Phenomenological and cosmological implications of hidden scale invariance

Archil Kobakhidze

THE UNIVERSITY OF SYDNEY

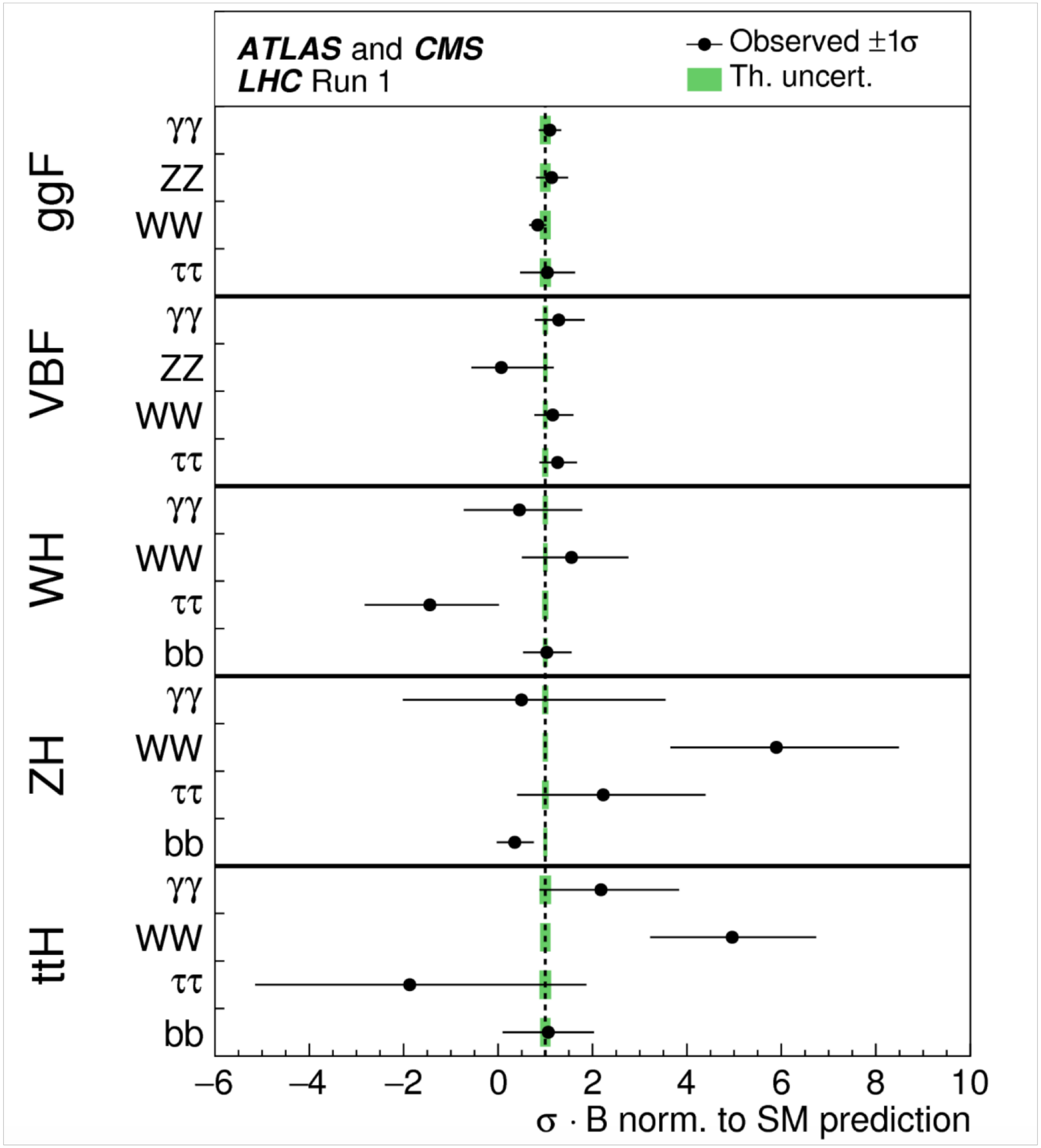
The key ideas were developed in a number of publications with Robert Foot, Kristian McDonald and Ray Volkas since 2007

Current 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.

