The Dilaton and its many Faces

Javi Serra

with B.Bellazzini, C.Csaki, J.Hubisz, J.Terning

arXiv:1209.3299
arXiv:1305.3919
arXiv:1312.0259
arXiv:14xx.xxxx

UC Irvine Joint Particle Physics Seminar
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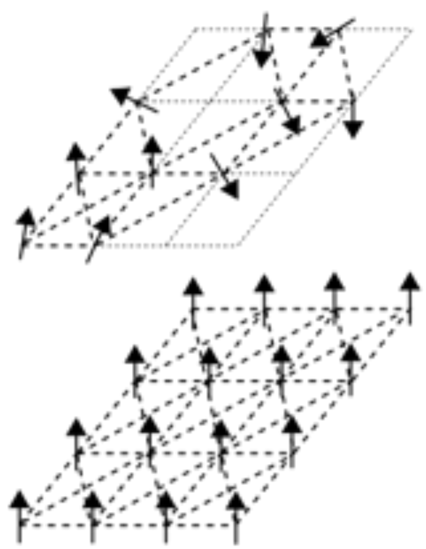
Quantum field theory of order parameter describes many physical systems with phase transitions

Ferromagnetism

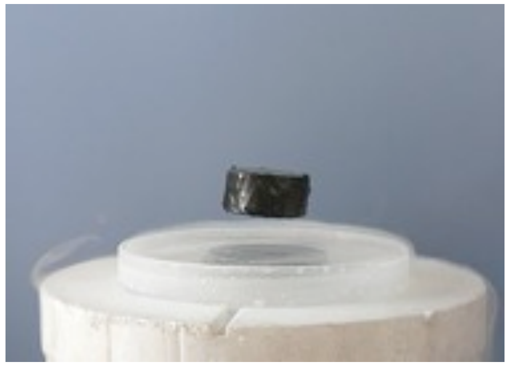
temperature

$T > T_C$

$T < T_C$

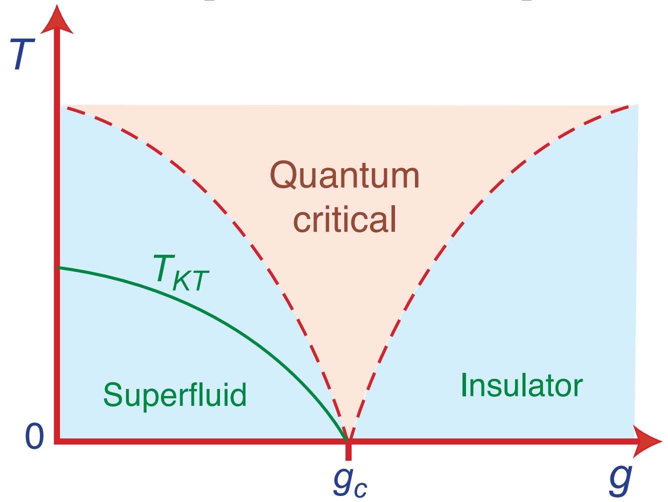


Superconductivity



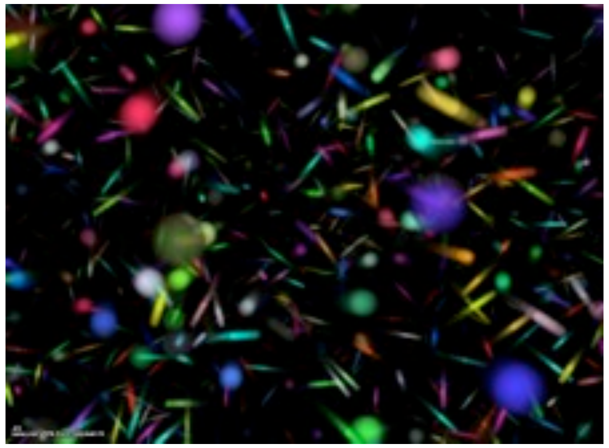
$T < T_C$

Superfluidity



coupling

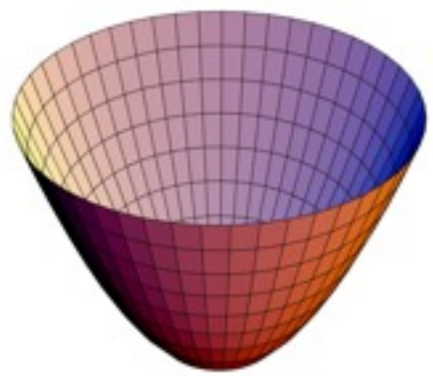
Vacuum State of Nature



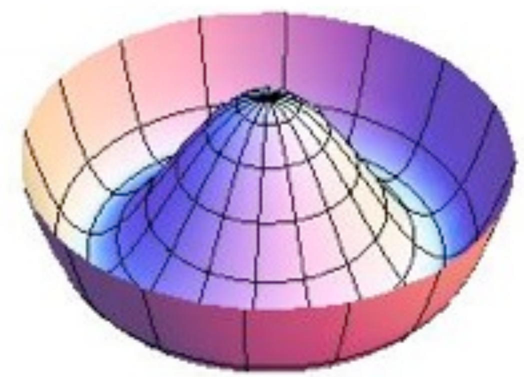
Inflation
ElectroWeak Symmetry Breaking
Quantum Chromodynamics

$$\mathcal{L} = (\partial\phi^\dagger)(\partial\phi) + m^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

Unbroken phase



Broken phase



Spontaneous Symmetry Breaking: $G \to H$

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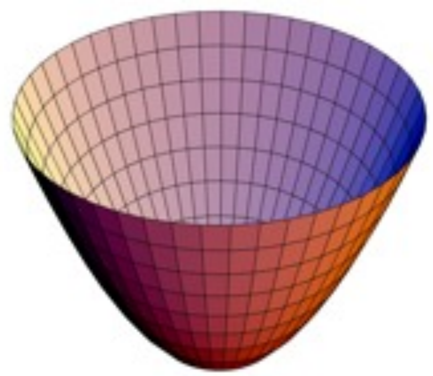

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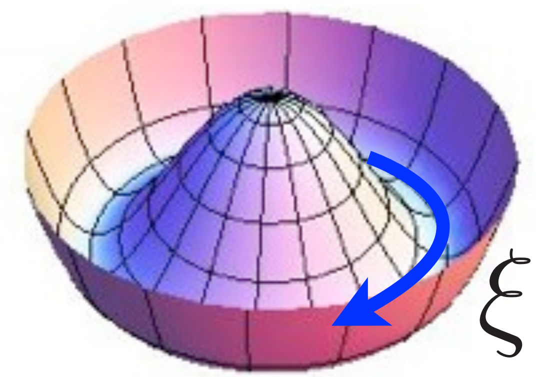


Spontaneous Symmetry Breaking: G -> H

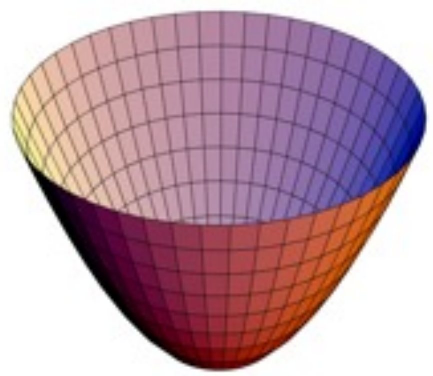
(approximately) Massless Goldstone modes appear = phases

$$\phi = \boxed{e^{i\xi}}(\langle\phi\rangle + \sigma)$$

Motivations

$$\mathcal{L} = (\partial\phi^\dagger)(\partial\phi) + m^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

Unbroken phase



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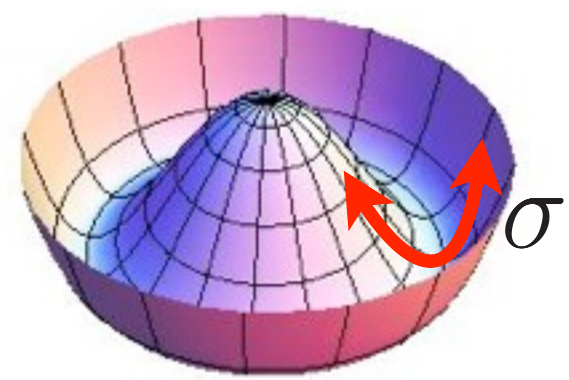


Spontaneous Symmetry Breaking: G -> H

No <u>amplitude mode</u> without adjusting paramaters = TUNING

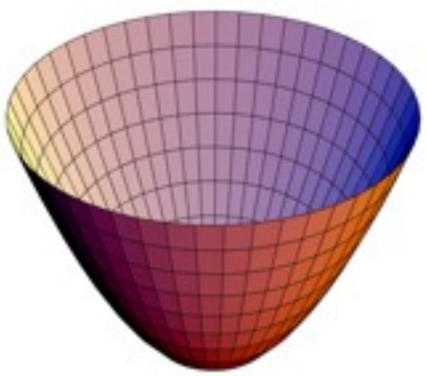
$$\phi = e^{i\xi}(\langle\phi\rangle + \boxed{\sigma})$$

$$m \sim (T - T_C), (j - j_C), (\Lambda - \Lambda_Q)$$

Fundamental scalars are unnatural

$$\mathcal{L} = (\partial\phi^\dagger)(\partial\phi) + m^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

Unbroken phase



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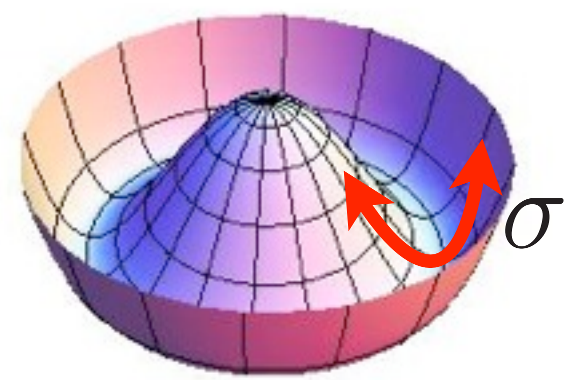

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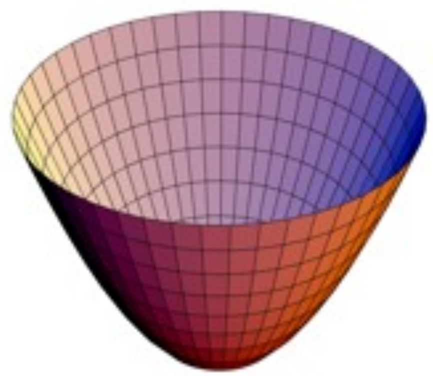

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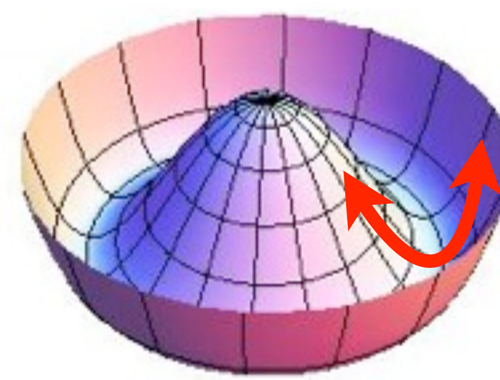

σ

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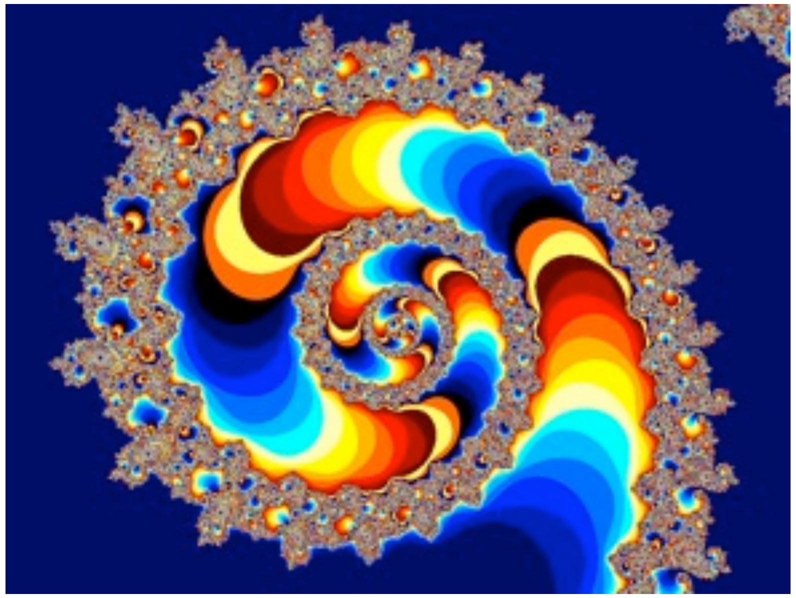
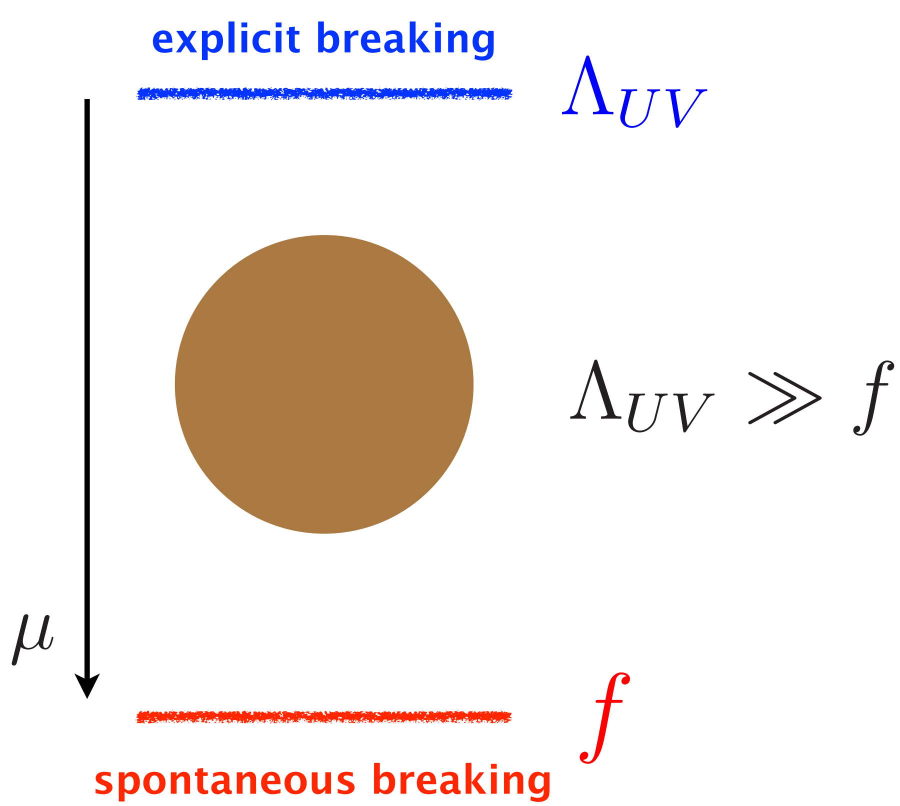
The Dilaton



What is the dilaton?



