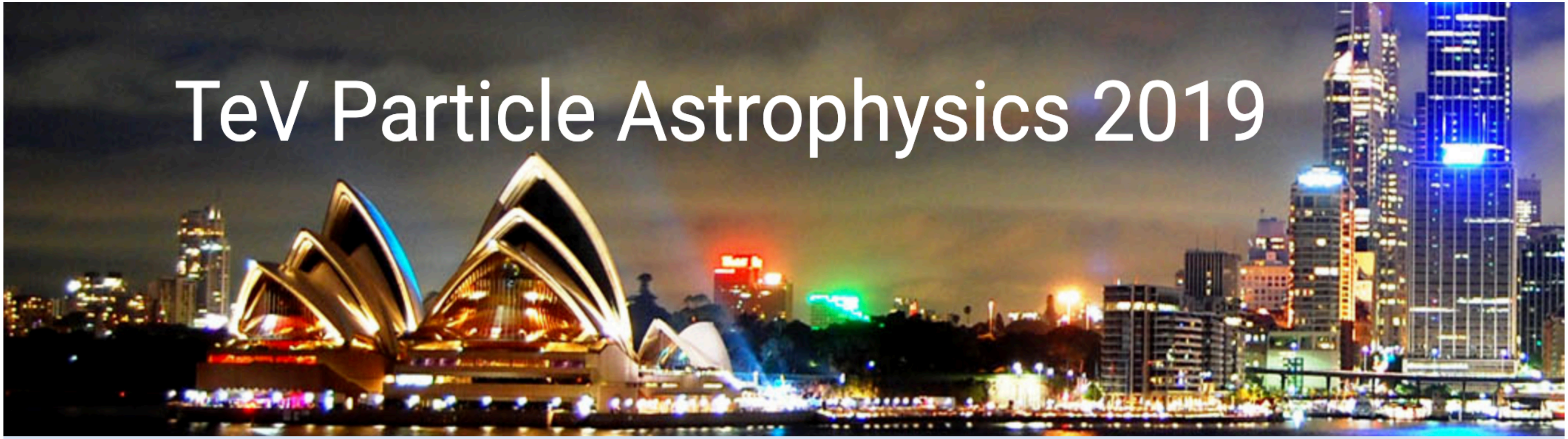
- QCD baryogenesis (work in progress)

(i) B+L sphaleron-mediated non-equilibrium processes are active;

(ii) The CKM CP violation @ low T is strong.

Conclusions

- Scale paradigm for natural mass hierarchies predicts a light, feebly coupled dilaton (could be dark matter).
- Electroweak phase transition driven by the QCD chiral phase transition and occurs at T~130 MeV.
- QCD phase transition could be strongly first order => quark matter nuggets, black holes, gravitational waves, QCD baryogenesis.
- Detection of a light scalar particle + the above astrophysical signatures will provide the strong evidence for the fundamental role of scale invariance in particle physics and cosmology.



2-6 December 2019
Australia/Sydney timezone

For more information see the conference webpage https://indico.cern.ch/event/828038/