CERN Workshop
Scale invariance in particle and cosmology, 31 Jan 2019

Higgs properties

ATLAS+CMS,
JHEP 08 (2016) 045

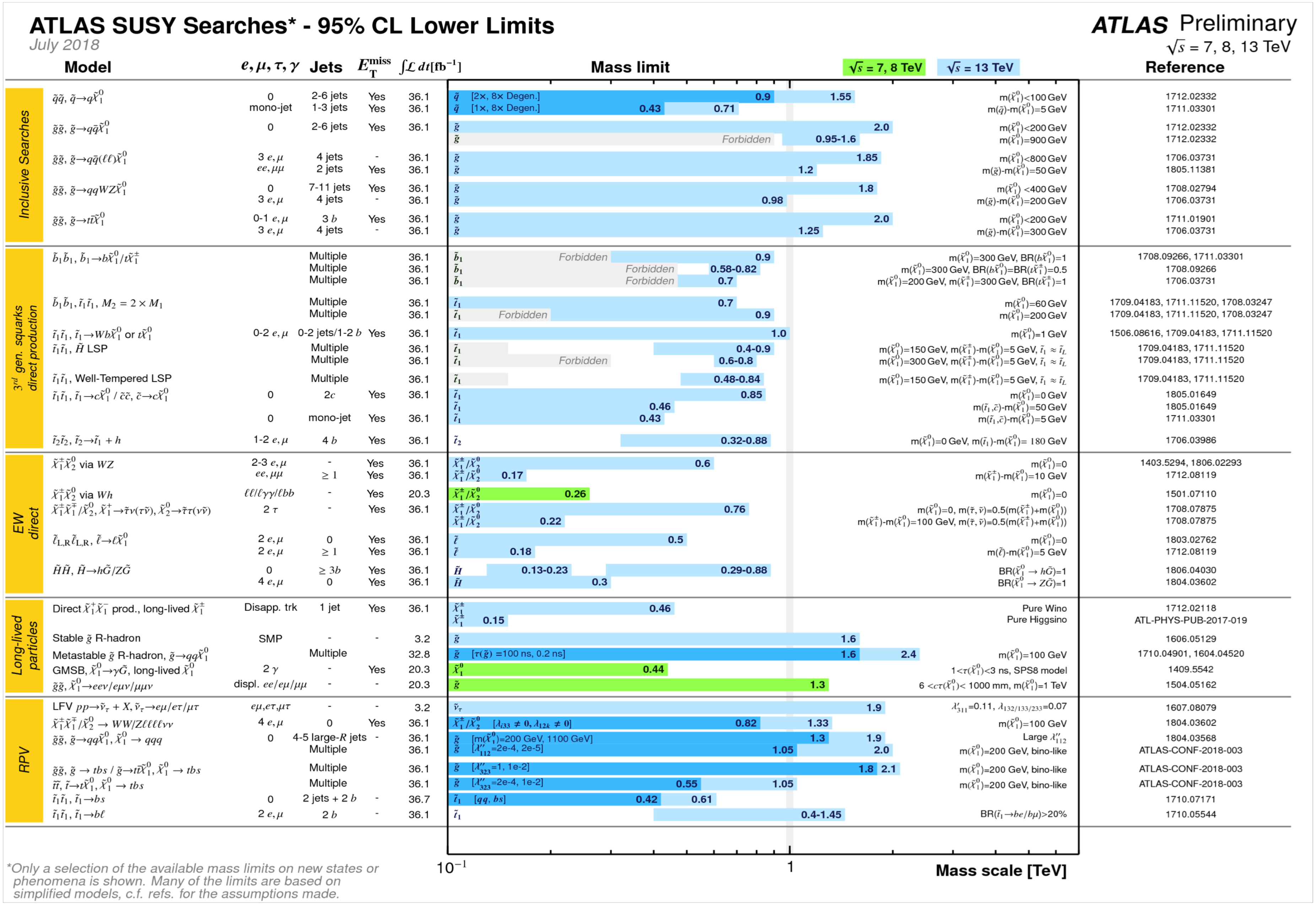


ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV



	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	$\tilde q$ [2x, 8x Degen.] 0.9 1.55	$m(\tilde\chi^0_1)$<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde q$ [1x, 8x Degen.] 0.43 0.71	$m(\tilde q)$-$m(\tilde\chi^0_1)$=5 GeV	1711.03301
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi^0_1$	0	2-6 jets	Yes	36.1	$\tilde g$ 2.0	$m(\tilde\chi^0_1)$<200 GeV	1712.02332
						$\tilde g$ Forbidden 0.95-1.6	$m(\tilde\chi^0_1)$=900 GeV	1712.02332
	$\tilde g\tilde g$, $\tilde g\to q\bar q(\ell\ell)\tilde\chi^0_1$	3 e,μ	4 jets	-	36.1	$\tilde g$ 1.85	$m(\tilde\chi^0_1)$<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	Yes	36.1	$\tilde g$ 1.2	$m(\tilde g)$-$m(\tilde\chi^0_1)$=50 GeV	1805.11381
	$\tilde g\tilde g$, $\tilde g\to qqWZ\tilde\chi^0_1$	0	7-11 jets	Yes	36.1	$\tilde g$ 1.8	$m(\tilde\chi^0_1)$ <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde g$ 0.98	$m(\tilde g)$-$m(\tilde\chi^0_1)$=200 GeV	1706.03731
	$\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	Yes	36.1	$\tilde g$ 2.0	$m(\tilde\chi^0_1)$<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde g$ 1.25	$m(\tilde g)$-$m(\tilde\chi^0_1)$=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi^0_1/t\tilde\chi^\pm_1$		Multiple		36.1	$\tilde b_1$ Forbidden 0.9	$m(\tilde\chi^0_1)$=300 GeV, BR($b\tilde\chi^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde b_1$ Forbidden 0.58-0.82	$m(\tilde\chi^0_1)$=300 GeV, BR($b\tilde\chi^0_1$)=BR($t\tilde\chi^\pm_1$)=0.5	1708.09266
			Multiple		36.1	$\tilde b_1$ Forbidden 0.7	$m(\tilde\chi^0_1)$=200 GeV, $m(\tilde\chi^\pm_1)$=300 GeV, BR($t\tilde\chi^\pm_1$)=1	1706.03731
	$\tilde b_1\tilde b_1$, $\tilde t_1\tilde t_1$, $M_2=2\times M_1$		Multiple		36.1	$\tilde t_1$ 0.7	$m(\tilde\chi^0_1)$=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde t_1$ Forbidden 0.9	$m(\tilde\chi^0_1)$=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde t_1\tilde t_1$, $\tilde t_1\to Wb\tilde\chi^0_1$ or $t\tilde\chi^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde t_1$ 1.0	$m(\tilde\chi^0_1)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde t_1\tilde t_1$, $\tilde H$ LSP		Multiple		36.1	$\tilde t_1$ 0.4-0.9	$m(\tilde\chi^0_1)$=150 GeV, $m(\tilde\chi^\pm_1)$-$m(\tilde\chi^0_1)$=5 GeV, $\tilde t_1\approx\tilde t_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde t_1$ Forbidden 0.6-0.8	$m(\tilde\chi^0_1)$=300 GeV, $m(\tilde\chi^\pm_1)$-$m(\tilde\chi^0_1)$=5 GeV, $\tilde t_1\approx\tilde t_L$	1709.04183, 1711.11520
	$\tilde t_1\tilde t_1$, Well-Tempered LSP		Multiple		36.1	$\tilde t_1$ 0.48-0.84	$m(\tilde\chi^0_1)$=150 GeV, $m(\tilde\chi^\pm_1)$-$m(\tilde\chi^0_1)$=5 GeV, $\tilde t_1\approx\tilde t_L$	1709.04183, 1711.11520
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi^0_1$ / $\tilde c\tilde c$, $\tilde c\to c\tilde\chi^0_1$	0	2c	Yes	36.1	$\tilde t_1$ 0.85	$m(\tilde\chi^0_1)$=0 GeV	1805.01649
						$\tilde t_1$ 0.46	$m(\tilde t_1,\tilde c)$-$m(\tilde\chi^0_1)$=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde t_1$ 0.43	$m(\tilde t_1,\tilde c)$-$m(\tilde\chi^0_1)$=5 GeV	1711.03301
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+h$	1-2 e,μ	4 b	Yes	36.1	$\tilde t_2$ 0.32-0.88	$m(\tilde\chi^0_1)$=0 GeV, $m(\tilde t_1)$-$m(\tilde\chi^0_1)$= 180 GeV	1706.03986