Scale (conformal) invariant sector

$$x \to e^{\alpha} x \,,\; \Phi(x) \to e^{d_\Phi \alpha} \Phi(e^{\alpha} x)$$

$$\mathcal{S}_{CFT} = \sum_{\mathcal{O}} \int d^4x \mathcal{O} \,,\; d_{\mathcal{O}} = 4$$

- *Irrelevant operators are unimportant at low energies.*
- *No relevant operators can be present.*

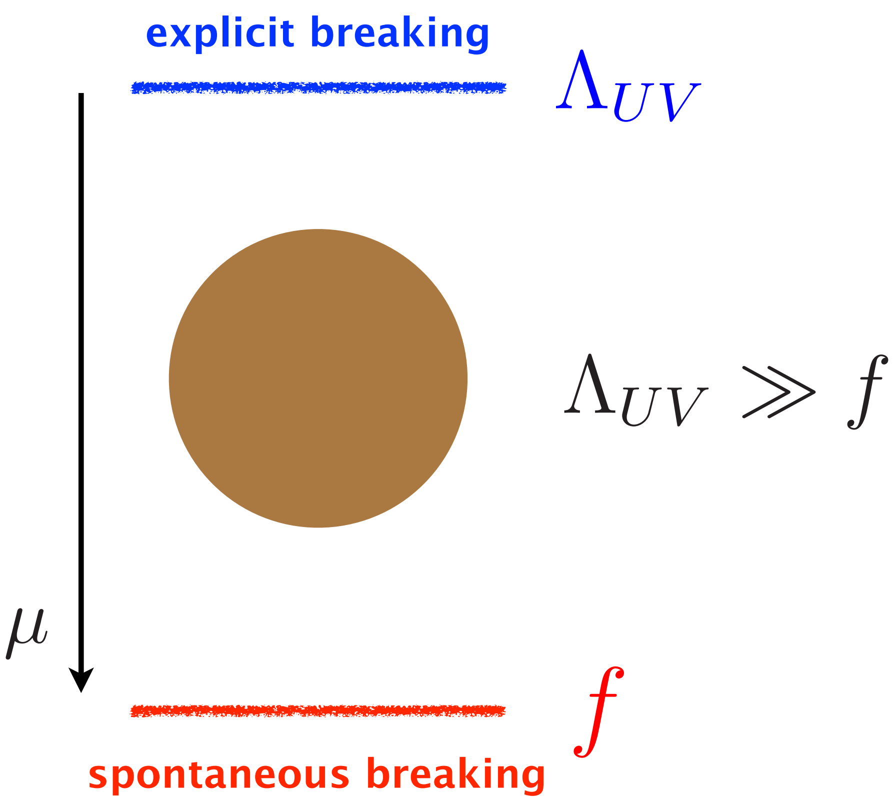
Spontaneous breaking of scale invariance

$$\langle \mathcal{O}(x) \rangle = f^{d_{\mathcal{O}}}$$

1 GB (enough): $\mathrm{SO}(4,2)/\mathrm{SO}(3,1)$

$$\chi \equiv f e^{\sigma/f} \to e^{\alpha} \chi$$
$$\sigma \to \sigma + \alpha f$$

What is the dilaton?



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Compositeness

$$\mathcal{O} = \bar{\psi}\psi$$

Supersymmetry

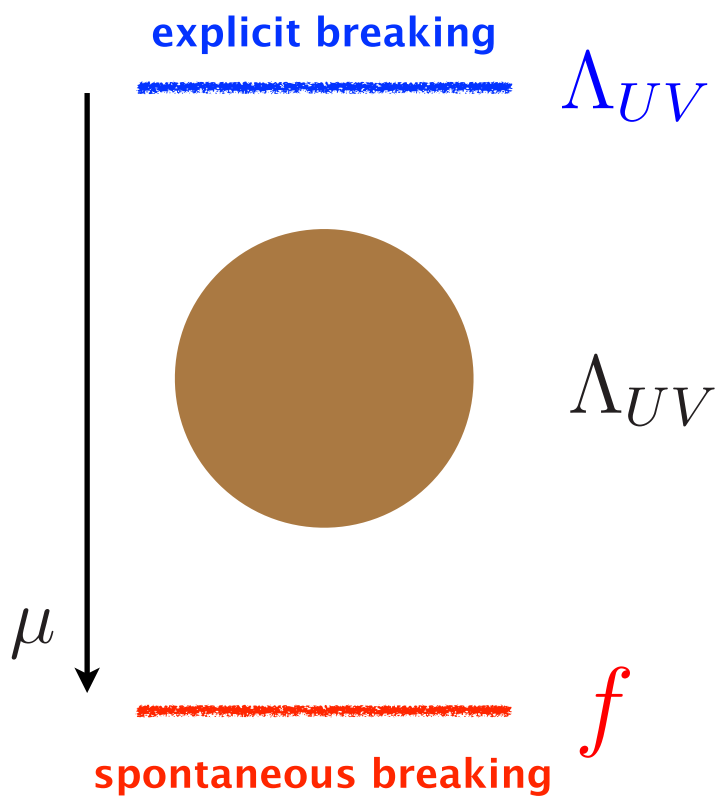
$$\mathcal{O} = (\phi, \psi)$$

Chiral symmetry is crucial in both cases

new states at
$\Lambda_{IR} \sim 4\pi f$

new states at
gf

What is the dilaton?



$$\Lambda_{UV} \gg f$$

Scale (conformal) invariant sector

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new states at $\Lambda_{IR} \sim 4\pi f$

new states at $g f$

Effective theory for CFT spontaneous breaking

The point is if there is a light amplitude mode when scale generates

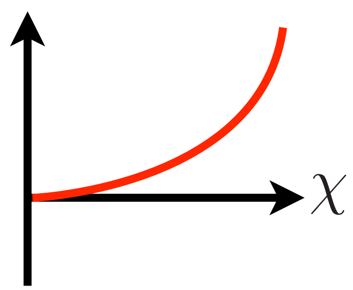
$$\mathcal{L}_{eff} = \frac{1}{2}(\partial\chi)^2 - a_0\chi^4 + \frac{a_{2,4}}{\chi^4}(\partial\chi)^4 + \cdots$$

Non-zero potential allowed

Fubini '76

standard GB:
$V(\pi) = 0$

$a_0 > 0$

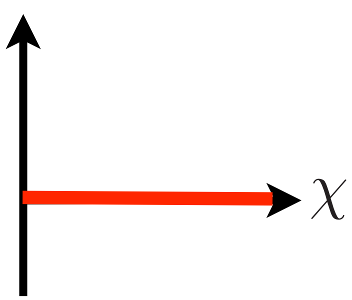


$\langle\chi\rangle \to 0$

CFT/AdS4

runaway

$a_0 = 0$

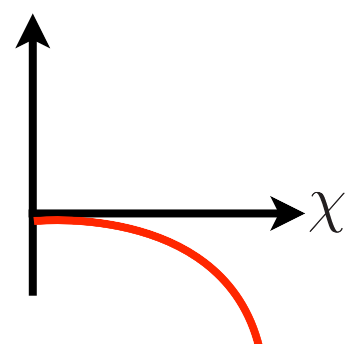


$\langle\chi\rangle = f = ?$

CFT/Poincare4

flat direction

$a_0 < 0$



$\langle\chi\rangle \to \infty$

CFT/dS4

runaway

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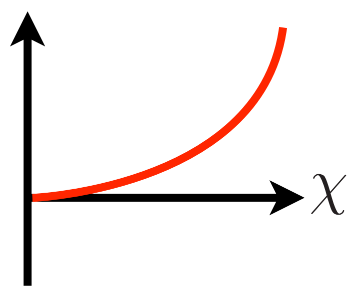

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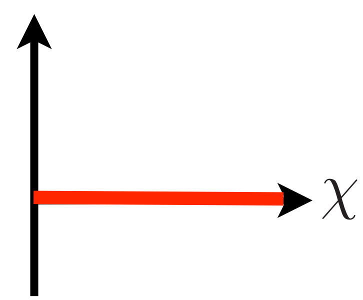

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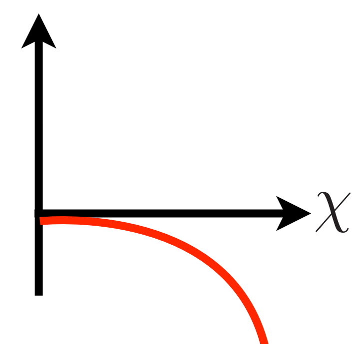

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CFT/dS4

runaway

TUNING

Flat directions are only natural in SUSY.

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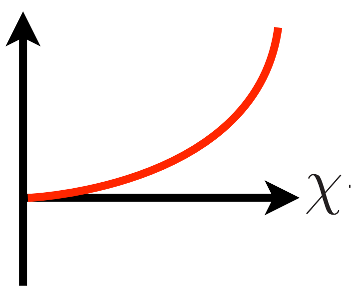


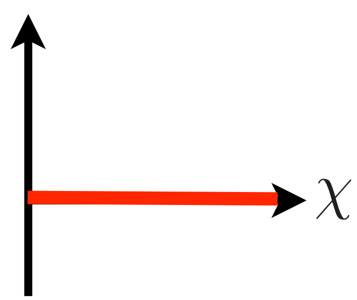
$\langle\chi\rangle \to 0$

CFT/AdS4

runaway

WE WISH

$a_0 = 0$



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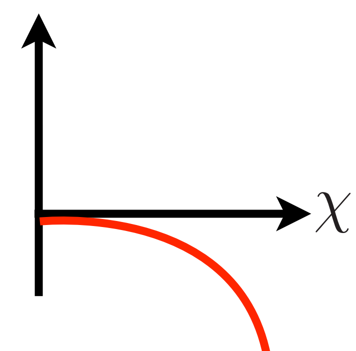


$\langle\chi\rangle \to \infty$

CFT/dS4

runaway

Effective theory for CFT spontaneous breaking

We need to add a perturbation (explicit breaking)

$$\mathcal{L} = \mathcal{L}_{CFT} + \lambda \mathcal{O} \qquad [\mathcal{O}] = 4 - \beta/\lambda \qquad \frac{d\lambda(\mu)}{d\log\mu} = \frac{\beta(\lambda)}{\lambda} \neq 0$$

$$\Big\downarrow \; \mu \to \chi$$

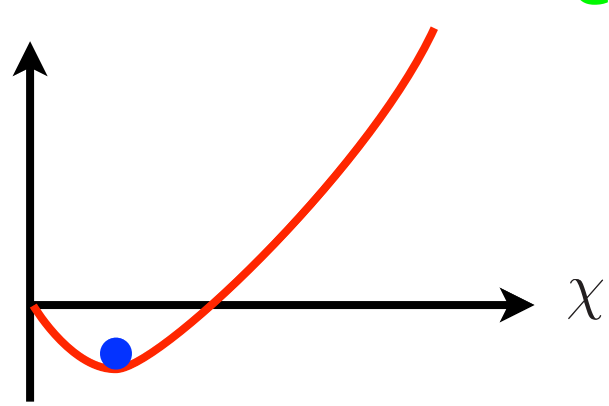
$$V(\chi) = \chi^4 F(\lambda(\chi))$$

$$F(\lambda(\chi)) = a_0 + \sum_n a_n \lambda^n(\chi)$$

Quartic gets dependence on running coupling.

"Running" potential

Coleman, Weinberg '73



The dilaton effectively scans the lanscape of quartics.

Minimum and dilaton mass

$$\langle \chi \rangle = f$$

$$V' = f^3[4F(\lambda(f)) + \beta F'(\lambda(f))] = 0$$

$$m_d^2 \simeq 4f^2 \beta F'(\lambda(f))$$

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Dimensional Transmutation

$$\lambda(\mu) = \lambda_0 \left(\frac{\mu_0}{\mu}\right)^{\beta/\lambda}$$

$$\mu \to \chi$$

$$\lambda(f) \sim \sqrt{a_0}$$

$$f \sim \mu_0 \left(\frac{\lambda_0}{\sqrt{a_0}}\right)^{\lambda/\beta}$$

A large hierarchy has been generated!

a_0 still matters for the dilaton mass

$$V' = f^3[4F(\lambda(f)) + \beta F'(\lambda(f))] = 0$$

$$m_d^2 \simeq 4f^2 \beta F'(\lambda(f)) = -16 f^2 F(\lambda(f))$$

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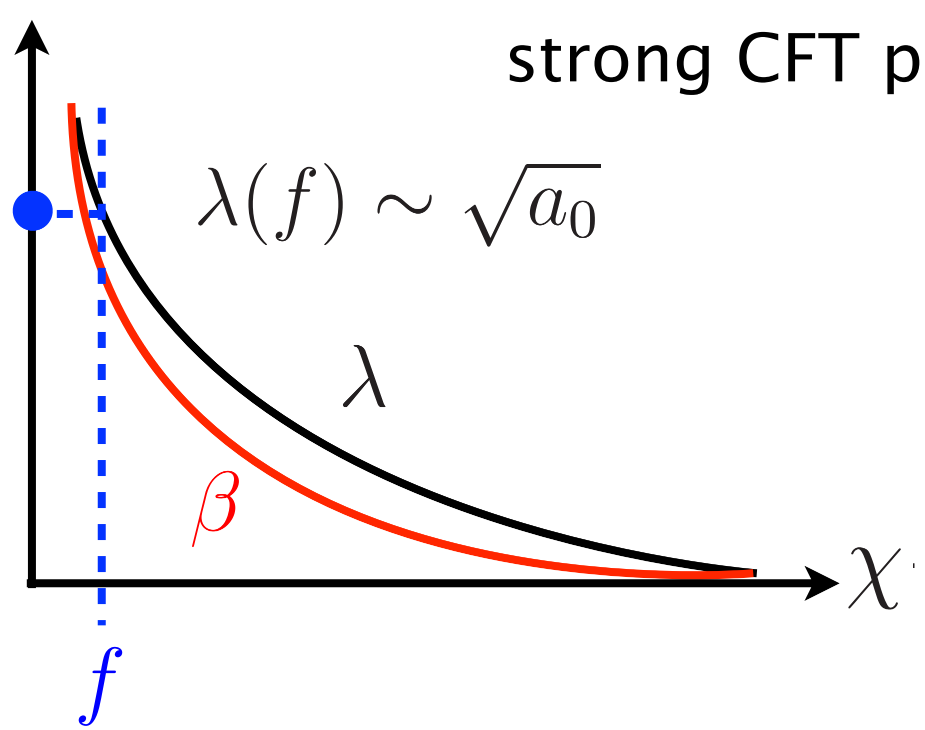
Generically there is NO small explicit breaking at f!