Welcome to TeVPA 2019 in Sydney

Constraints on light dilaton

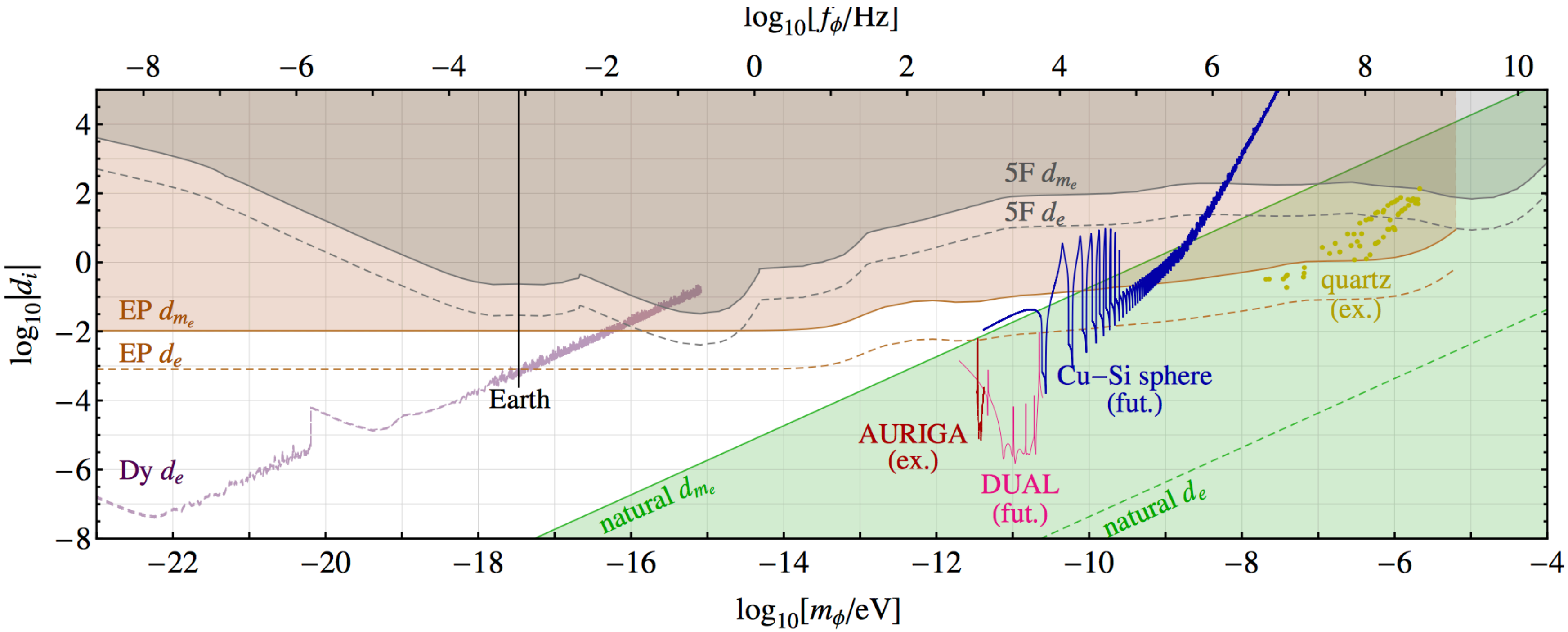


FIG. 1. Scalar field parameter space, with mass m_ϕ and corresponding DM oscillation frequency $f_\phi = m_\phi/2\pi$ on the bottom and top horizontal axes, and couplings of both an electron mass modulus ($d_i = d_{m_e}$) and electromagnetic gauge modulus ($d_i = d_e$) on the vertical axis. Natural parameter space for a 10 TeV cutoff is depicted in green, while the other regions and dashed curves represent 95% CL limits from fifth-force tests ("5F", gray), equivalence-principle tests ("EP", orange), atomic spectroscopy in dysprosium ("Dy", purple), and low-frequency terrestrial seismology ("Earth", black). The blue curve shows the projected SNR = 1 reach of a proposed resonant-mass detector—a copper-silicon (Cu-Si) sphere 30 cm in radius—after 1.6 y of integration time, while the red curve shows the reach for the current AURIGA detector with 8 y of recasted data. Rough estimates of the 1-y reach of a proposed DUAL detector (pink) and several harmonics of two piezoelectric quartz resonators (gold points) are also shown.

taken from arXiv:1508.01798, Arvanitaki, Dimopoulos Tilburg, 15'

Light dilaton dark matter

- Light, superweekly coupled dilaton is a candidate for dark matter particle

- Metastability implies:

$$\Lambda \gtrsim \left(10^{-3}\frac{m_h^6}{H_0}\right)^{1/5} \sim 10^{10}\ \mathrm{GeV}$$

$$\text{or } m_\chi \lesssim \ \mathrm{keV}$$

- Non-thermal dark matter (similar to axion), for $m_\chi \lesssim eV$ behaves as an oscillating classical field