EW direct	$\tilde\chi^\pm_1\tilde\chi^0_2$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.6	$m(\tilde\chi^0_1)$=0	1403.5294, 1806.02293
		$ee,\mu\mu$	$\geq$ 1	Yes	36.1	$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.17	$m(\tilde\chi^\pm_1)$-$m(\tilde\chi^0_1)$=10 GeV	1712.08119
	$\tilde\chi^\pm_1\tilde\chi^0_2$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.26	$m(\tilde\chi^0_1)$=0	1501.07110
	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_2$, $\tilde\chi^+_1\to\tilde\tau\nu(\tau\tilde\nu)$, $\tilde\chi^0_2\to\tilde\tau\tau(\nu\tilde\nu)$	2 τ	-	Yes	36.1	$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.76	$m(\tilde\chi^0_1)$=0, $m(\tilde\tau,\tilde\nu)$=0.5($m(\tilde\chi^\pm_1)$+$m(\tilde\chi^0_1)$)	1708.07875
						$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.22	$m(\tilde\chi^\pm_1)$-$m(\tilde\chi^0_1)$=100 GeV, $m(\tilde\tau,\tilde\nu)$=0.5($m(\tilde\chi^\pm_1)$+$m(\tilde\chi^0_1)$)	1708.07875
	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi^0_1$	2 e,μ	0	Yes	36.1	$\tilde\ell$ 0.5	$m(\tilde\chi^0_1)$=0	1803.02762
		2 e,μ	$\geq$ 1	Yes	36.1	$\tilde\ell$ 0.18	$m(\tilde\ell)$-$m(\tilde\chi^0_1)$=5 GeV	1712.08119
	$\tilde H\tilde H$, $\tilde H\to h\tilde G/Z\tilde G$	0	$\geq$ 3b	Yes	36.1	$\tilde H$ 0.13-0.23 0.29-0.88	BR($\tilde\chi^0_1\to h\tilde G$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde H$ 0.3	BR($\tilde\chi^0_1\to Z\tilde G$)=1	1804.03602
Long-lived particles	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde\chi^\pm_1$ 0.46	Pure Wino	1712.02118
						$\tilde\chi^\pm_1$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde g$ R-hadron	SMP	-	-	3.2	$\tilde g$ 1.6		1606.05129
	Metastable $\tilde g$ R-hadron, $\tilde g\to qq\tilde\chi^0_1$		Multiple		32.8	$\tilde g$ [$\tau(\tilde g)$ =100 ns, 0.2 ns] 1.6 2.4	$m(\tilde\chi^0_1)$=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde\chi^0_1\to\gamma\tilde G$, long-lived $\tilde\chi^0_1$	2 γ	-	Yes	20.3	$\tilde\chi^0_1$ 0.44	1<$\tau(\tilde\chi^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde g\tilde g$, $\tilde\chi^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde g$ 1.3	6 <$c\tau(\tilde\chi^0_1)$< 1000 mm, $m(\tilde\chi^0_1)$=1 TeV	1504.05162
RPV	LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde\nu_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde\chi^\pm_1/\tilde\chi^0_2$ [$\lambda_{i33}\neq 0,\lambda_{12k}\neq 0$] 0.82 1.33	$m(\tilde\chi^0_1)$=100 GeV	1804.03602
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^0_1$, $\tilde\chi^0_1\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde g$ [$m(\tilde\chi^0_1)$=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde g$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	$m(\tilde\chi^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde g\tilde g$, $\tilde g\to tbs$ / $\tilde g\to t\bar t\tilde\chi^0_1$, $\tilde\chi^0_1\to tbs$		Multiple		36.1	$\tilde g$ [λ''_{323}=1, 1e-2] 1.8 2.1	$m(\tilde\chi^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde t\tilde t$, $\tilde t\to t\tilde\chi^0_1$, $\tilde\chi^0_1\to tbs$		Multiple		36.1	$\tilde g$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	$m(\tilde\chi^0_1)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde t_1\tilde t_1$, $\tilde t_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde t_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde t_1\tilde t_1$, $\tilde t_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde t_1$ 0.4-1.45	BR($\tilde t_1\to be/b\mu$)>20%	1710.05544