F is the vacuum energy (CC) in units of f: $F(f) \sim a_0 \sim \dfrac{\Lambda_{IR}^4}{16\pi^2 f^4} \sim 16\pi^2$

QCD-like

strong CFT perturbation



$$m_d^2 \sim 16\pi^2 f^2 \sim \Lambda_{IR}^2$$

NO remnant of scaling symmetry

NO dilaton in QCD-like theories

Holdom, Terning '88

Effective theory for CFT spontaneous breaking

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We can get small explicit breaking at f by tuning

Start with small vacuum energy ~ flat direction.

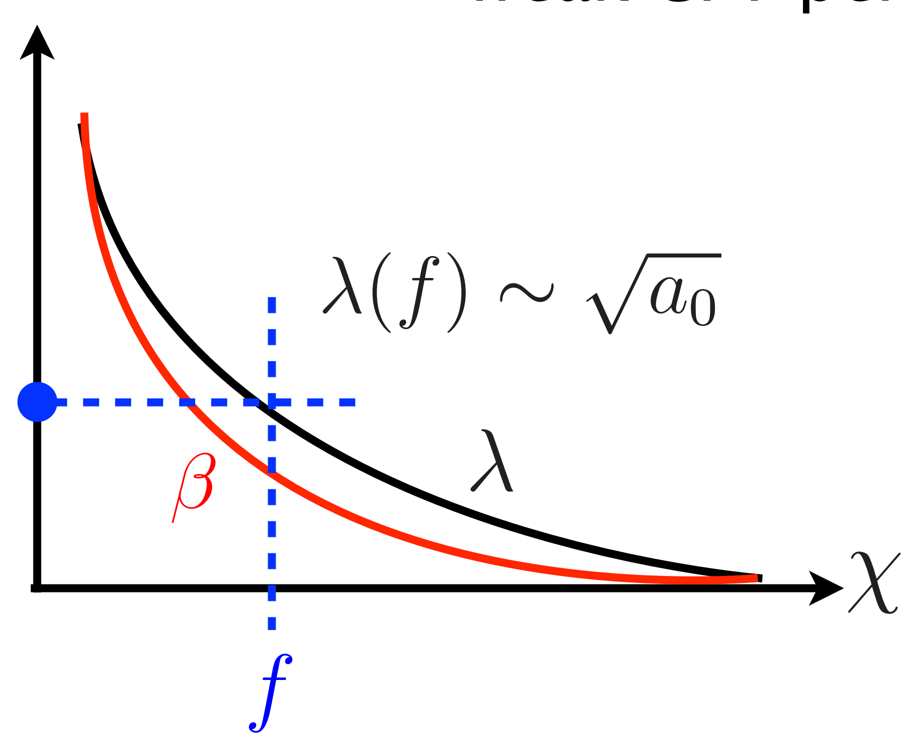
tuned-QCD-like

weak CFT perturbation

Randall, Sundrum '99

Goldberger, Wise '99

$a_0 \sim \frac{16\pi^2}{\Delta}$



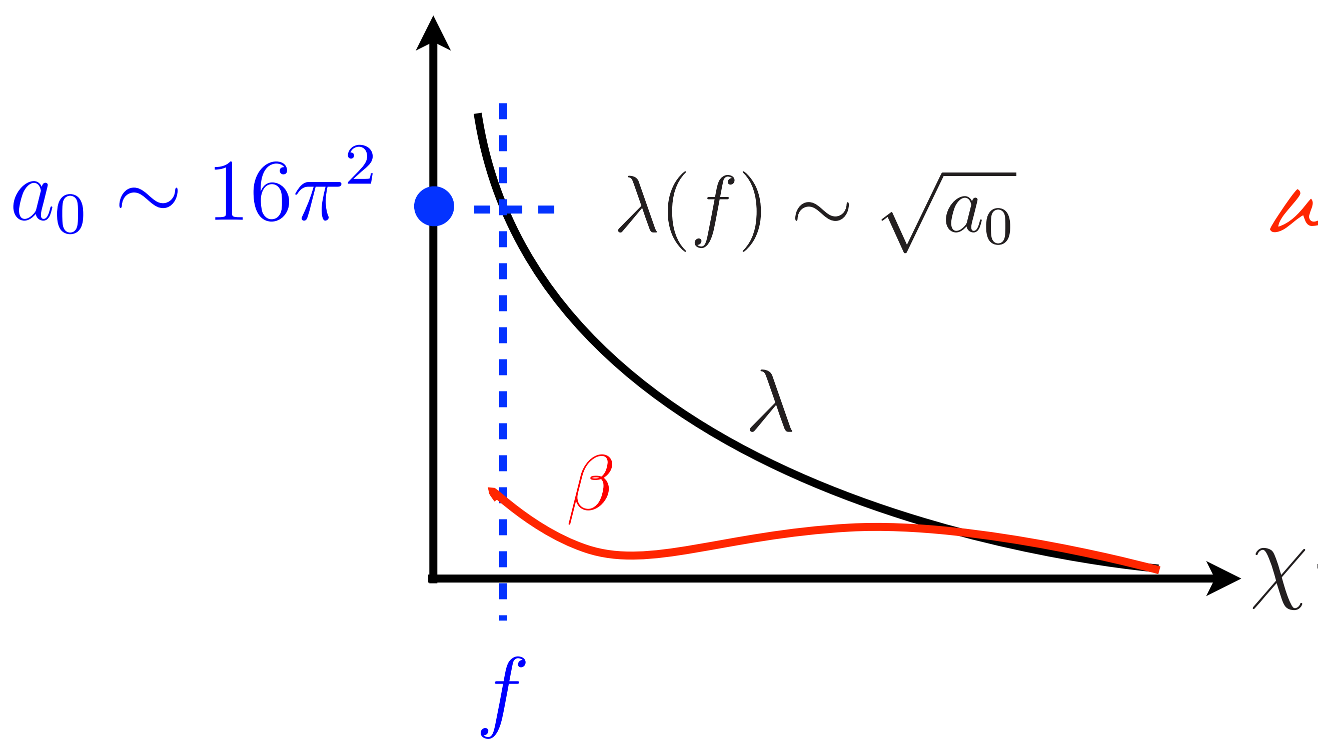
with TUNING: $\Delta \gtrsim \frac{\Lambda_{IR}}{m_d}$

But there is an unorthodox way out

CPR construction

Strong CFT perturbation but small breaking

$$m_d^2 \simeq 4f^2\beta F'(\lambda(f)) = -16f^2 F(\lambda(f)) = -16V(f)/f^2$$



Without "TUNING"

$$m_d^2 \ll \Lambda_{IR}^2$$

Let the dilaton scan the lanscape of quartics but keep the slow running always.

Contino, Pomarol, Rattazzi, '10

Bellazzini, Csaki, Hubisz, Terning, JS, '13

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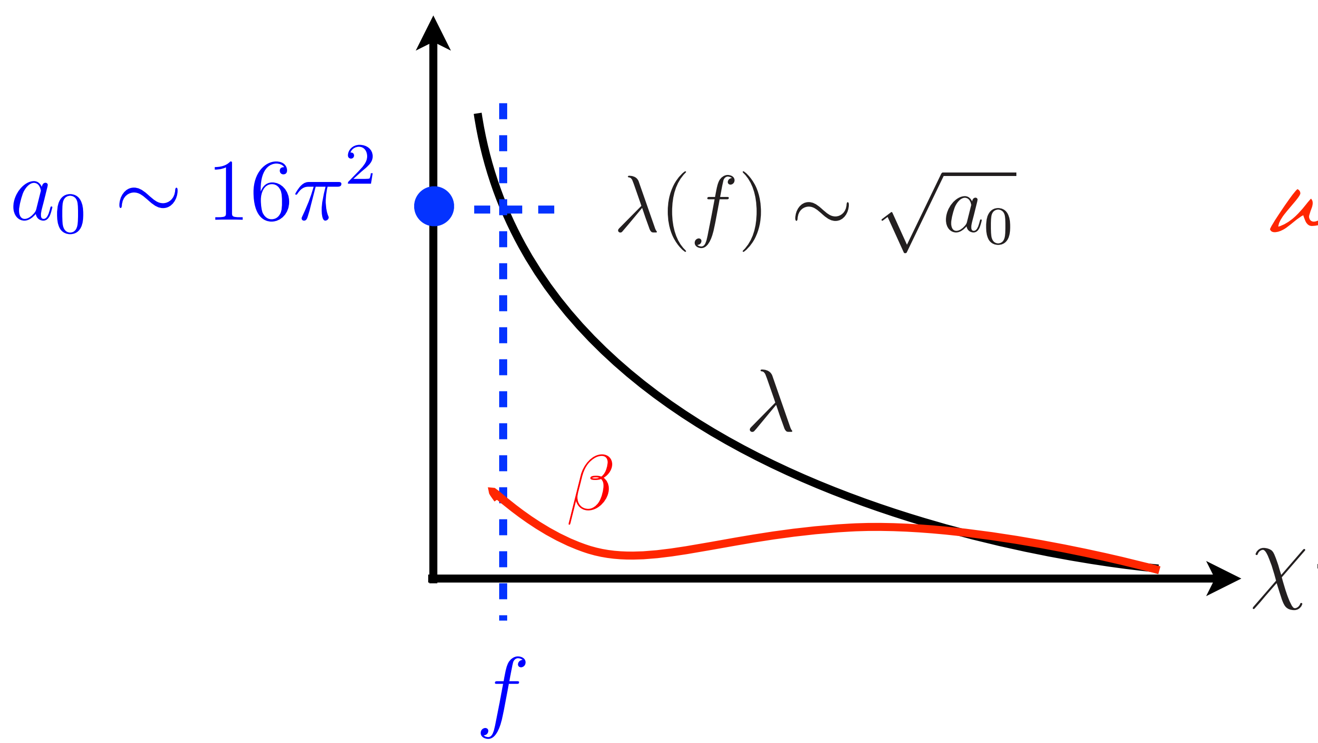

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An Extra-D Computable Example

An amazing conjecture

type IIB string theory on $\mathrm{AdS}_5 \times S^5$ $\longleftrightarrow$ $\mathcal{N} = 4$ SU(N) 4D gauge theory

Maldacena '97

$$\frac{R_{AdS}^4}{l_s^4} = 4\pi g_{YM}^2 N$$

An amazing conjecture

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Maldacena '97

$$\frac{R_{AdS}^4}{l_s^4} = 4\pi g_{YM}^2 N$$

Serves as a computational tool to describe systems that are strongly coupled.

$$g_{YM}^2 N \gg 1$$

$$N \gg 1$$

weakly coupled 5-dimensional gravity		strongly coupled 4-dimensional CFT
$\mathbf{AdS}_5$	$\longleftrightarrow$	$\mathbf{CFT}_4$

$$\mathbf{AdS}_5 \longleftrightarrow \mathbf{CFT}_4$$

5D field – 4D operator connection

$$\phi(x^\mu, y) \longleftrightarrow \mathcal{O}$$

$$\phi_0 = \phi(x^\mu, y)|_{\mathrm{AdS\,boundary}} \longleftrightarrow \lambda_0$$

Generating functional

$$Z[\phi_0] = \int \mathcal{D}\phi_{CFT}\ e^{-S_{CFT}[\phi_{CFT}] - \int d^4x\, \phi_0 \mathcal{O}} = \int_{\phi_0} \mathcal{D}\phi\ e^{-S_{bulk}[\phi]} \equiv e^{iS_{eff}[\phi_0]}$$

$$\langle \mathcal{O} \ldots \mathcal{O} \rangle = \frac{\delta^n S_{eff}}{\delta\phi_0 \ldots \delta\phi_0}$$

AdS/CFT correspondence

$$\mathbf{AdS}_5 \longleftrightarrow \mathbf{CFT}_4$$

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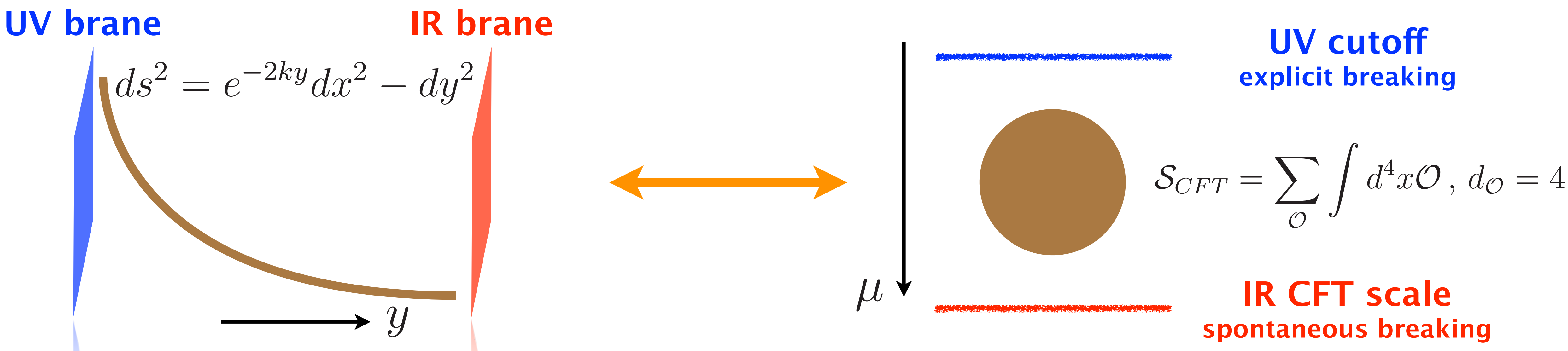
$$\langle \mathcal{O}\ldots\mathcal{O}\rangle = \frac{\delta^n S_{eff}}{\delta\phi_0\ldots\delta\phi_0}$$

This correspondence has found many applications:

- ✦ Quantum gravity
- ✦ Electroweak hierarchy problem
- ✦ Quark-gluon plasma
- ✦ Superconductors, superfluids

and still offers many avenues for investigation.

Randall & Sundrum solved a hierarchy problem with a slice of AdS



Randall, Sundrum ’99

$$\mathbf{AdS}_5 \longleftrightarrow \mathbf{CFT}_4$$

$$e^{-ky} \longleftrightarrow \mu$$

$$e^{-ky_0} \longleftrightarrow \mu_0$$

$$e^{-ky_1} \longleftrightarrow \chi$$

radion $\longleftrightarrow$ dilaton

The brane separation (hierarchy of scales) is fixed by χ.

5D gravitational action

$$S = -\int_{y=y_0} dx^4 \sqrt{g_0}\Lambda_0 - \int \sqrt{g}\left(\frac{1}{2\kappa^2}\mathcal{R} + \Lambda_{(5)}\right) - \int_{y=y_1} dx^4 \sqrt{g_1}\Lambda_1$$

Effective potential

$$k = \sqrt{\frac{-\Lambda_{(5)}\kappa^2}{6}}$$

$$V(\chi) = \left(\Lambda_0 + \Lambda_{(5)}/k\right)\mu_0^4/k^4 + \left(\Lambda_1 - \Lambda_{(5)}/k\right)\chi^4$$

5D gravitational action

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Effective potential

$$k = \sqrt{\frac{-\Lambda_{(5)}\kappa^2}{6}}$$

$$V(\chi) = (\Lambda_0 \underbrace{+ \Lambda_{(5)}}_{\Lambda_{(4)}=0}/k)\,\mu_0^4/k^4 + (\Lambda_1 \underbrace{- \Lambda_{(5)}}_{a_0=0}/k)\,\chi^4$$

2 TUNINGS! Vanishing cosmological constant and dilaton flat direction.

Raman-Sundrum and followers tuned brane tension.

Brane distance is free.

This solution is not stable under perturbations.

Csaki, Graesser, Kolda, Terning '99

Explicit breaking perturbation in AdS/CFT

$$S = \int d^5x\sqrt{g}\left(-\frac{1}{2\kappa^2}\mathcal{R} + \frac{1}{2}g^{MN}\partial_M\phi\partial_N\phi - V(\phi)\right) - \int d^4x\sqrt{g_0}V_0(\phi) - \int d^4x\sqrt{g_1}V_1(\phi)$$

$$\mathbf{AdS}_5 \longleftrightarrow \mathbf{CFT}_4$$

radion $\longleftrightarrow$ dilaton

$V(\phi) = \Lambda_{(5)}$ $\quad \phi \longleftrightarrow \mathcal{O}$ exactly marginal

$V'(\phi) = dV/d\phi \longleftrightarrow \beta(\lambda) = d\lambda/d\log\mu$ running

$(\partial\phi)|_{y=y_0} = 0$ $\quad \phi|_{y=y_0} \longleftrightarrow \lambda_0$

$$\mathcal{L} = \mathcal{L}_{CFT} + \lambda\mathcal{O}$$

A simple example, scalar with bulk mass

$$V(\phi) = \Lambda_{(5)} + m^2\phi^2$$

Scaling dimension of operator:

$$d_{\mathcal{O}} = 2 + \sqrt{4 + m^2/k^2}$$

Scalar solution of E.O.M. in RS:

$$\phi(y) = \underbrace{\phi_0 e^{-ky(4-d_{\mathcal{O}})}}_{\text{running}} + \underbrace{\phi_1 e^{-kyd_{\mathcal{O}}}}_{\text{condensate}}$$

$$\frac{d\lambda}{d\log\mu} \equiv \beta(\lambda) = (4-d_{\mathcal{O}})\lambda$$

$$\phi_0 = \lim_{\mu_0\to\infty} \mu_0^{4-d_{\mathcal{O}}}\lambda_0$$

$$\phi_1 = \frac{\langle\mathcal{O}\rangle}{2d_{\mathcal{O}}-4}$$

The general stabilized RS is this:

$$S = \int d^5x\sqrt{g}\left(-\frac{1}{2\kappa^2}\mathcal{R} + \frac{1}{2}g^{MN}\partial_M\phi\partial_N\phi - V(\phi)\right) - \int d^4x\sqrt{g_0}V_0(\phi) - \int d^4x\sqrt{g_1}V_1(\phi)$$

Bellazzini, Csaki, Hubisz, Terning, JS, '13

UV brane

$$ds^2 = e^{-2A(y)}dx^2 - dy^2$$

$$\longrightarrow y$$

IR brane

flat metric ansatz

good approximation

bulk E.O.M.

$$\begin{aligned} 4A'^2 - A'' &= -\frac{2\kappa^2}{3}V(\phi) \\ A'^2 &= \frac{\kappa^2\phi'^2}{12} - \frac{\kappa^2}{6}V(\phi) \\ \phi'' &= 4A'\phi' + \frac{\partial V}{\partial\phi}. \end{aligned}$$

boundary conditions

$$\begin{aligned} 2A'|_{y=y_0,y_1} &= \pm\frac{\kappa^2}{3}V_{0,1}(\phi)|_{y=y_0,y_1} \\ 2\phi'|_{y=y_0,y_1} &= \pm\frac{\partial V_{0,1}}{\partial\phi}|_{y=y_0,y_1}, \end{aligned}$$

We derived the effective potential integrating over the extra-d

$$\int_{y_0}^{y_1} dy\, \mathcal{L}_{bulk} + \mathcal{L}_{boundary}(y_{0,1})$$

$$\Downarrow \qquad V_{eff} = V_{UV} + V_{IR}$$

$$V_{UV/IR} = e^{-4A(y_{0,1})}\left[V_{0,1}\left(\phi(y_{0,1})\right) \mp \frac{6}{\kappa^2} A'(y_{0,1})\right]$$

Useful identification:

$$e^{-A(y_0)} \longleftrightarrow \mu_0$$

$$e^{-A(y_1)} \longleftrightarrow \chi$$

We obtain just what we expected, again.

$$V_{UV} = \mu_0^4 F(\lambda(\mu_0)) \qquad V_{IR} = \chi^4 F(\lambda(\chi))$$

UV vacuum energy

$$V_{UV} = \mu_0^4 \left[\Lambda_0 + \frac{\Lambda_{(5)}}{k} \right]$$

Modulated, slowly running, dilaton quartic, *with no TUNING!*

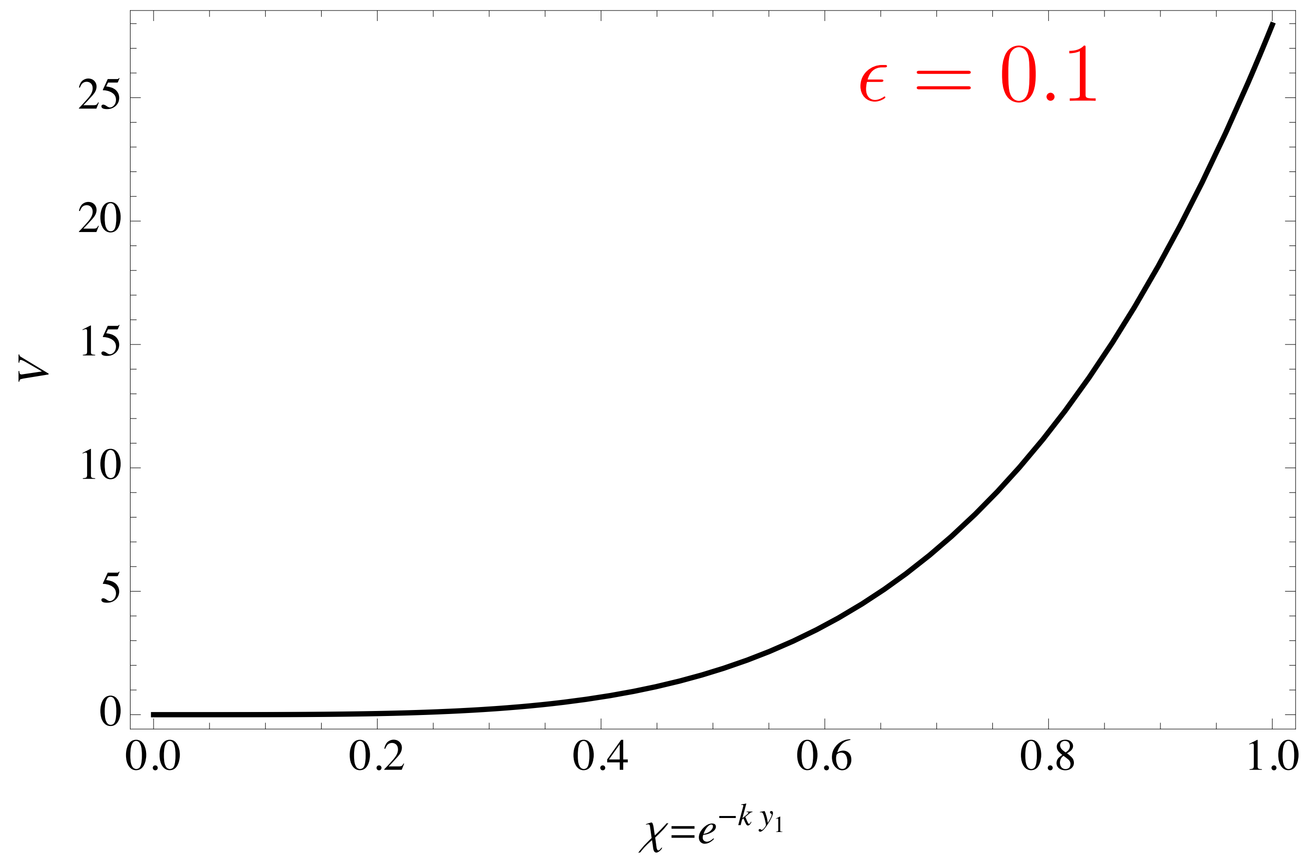
$$V_{IR} = \chi^4 \left[\Lambda_1 - \frac{\Lambda_{(5)}}{k} \cosh\left(\frac{2\kappa}{\sqrt{3}} (v_1 - \boxed{v_0 (\mu_0/\chi)^\epsilon}) \right) \right]$$

$$m^2 = -2\epsilon k^2 \qquad \epsilon \ll 1 \qquad d_{\mathcal{O}} \approx 4 - \epsilon$$

As announced in the 4D effective Lagrangian analisys, this potential yields a large hierarchy, a light dilaton, and a small cosmological constant

NATURAL & CORRELATED

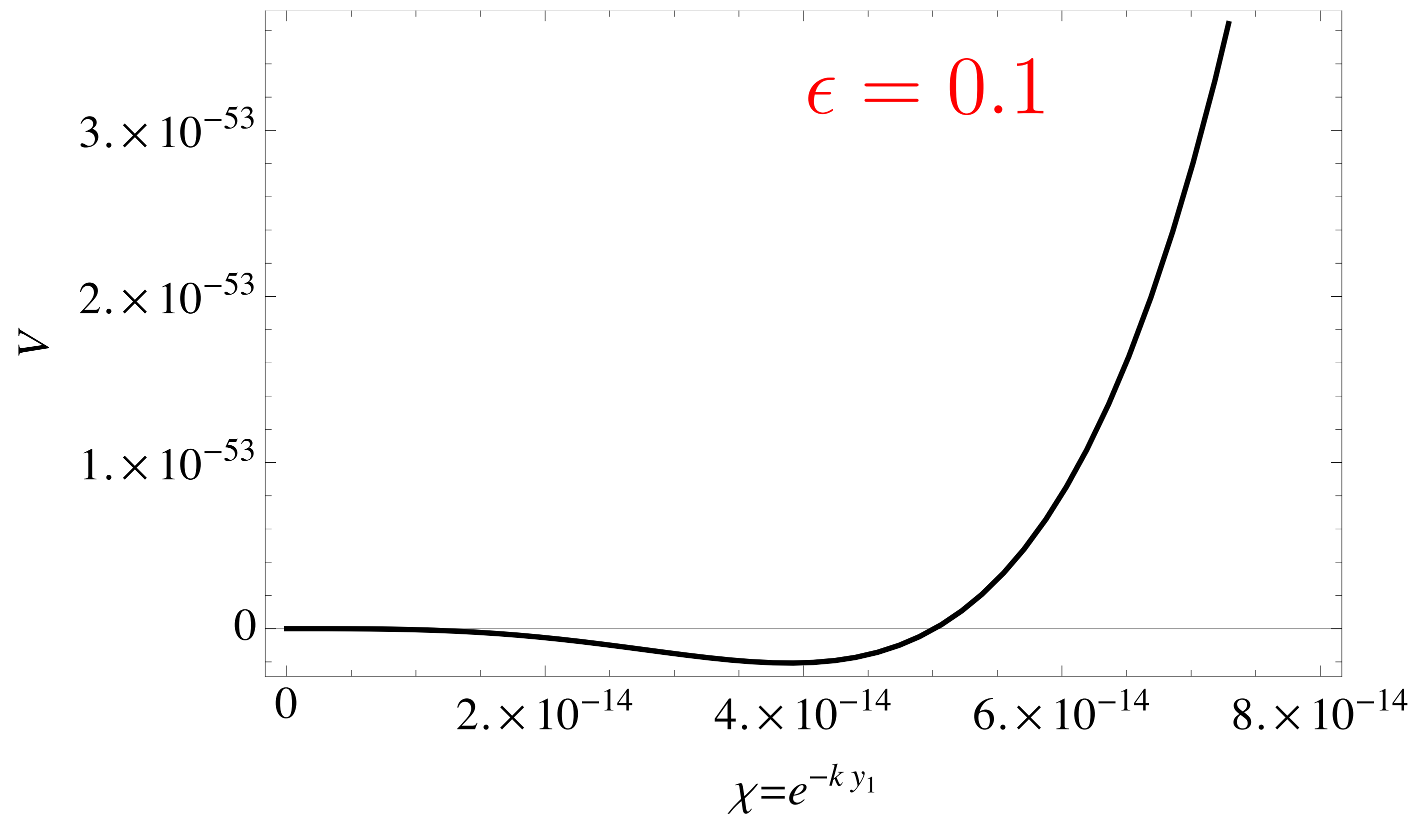
The large hierarchy



$$\langle \chi \rangle = f \qquad \frac{f}{\mu_0} = \left(\frac{v_0}{v_1 - \operatorname{sign}(\epsilon)\frac{\sqrt{3}}{2\kappa}\,\operatorname{arcsech}(\Lambda_{(5)}/k\Lambda_1)} \right)^{1/\epsilon}$$

Thanks to slow running for long time.