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

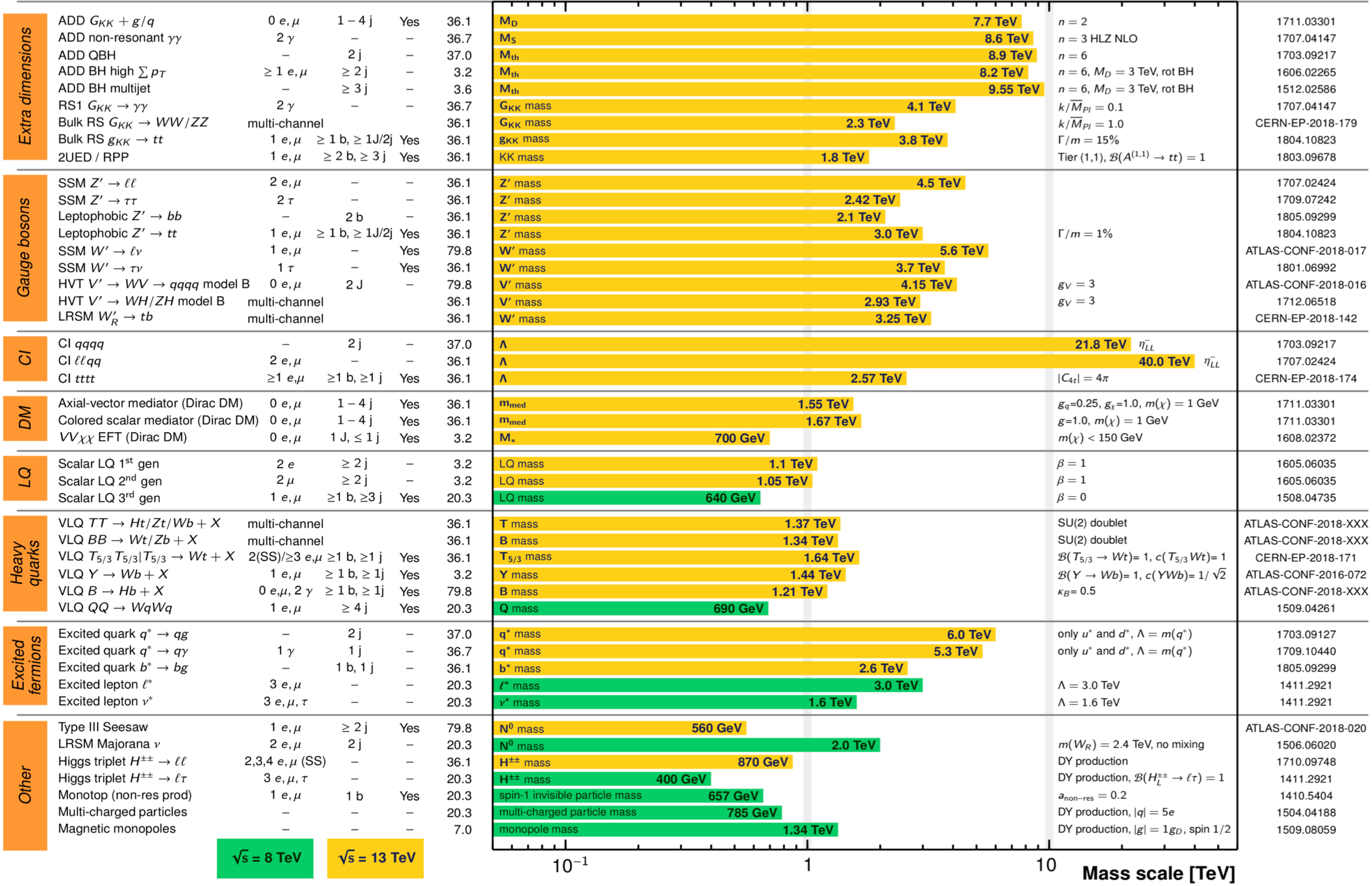
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \text{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 − 4 j	Yes	36.1	M_D	🟨 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	🟨 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th}	🟨 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th}	🟨 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	🟨 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass	🟨 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	🟨 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass	🟨 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass	🟨 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass	🟨 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	🟨 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	🟨 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass	🟨 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass	🟨 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass	🟨 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	V' mass	🟨 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass	🟨 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass	🟨 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	Λ	🟨 21.8 TeV η_{LL}^-		1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ	🟨 40.0 TeV η_{LL}^-		1707.02424
	CI $tttt$	≥1 e, μ	≥1 b, ≥1 j	Yes	36.1	Λ	🟨 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	🟨 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	🟨 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_*	🟨 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass	🟨 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass	🟨 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass	🟩 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass	🟨 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	🟨 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $T_{5/3} T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	🟨 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	Y mass	🟨 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e, μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass	🟨 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-XXX
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass	🟩 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass	🟨 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass	🟨 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass	🟨 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass	🟩 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass	🟩 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass	🟨 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass	🟩 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass	🟨 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	🟩 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass	🟩 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass	🟩 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass	🟩 1.34 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

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

Higgs and naturalness

- Some people started to question the validity of the naturalness principle (though there are different (mis)interpretations of naturalness).
- The naturalness principle reflects our current understanding of basics of QFT (e.g., locality, unitarity). A failure of naturalness would mean that these basics must be fundamentally reviewed.
- …or we need a new paradigm.

Outline

- Higgs and naturalness (again)
- Scale invariant Standard Model with light dilaton
- Electroweak phase transition in the Standard Model with light dilaton and its implications
- Conclusion

Higgs and naturalness

- P. Dirac was the first who recognized importance of naturalness in quantum physics. He asserted that all the dimensionless parameters of a theory must be of the same order of magnitude (strong naturalness principle) – why? – because in quantum theory all the parameters are related to each other via quantum corrections!

- Dirac's Large (Small) Number Hypothesis:

Gravity/EM $\alpha \left(\frac{m_e}{M_P}\right)\left(\frac{m_p}{M_P}\right) \approx 10^{-40}$ is = $\left(\frac{m_p}{M_U}\right)^{1/2} \approx 10^{-40}$

Predicts time variation of Newton's constant, which turned out to be at odds with observations.