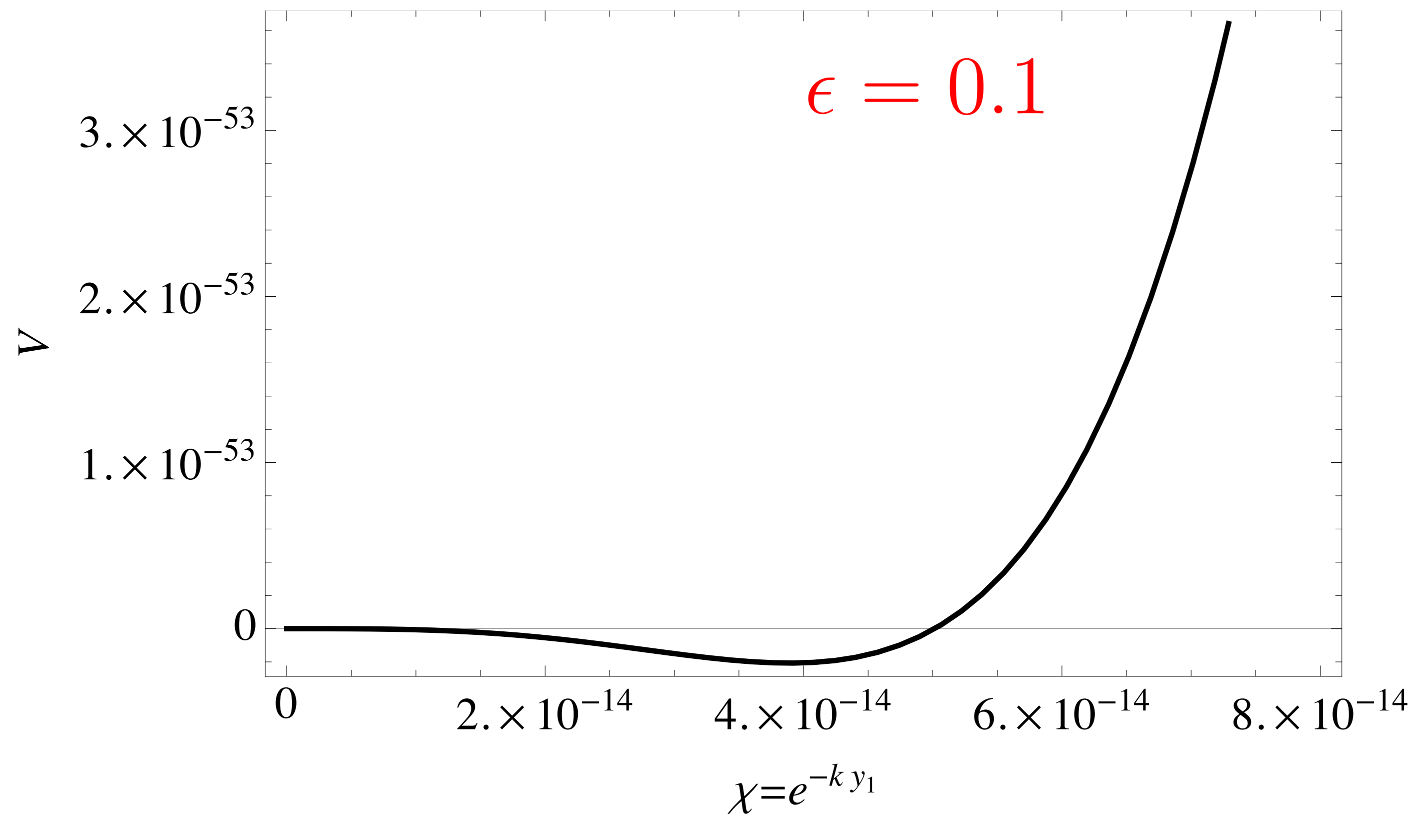
The light dilaton



$$m_\chi^2 \sim \epsilon \frac{32\sqrt{3}kv_0}{\kappa} \tanh\left(\frac{\kappa}{\sqrt{3}} (v_1 - v_0(\mu_0/f)^\epsilon) \right) f^2 (\mu_0/f)^\epsilon$$

Thanks to slow running at the minimum.

The small cosmological constant



$$V_{IR}^{min} = -\epsilon \frac{2\sqrt{3} k v_0}{\kappa} \tanh\left(\frac{\kappa}{\sqrt{3}}\left(v_1 - v_0(\mu_0/f)^{\epsilon}\right)\right) f^4 (\mu_0/f)^{\epsilon}$$

Thanks to slow running at the minimum.

1) Small CC and light dilaton signal the **approximate scale invariance** at the condensation scale:

$$V'(\phi) = dV/d\phi \longleftrightarrow \beta(\lambda) = d\lambda/d\log\mu$$

Change the bulk potential, change the running.

Chacko, Mishra, Stolarski '13

Comments on the Cosmological Constant .

1) Small CC and light dilaton signal the **approximate scale invariance** at the condensation scale:

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Change the bulk potential, change the running.

Chacko, Mishra, Stolarski '13

2) The suppression is parametrically better than in **SUSY**:

SUSY

$$\Lambda_{(4)} = c(m_b^4 - m_f^4) \simeq c(m_b^2 + m_f^2)g_s^2 F_s^2$$

CFT

$$\Lambda_{(4)} = \tilde{c}\,\epsilon(4\pi)^2 f^4 \simeq \tilde{c}\,\epsilon\Lambda^2 f^2$$

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3) Our result is consistent with **Weinberg's no-go theorem**:

$\epsilon = 0$ *can remove the CC, but* $\epsilon \neq 0$ *is required for a unique vacuum*

The requirement is that a very light state must be in the spectrum!

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The requirement is that a very light state must be in the spectrum!

4) UV contribution to the CC?

Phenomenological Aplications

1) A Higgs-like Dilaton

The Electroweak Hierarchy Problem .

Why are particles (nearly) massless relative to Planckian scales? $v << M_P$

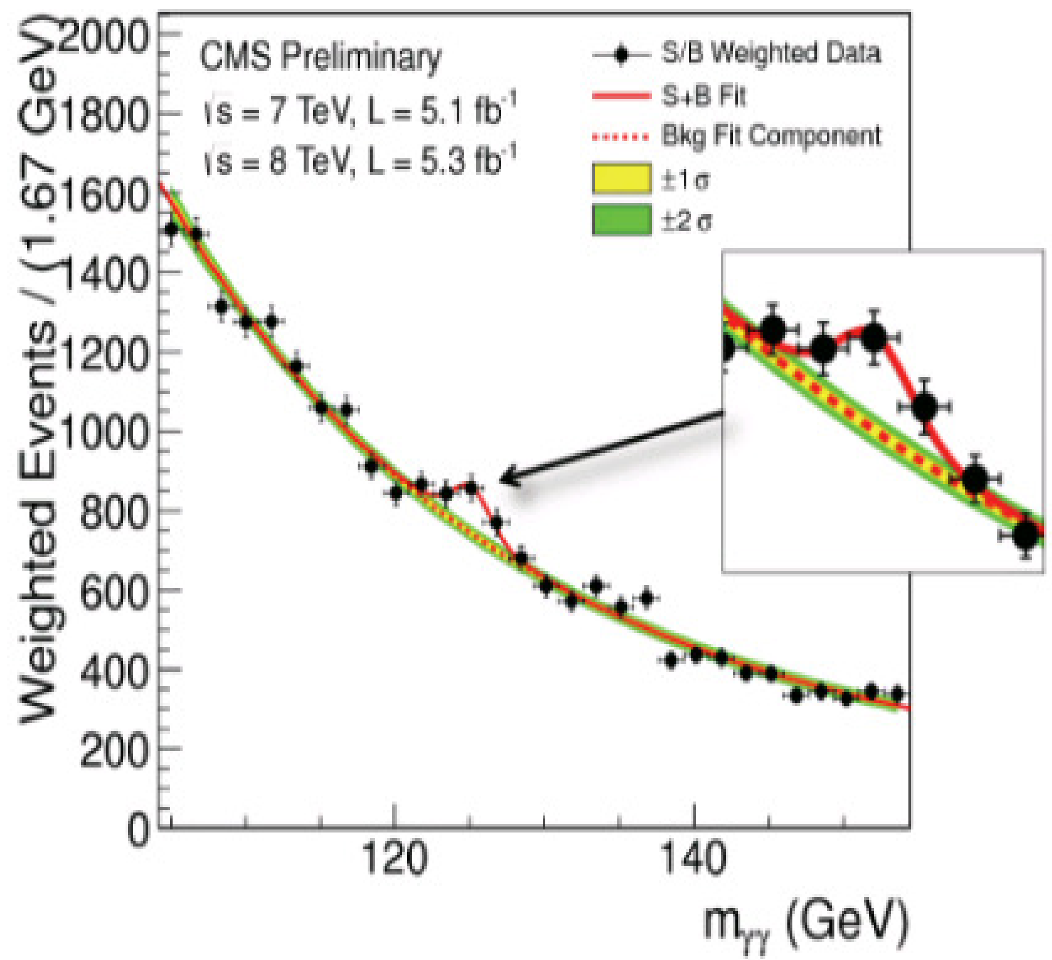
What protects the Higgs from getting a huge mass from quantum effects?

The answer pursued in this talk is

COMPOSITENESS

We observed the 3 phase modes long ago = longitudinal polarizations of W and Z gauge bosons

But now we have observed the amplitude mode!



and nothing else!

We have never encountered something like this in particle physics

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longitudinal polarizations of W and Z gauge bosons

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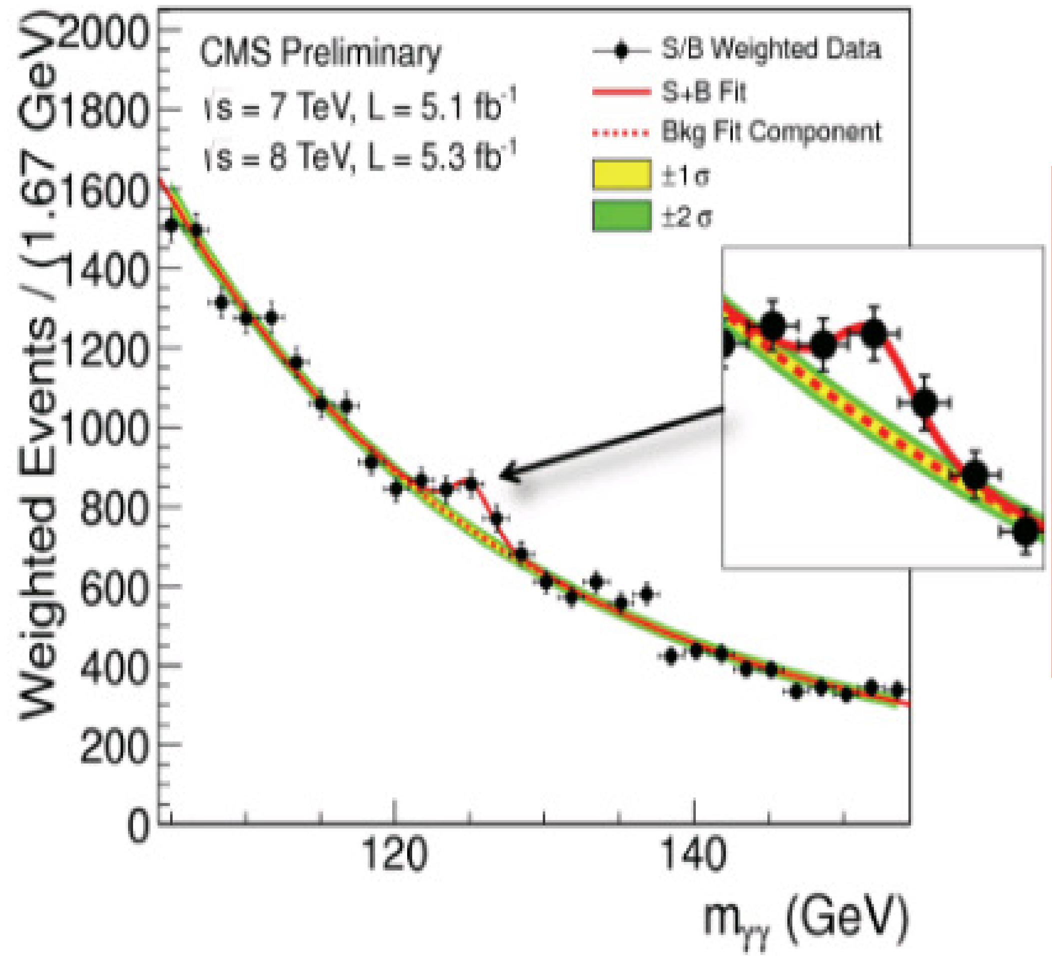


Dilaton?

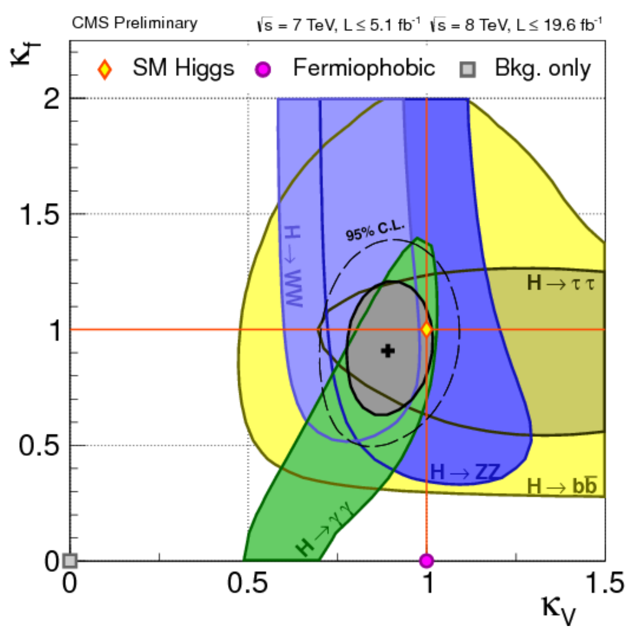
$$m_\chi \ll \Lambda \sim 4\pi f$$

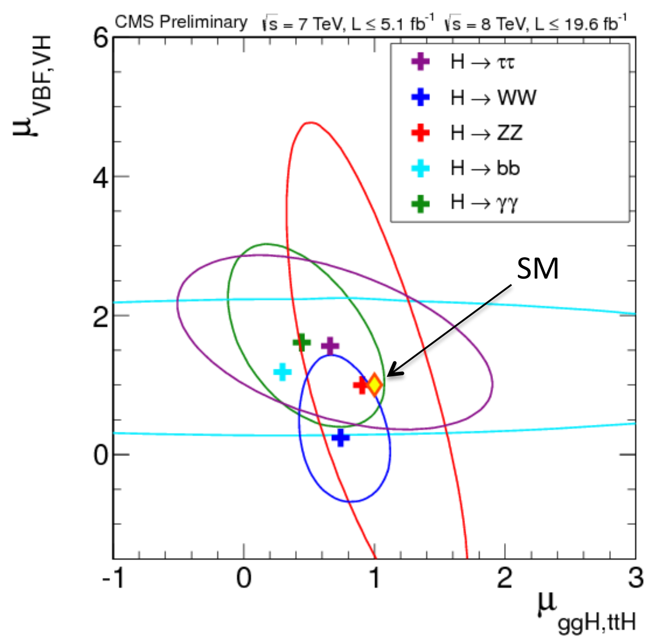
$$\langle \chi \rangle \equiv f \sim v$$

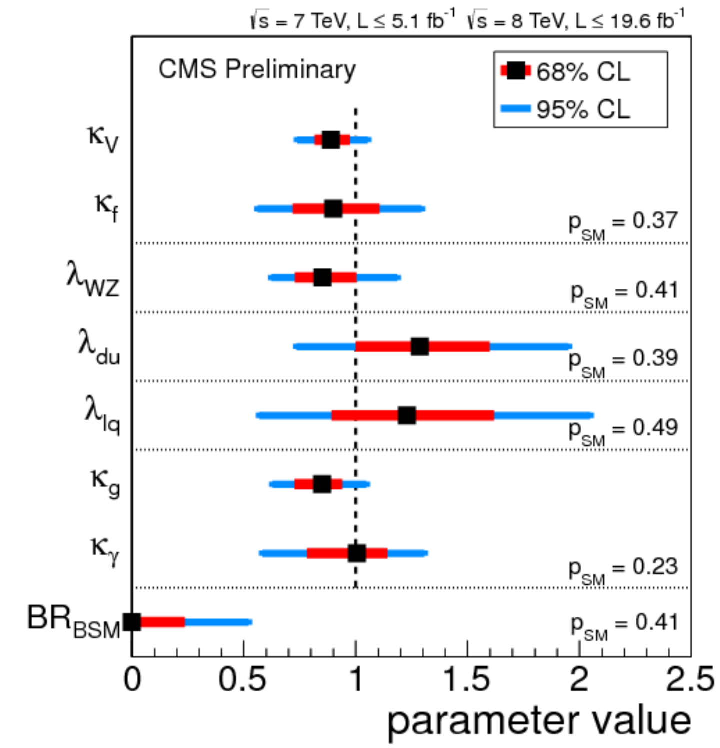
and nothing else!

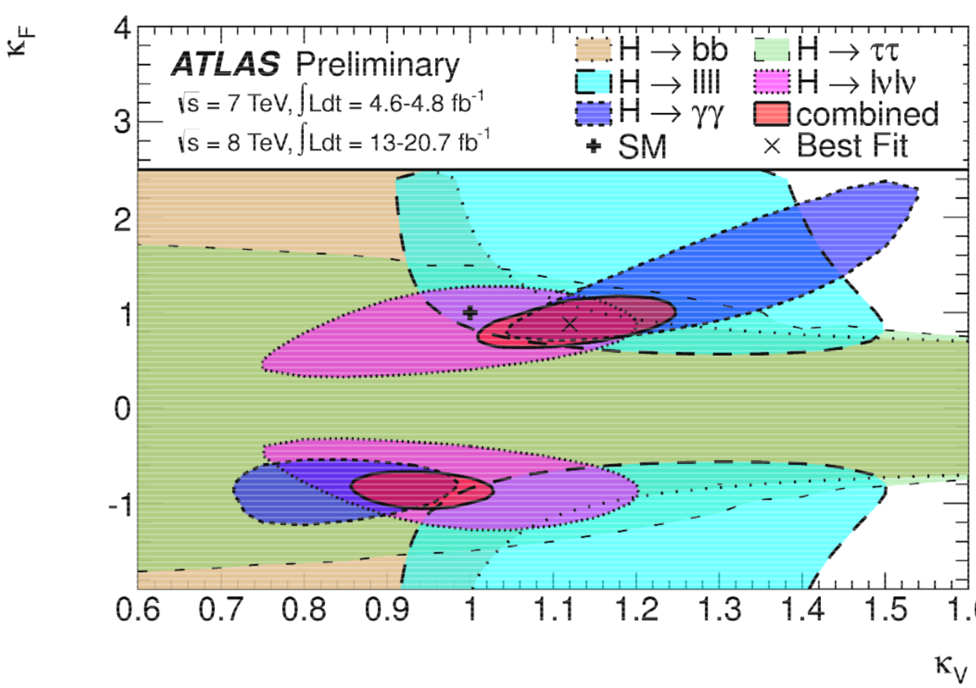
We have never encountered something like this in particle physics

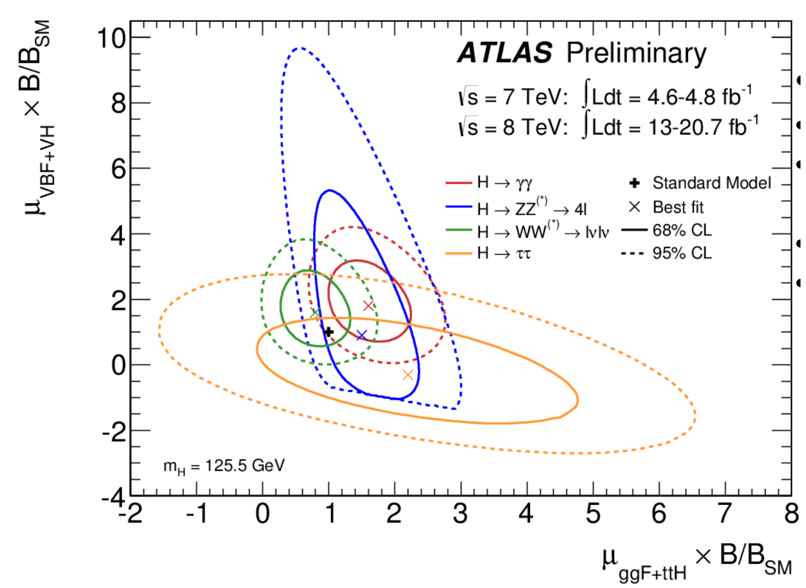
LHC Higgs Data: Couplings

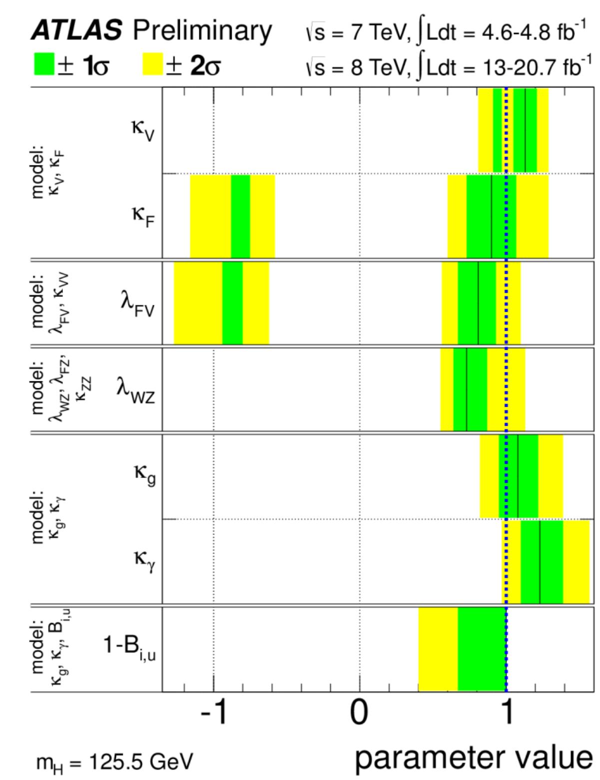








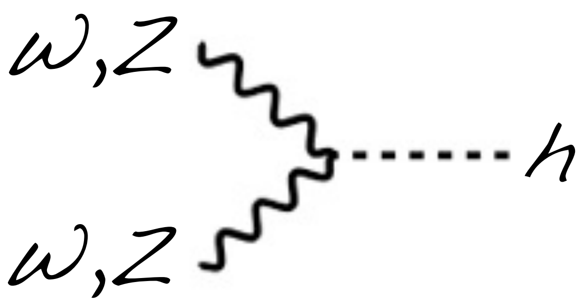


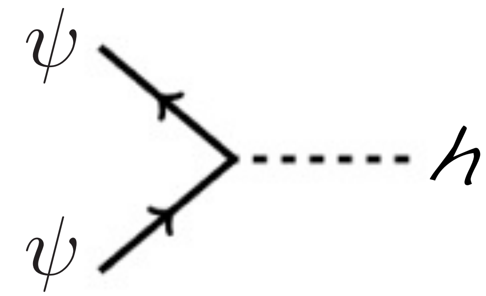


Customary parametrization of Higgs couplings

0-derivatives:

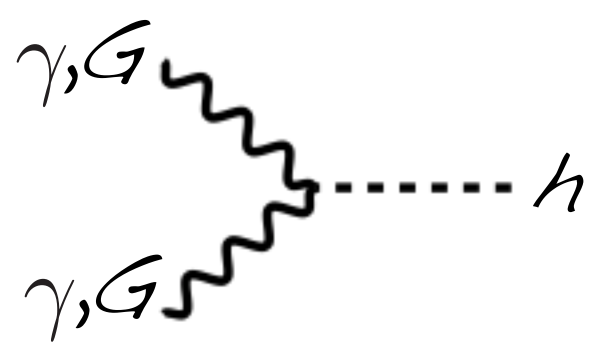
$$\mathcal{L}_{(0)} = \frac{h}{v}\left[c_V\left(2m_W^2 W_\mu^\dagger W^\mu + m_Z^2 Z_\mu Z^\mu\right) - c_t \sum_{\psi=u,c,t} m_\psi \bar{\psi}\psi - c_b \sum_{\psi=d,s,b} m_\psi \bar{\psi}\psi - c_\tau \sum_{\psi=e,\mu,\tau} m_\psi \bar{\psi}\psi\right]$$





2-derivatives:

$$\mathcal{L}_{(2)} = -\frac{h}{4v}\left[2c_{WW} W_{\mu\nu}^\dagger W^{\mu\nu} + c_{ZZ} Z_{\mu\nu} Z^{\mu\nu} + 2c_{Z\gamma} A_{\mu\nu} Z^{\mu\nu} + c_{\gamma\gamma} A_{\mu\nu} A^{\mu\nu} - c_{gg} G_{\mu\nu}^a G_{\mu\nu}^a\right]$$



Standard Model

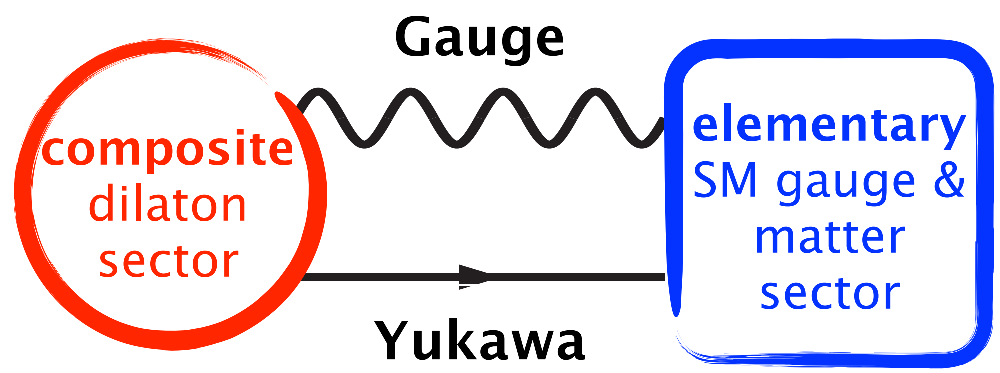
$$c_V = c_t = c_b = c_\tau = 1$$

$$c_{\gamma\gamma} = c_{Z\gamma} = c_{gg} = 0$$

Dilaton

Couplings to SM fields dictated by scale invariance and its breaking

$$\chi, \mathcal{O}_H, \mathcal{O}_\psi, \mathcal{J}^i_\mu$$



$$\psi, A_\mu$$

Dilaton Couplings to the Standard Model

Dilaton

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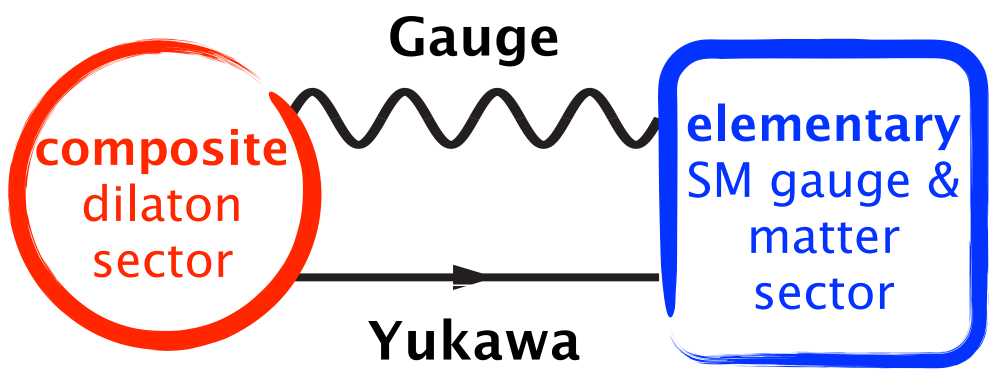
$\chi, \mathcal{O}_H, \mathcal{O}_\psi, \mathcal{J}^i_\mu$