- Lesson: The principle applies to microscopic parameters. Macroscopic parameters, such as mass of the universe M_U can be random (maybe CC is the same?).

Higgs and naturalness

- G. ‘t Hooft: Dimensionless parameter can be small if it is supported by a symmetry (technical naturalness):

$$\left(\frac{m_e}{M_P}\right) << 1-$$ chiral symmetry

$$\left(\frac{m_p}{M_P}\right) << 1-$$ dimensional transmutation in QCD, a.k.a. scale invariance

- Higgs mass naturalness:

$$\left(\frac{m_h}{M_P}\right) << 1-$$???

Higgs and naturalness

- Consider an effective theory with a ‘physical’ cut-off Λ, which contains scalars, S, fermions, F, and vector fields, V.
- 1-loop scalar mass term:

$$m_S^2(\mu) = m_S^2(\Lambda) + \frac{1}{32\pi^2}\mathrm{STr}\ g_A\left[\Lambda^2 - M_A^2 \ln\left(\Lambda^2/\mu^2\right)\right]$$

$$\mathrm{STr} \equiv (-1)^{2J_A}(2J_A + 1)$$

- $m_S^2 << \Lambda^2$ requires fine-tuning and thus is unnatural (hierarchy problem)

- According to ‘t Hooft we need a symmetry to remove quadratic dependence on UV scale

Higgs and naturalness

- Supersymmetry

  Non-renormalisation theorem:

$$\mathrm{STr}\ g_A = 0$$ (holds in for softly broken supersymmetry)

$$\mathrm{STr}\ g_A M_A^2 = 0$$

Quadratic divergences are absent in softly broken supersymmetry!

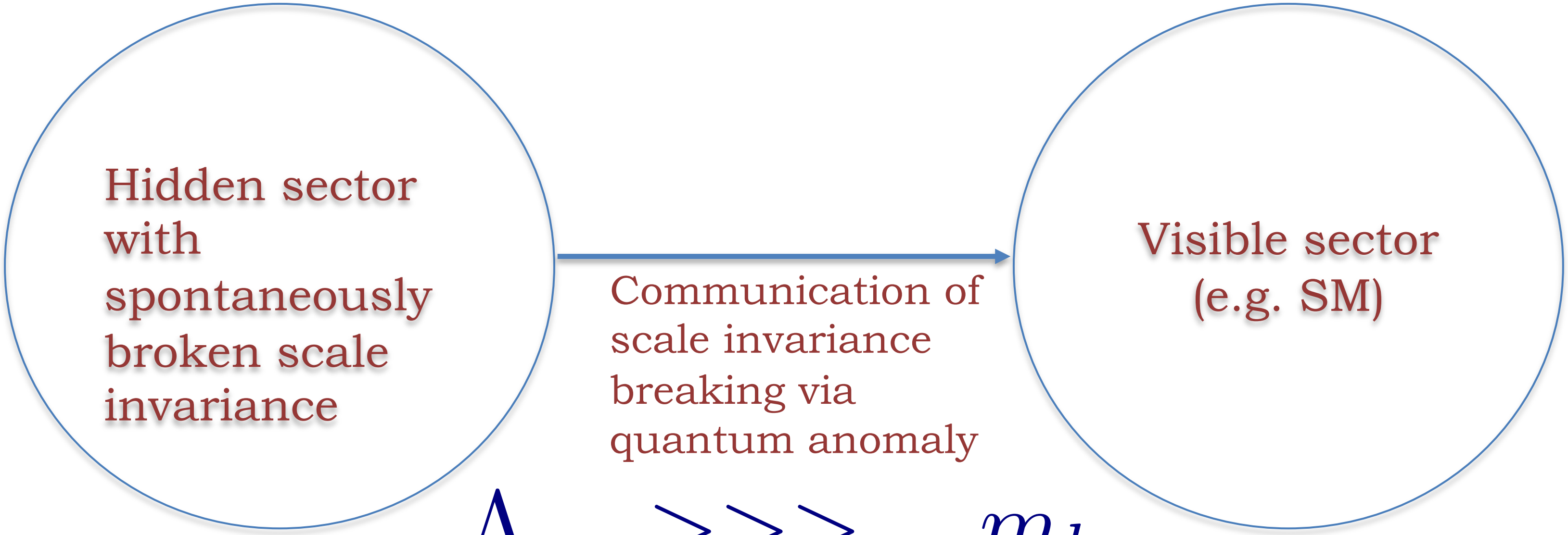
- Scale invariance

$$m_S^2(\mu = \Lambda) = 0 \rightarrow \bar{m}_S^2(\Lambda) + \mathrm{STr} g_A \Lambda^2 = 0$$

Classical scale invariance is broken spontaneously and explicitly by logarithmic quantum corrections,

$$T_\mu^\mu = \sum_i \beta_i \mathcal{O}_i$$ - dimensional transmutation

Scale invariant paradigm



Hidden sector with spontaneously broken scale invariance

Communication of scale invariance breaking via quantum anomaly

Visible sector (e.g. SM)

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

- There is only one scale invariance, one anomaly and hence 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.

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

- 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

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

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

- 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… [see Lindner's talk].

Scale invariant SM with light dilaton

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

$$\left.\frac{dV}{d\chi}\right|_{\Phi=\langle\Phi\rangle,\chi=\langle\chi\rangle} = 0 \qquad \rho(\Lambda) = 0 \ ,$$

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

$$V(v_{ew}, v_\chi) = 0 \qquad \xi(\Lambda) = \frac{v_{ew}^2}{v_\chi^2} \ .$$

- Scalar mass spectrum:

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

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

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

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

Scale invariant SM with light dilaton

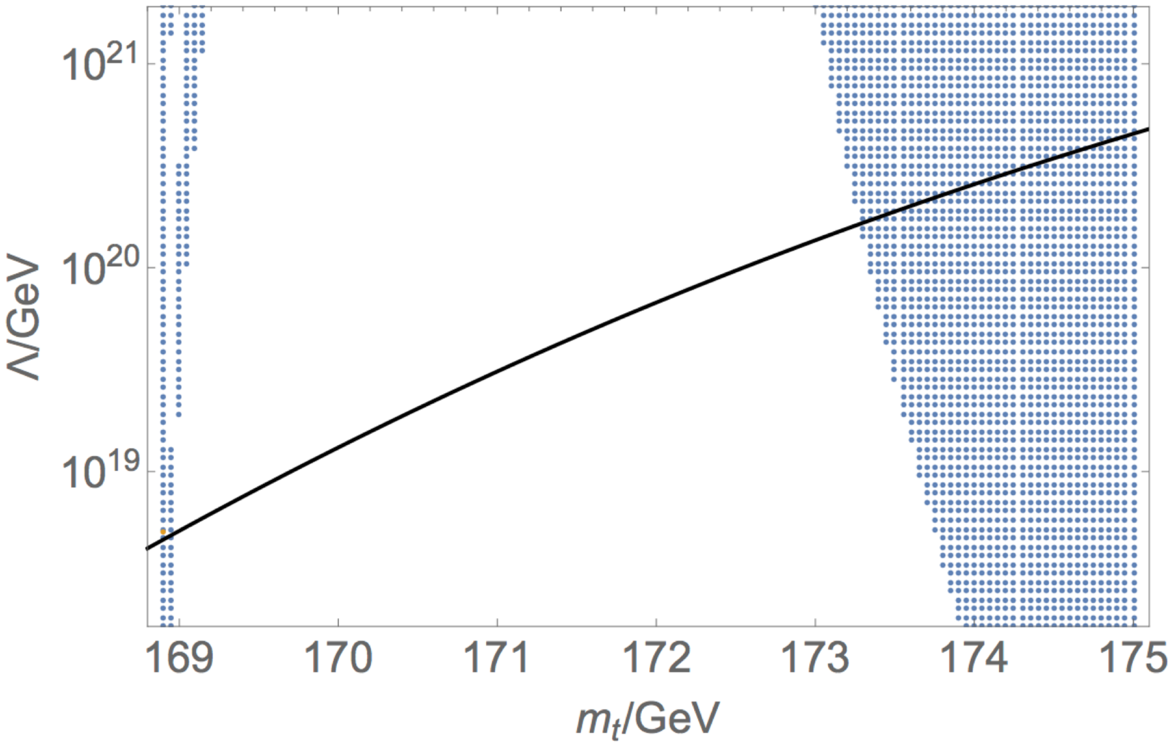


Figure 1: Plot of the allowed range of parameters (shaded region) with $m_\chi^2(v_{ew}) > 0$, i.e., the electroweak vacuum being a minimum. The solid line displays the cut-off scale Λ as function of the top-quark mass m_t for which the conditions in Eq. (6) are satisfied.

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

Scale invariant SM with light dilaton

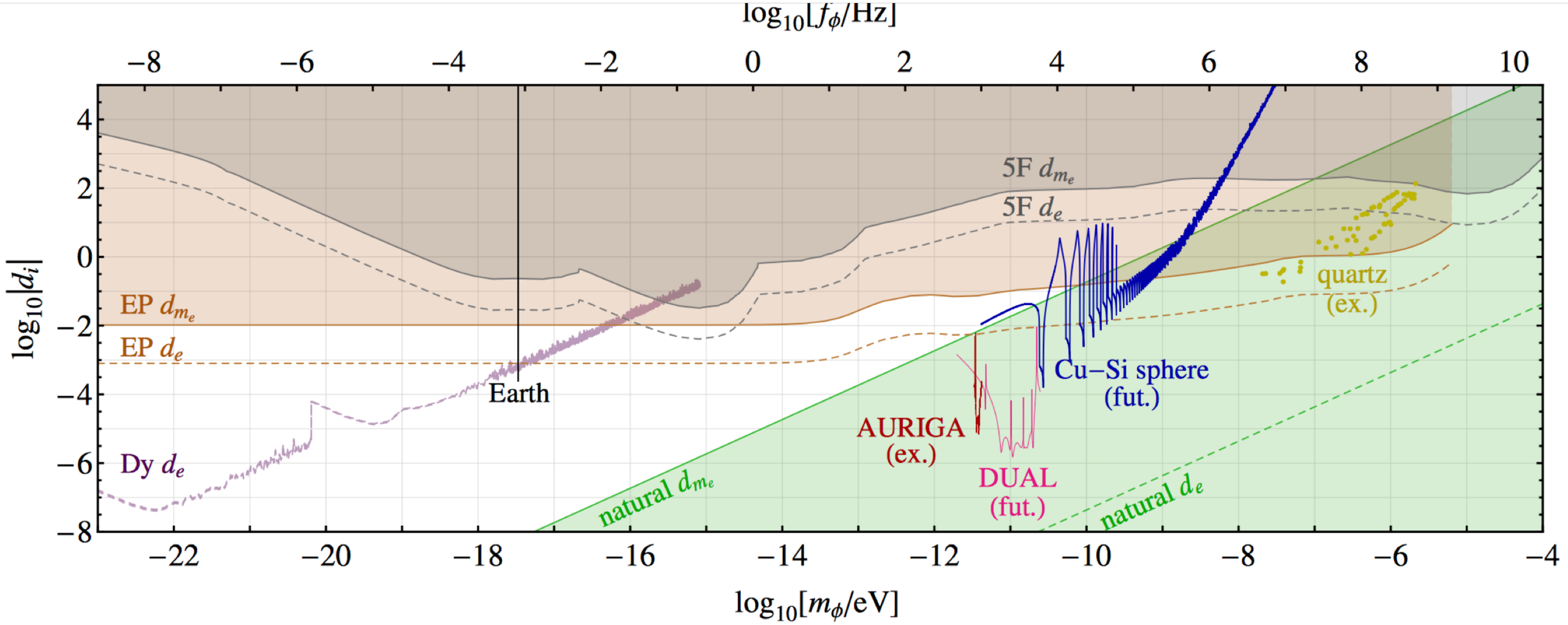


FIG. 1. Scalar field parameter space, with mass m_ϕ and corresponding DM oscillation frequency $f_\phi = m_\phi/2\pi$ on the bottom and top horizontal axes, and couplings of both an electron mass modulus ($d_i = d_{m_e}$) and electromagnetic gauge modulus ($d_i = d_e$) on the vertical axis. Natural parameter 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

Scale invarince – a natural framework for inflation [Barrie, AK, Liang, 16']

$$
\begin{aligned}
S_{\lambda\chi} &= \int dx^4\sqrt{-g}\left[\left(\xi\chi^2+\sum_{i=1}^{N}\xi_i(\lambda\chi)\phi_i^2\right)R-\frac{1}{2}\partial_\mu\chi\partial^\mu\chi-\frac{1}{2}\sum_{i=1}^{N}\partial_\mu\phi_i\partial^\mu\phi_i-V(\phi_i,\chi)+\ldots\right]\\
V(\phi_i,\chi) &= \sum_{\{i_n\}}\sigma_{i_1,\ldots,i_n}(\lambda\chi)\ \chi^{(4-n)}\phi_{i_1}\ldots\phi_{i_n}\ .
\end{aligned}
$$

$$
\begin{aligned}
\bar{S}_\rho &= \int dx^4\sqrt{-g}\left[\zeta(\rho)\rho^2R-\frac{1}{2}\partial_\mu\rho\partial^\mu\rho-V(\rho)\right]\\
V(\rho) &= \sigma(\rho)\rho^4\ ,
\end{aligned}
$$

$$
\begin{aligned}
\zeta(\rho) &= \zeta_0+\frac{(12\zeta_0+1)\sigma_0}{8\pi^2}\ln\left(\frac{\rho}{\rho_0}\right)\ ,\\
\sigma(\rho) &= \sigma_0+\frac{9\sigma_0^2}{2\pi^2}\ln\left(\frac{\rho}{\rho_0}\right)\ .
\end{aligned}
$$

In the Weyl limit, $\zeta_0 \to -1/12,\ \text{and}\sigma_0 \to 0\ ,\sigma_0^2(\zeta_0/(1+12\zeta_0))^{1/2} \to \text{const}$

Linear field inflation

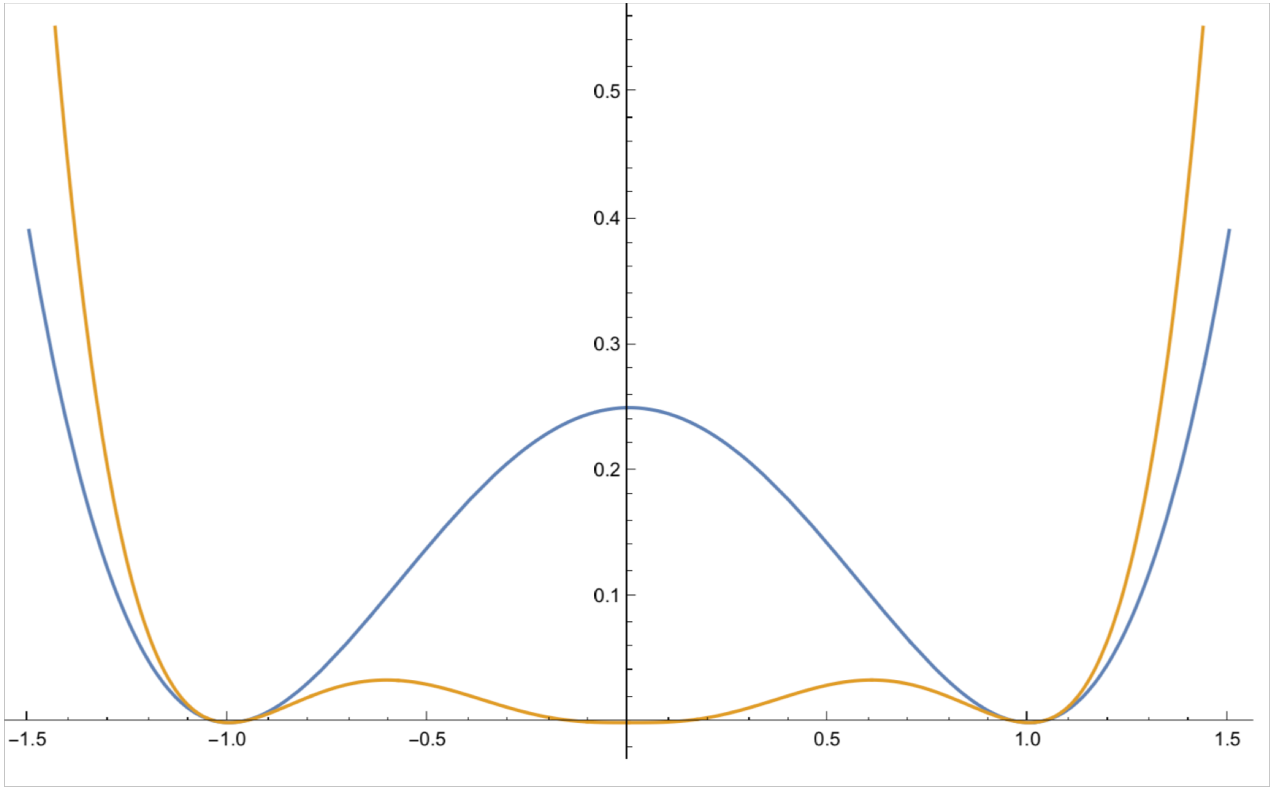
$$
\begin{aligned}
n_s-1 &\approx -0.025\left(\frac{N_\star}{60}\right)^{-1}\ ,\\
r &= 0.0667\left(\frac{N_\star}{60}\right)^{-1}\ .
\end{aligned}
$$

More comprehensive discussions in talks by: Gong, Kamada, Rubio, Bezrukov

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:

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

- 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

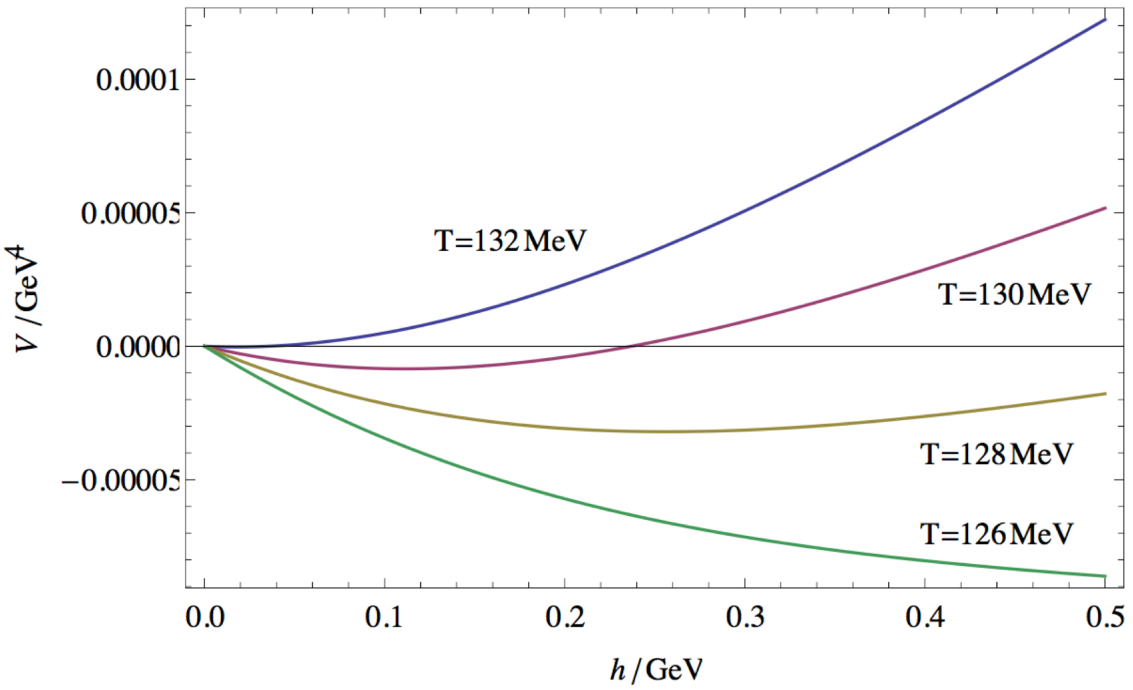


Figure 2: $V_T(h) - V_T(0)$ for different temperatures below the chiral phase transition.

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.

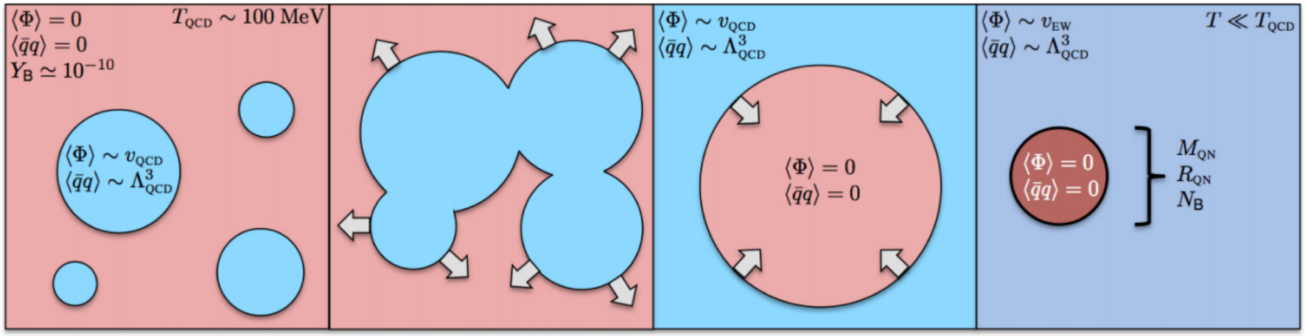


Figure 2: A cartoon illustrating the cosmological dynamics leading to the formation of nuggets of six-flavor quark matter. A first-order QCD phase transition causes the baryon number to accumulate into pockets of quark gluon plasma, which eventually cool to form 6FQM nuggets.

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…) – work in progress

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

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

$$R \sim 1/H_{\rm QCD} \sim M_P/T^2_{\rm QCD},$$

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

- QCD baryogenesis(?) – work in progress

Conclusion

- Scale paradigm for natural mass hierarchies predicts a light, feebly coupled dilaton.

- The light dilaton can constitute dark matter

- Scale invariance is a favourable framework for cosmic inflation

- 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, cold baryogenesis.

- Detection of a light scalar particle + the above astrophysical signatures will provide strong evidence for the fundamental role of scale invariance in particle physics and cosmology.