ψ, A_μ

Scale invariance

$$\sum_i \langle \mathcal{O}_i \rangle \equiv f \to \chi$$

Electroweak symmetry breaking

$$\langle \mathcal{O}_H \rangle = v$$

$$\boxed{v \to \frac{v}{f}\chi}$$

Dilaton

Couplings to SM fields dictated by scale invariance and its breaking

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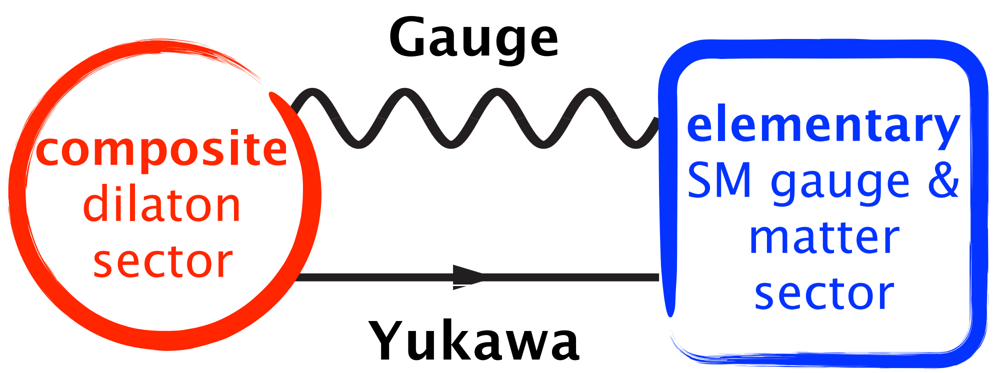

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$$\boxed{v \to \frac{v}{f}\chi}$$

Scale explicit breaking

Gauge couplings

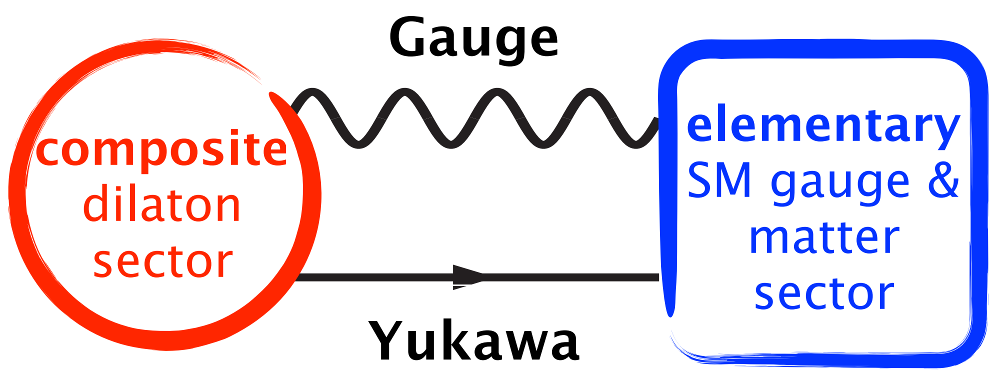
$$A^i_\mu \mathcal{J}^{\mu i}$$

$$\boxed{d(A_i) = 1 - \frac{b^i_{UV}}{8\pi^2} + \frac{b^i_{IR}}{8\pi^2}}$$

Dilaton

Couplings to SM fields dictated by scale invariance and its breaking

$\chi, \mathcal{O}_H, \mathcal{O}_\psi, \mathcal{J}^i_\mu$



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Scale invariance

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Scale explicit breaking

Gauge couplings

$$A^i_\mu \mathcal{J}^{\mu i}$$

$$\boxed{d(A_i) = 1 - \frac{b^i_{UV}}{8\pi^2} + \frac{b^i_{IR}}{8\pi^2}}$$

Yukawa couplings

$$\psi \mathcal{O}_\psi$$

$$\boxed{d(\mathcal{O}_\psi) = 3/2 - \gamma_\psi}$$

Dilaton

$$c_V = \frac{v}{f}$$

$$c_f = \frac{v}{f}(1+\gamma_f)$$

$$c_{\gamma\gamma,gg} = \frac{(g'^2, g_S^2)}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(EM,3)} - b_{UV}^{(EM,3)}\right)$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v}{f}\left(b_{IR}^{(2)} - b_{UV}^{(2)}\right)$$

Dilaton

<1 (model independent)

$$c_V = \boxed{\frac{v}{f}}$$

$$c_f = \boxed{\frac{v}{f}}(1+\gamma_f)$$

$$c_{\gamma\gamma,gg} = \frac{(g'^2, g_S^2)}{16\pi^2}\boxed{\frac{v}{f}}\left(b_{IR}^{(EM,3)} - b_{UV}^{(EM,3)}\right)$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\boxed{\frac{v}{f}}\left(b_{IR}^{(2)} - b_{UV}^{(2)}\right)$$

Dilaton

scaling anomalies
<1, >1 (model dependent)

$$c_V = \frac{v}{f}$$

$$c_f = \frac{v}{f}\boxed{(1+\gamma_f)}$$

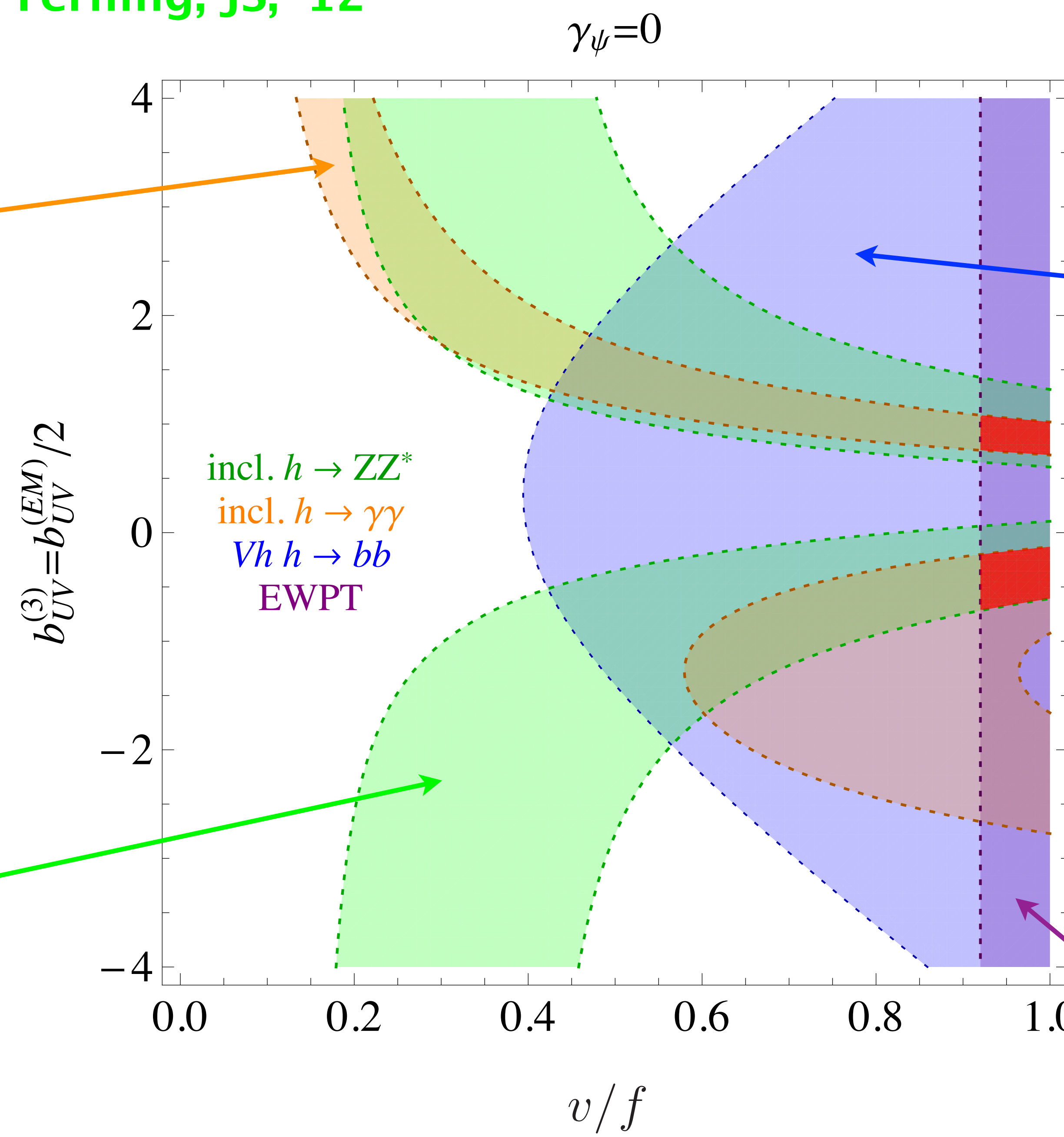
$$c_{\gamma\gamma,gg} = \frac{(g'^2, g_S^2)}{16\pi^2}\frac{v}{f}\boxed{\left(b_{IR}^{(EM,3)} - b_{UV}^{(EM,3)}\right)}$$

$$c_{Z\gamma} \sim \frac{g^2}{16\pi^2}\frac{v}{f}\boxed{\left(b_{IR}^{(2)} - b_{UV}^{(2)}\right)}$$

Contrasting with Higgs Data

Bellazzini, Csaki, Hubisz, Terning, JS, '12

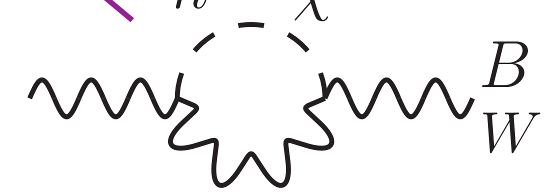
gluon fusion
to photons
$gg \rightarrow h \rightarrow \gamma\gamma$



vector boson fusion
to bottoms
$qq \rightarrow jjh \rightarrow jjb\bar{b}$

gluon fusion
to Z's
$gg \rightarrow h \rightarrow ZZ^*$

EWPT



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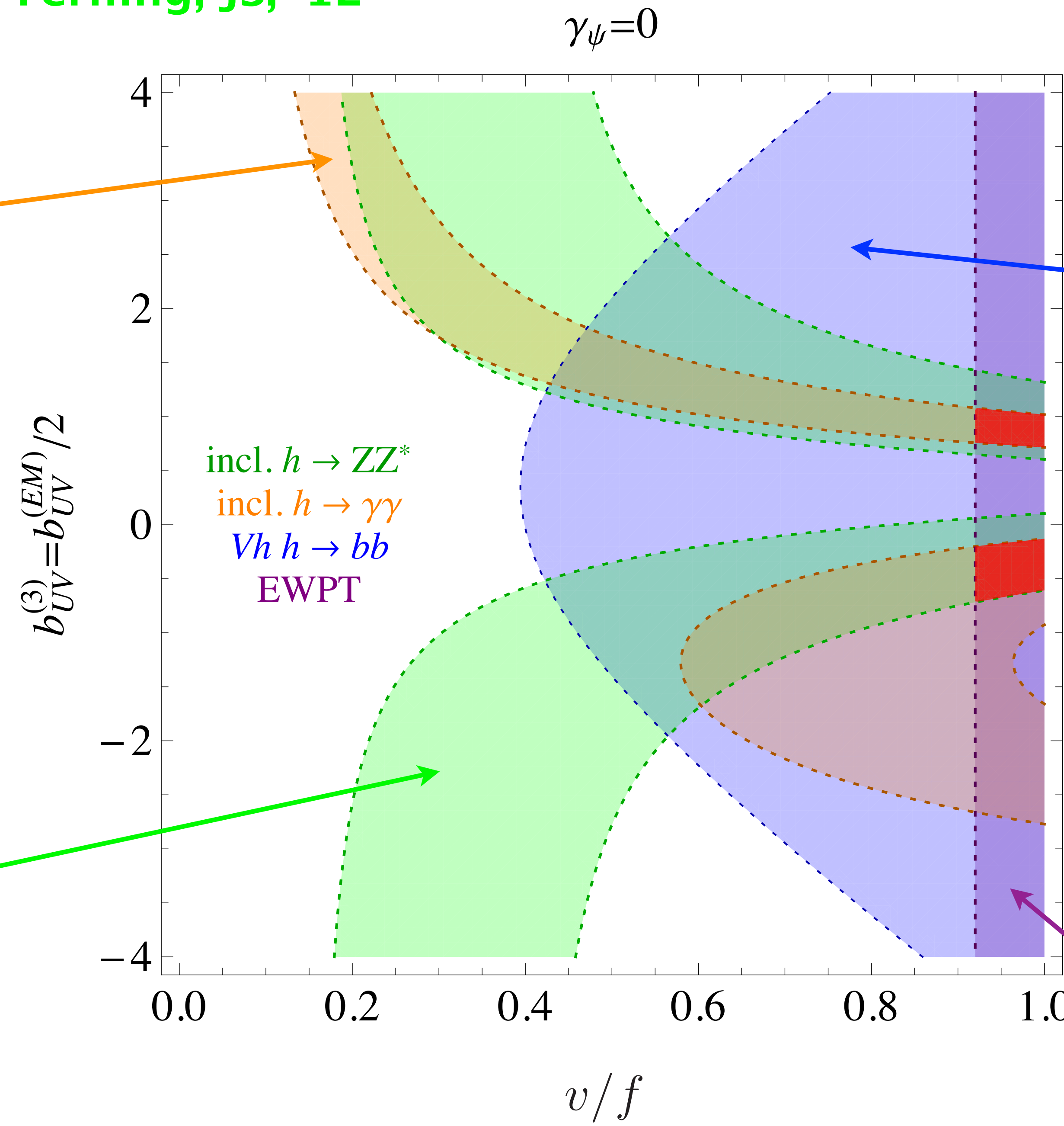
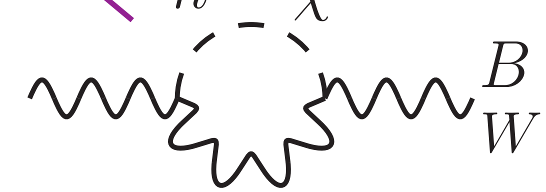


vector boson fusion
to bottoms
$$qq \to jjh \to jjb\bar{b}$$

gluon fusion
to Z's
$$gg \to h \to ZZ^*$$

EWPT
$$h = \chi$$



Consistency with data requires:

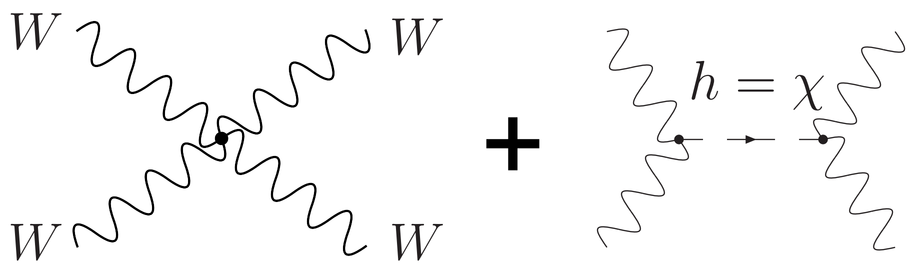
$$\frac{v}{f} \simeq 1$$

$$b^{(i)}, \gamma_f \lesssim O(1)$$ consistent with $m_\chi \ll 4\pi f$

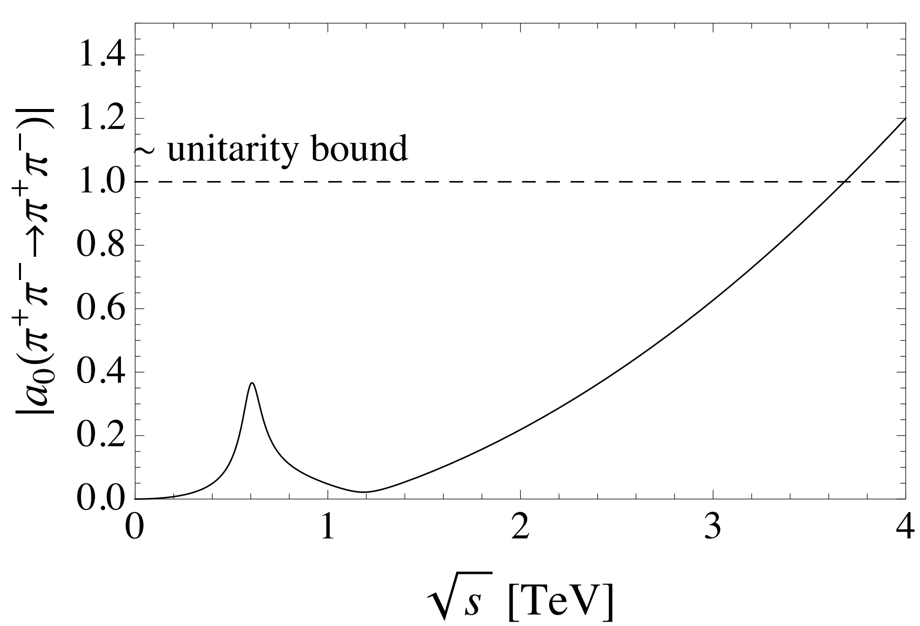
The genuine effect of compositeness is the growth of scattering amplitudes with energy

WW scattering

Partial unitarization only. There is a O(s) growth



$$\mathcal{A}(s) \simeq \frac{s}{v^2}(1 - c_V^2) = s\frac{1 - v^2/f^2}{v^2}$$



Customary parametrization of double (triple) Higgs couplings

$$\mathcal{L}^{h^2}_{(0)} = \frac{h^2}{v^2}\left[\frac{d_V}{2}\left(2m_W^2 W^\dagger_\mu W^\mu + m_Z^2 Z_\mu Z^\mu\right) - d_\psi m_\psi \bar{\psi}\psi\right]$$

$$\mathcal{L}^{h^2}_{(2)} = \frac{h^2}{v^2}\left[\frac{d_{gg}}{2} G^a_{\mu\nu} G^{\mu\nu a} + \cdots\right] \qquad \mathcal{L}^{h^3}_{(0)} = -c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3$$

Standard Model

$$d_V = c_3 = 1$$

$$d_\psi = d_{gg} = 0$$

Dilaton

$$d_V = \frac{v^2}{f^2}$$

$$d_\psi = \frac{1}{2}\frac{v^2}{f^2}\gamma_\psi$$

$$d_{gg} = -\frac{g_s^2}{32\pi^2}\frac{v^2}{f^2}\left(b^{(3)}_{IR} - b^{(3)}_{UV}\right)$$

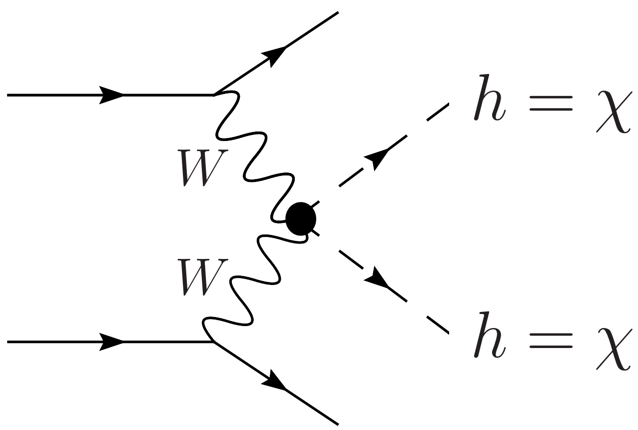
$$c_3 = \frac{1}{3}\frac{v}{f}\left(5 + \alpha\frac{m_\chi^2}{(4\pi f)^2}\right)$$

Implications: Double Dilaton Production

The genuine effect of compositeness is the growth of scattering amplitudes with energy, in particular W_L and h

WW to hh scattering

There is NO $O(s)$ growth, but $O(s^2)$!



$$\mathcal{A}(s) \simeq \frac{s}{v^2}(d_V - c_V^2) \simeq 0 + O(s^2/f^4)$$

$$\sqrt{d_V} = c_V = \frac{v}{f}$$

$$\frac{a_{2,4}}{(4\pi)^2}\frac{(\partial\chi)^4}{\chi^4}$$ in the dilaton "chiral" Lagrangian

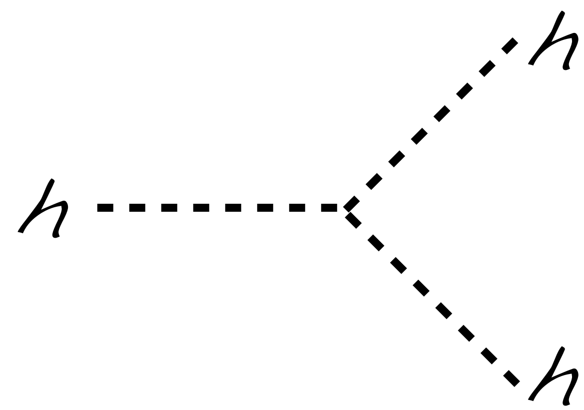
Differential feature w.r.t. composite Higgs:

dilaton is NOT part of SU(2) doublet

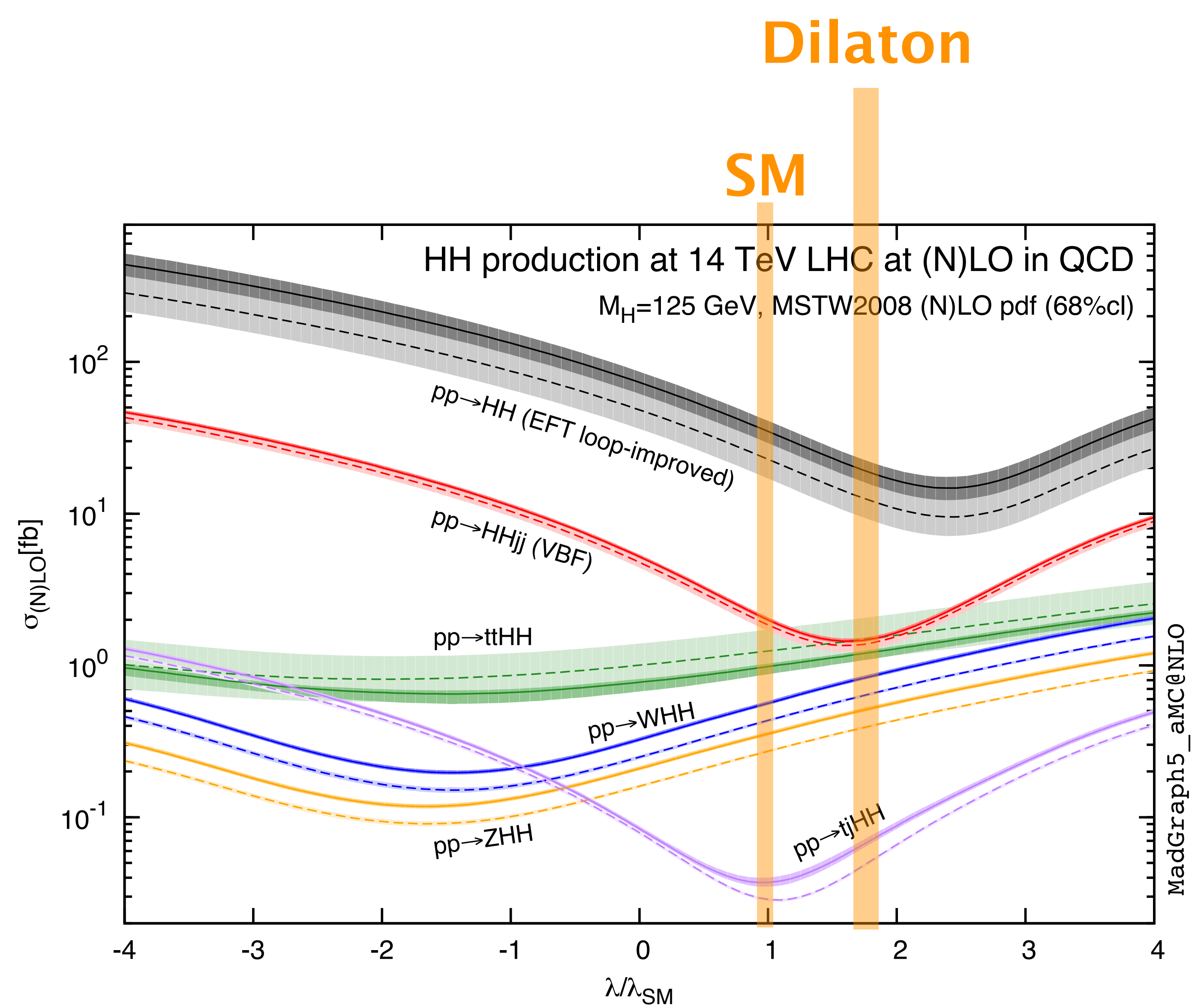
$$\mathcal{A}(WW \to WW) \neq \mathcal{A}(WW \to \chi\chi)$$
$$s \to \infty$$

Implications: Double Dilaton Production

There is one differential feature w.r.t the SM Higgs even if $v/f \sim 1$ and no anomalous dimensions!



$\sim 5/3 \times SM$



Frederix et al '14

Phenomenological Aplications 2) Cosmological Phase Transitions

There is one very important consequence of a
true spontaneous breaking of scale invariance

$$\Lambda_{eff} = V(\langle\chi\rangle) \sim \epsilon\langle\chi\rangle^4$$

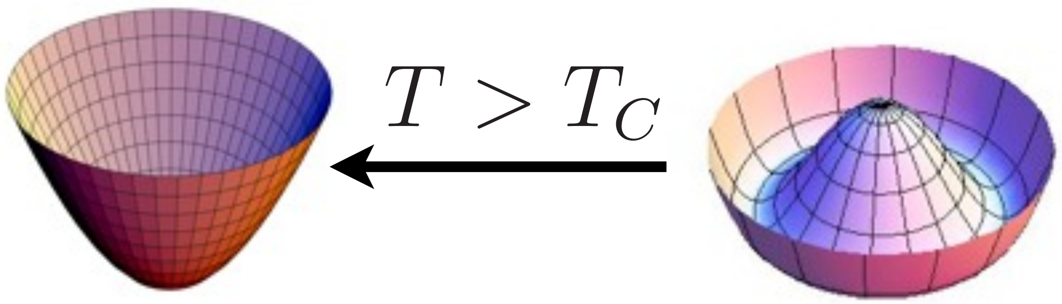
$$m_\chi^2 \sim \epsilon\langle\chi\rangle^2$$

Could this ocurr in any of the known phase transitions?

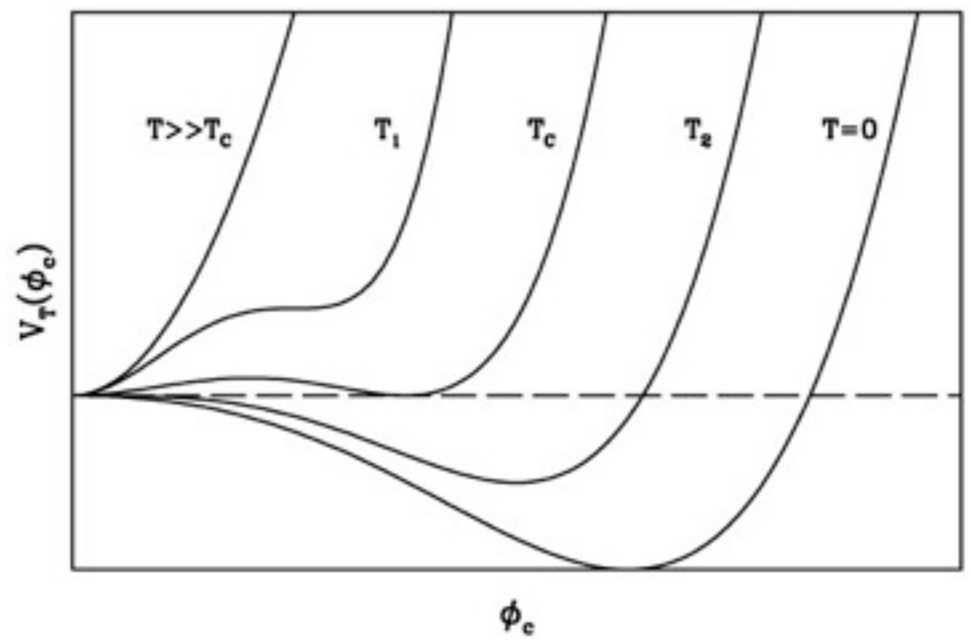
This is a very speculative idea, but the next question
per se is very interesting:

How can we learn anything about the
CC?

As the Universe expands, it cools off, and phase transitions take place (QCD, ElectroWeak,...)



Second order PT



Restoration of symmetry at high Temperature.

The energy densities change during PT's, and the Universe is sensitive to it.

Homogeneous & isotropic (flat) Universe

$$ds^2 = -dt^2 + a^2(t)dx_i^2$$

Einstein equations $G_{\mu\nu} = T_{\mu\nu}$

Assuming a perfect fluid:

$$T^{\mu}_{\ \nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & -p & 0 & 0 \\ 0 & 0 & -p & 0 \\ 0 & 0 & 0 & -p \end{pmatrix}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\rho$$

$$\frac{\ddot{a}}{a} = -\frac{1}{6}(\rho + 3p)$$

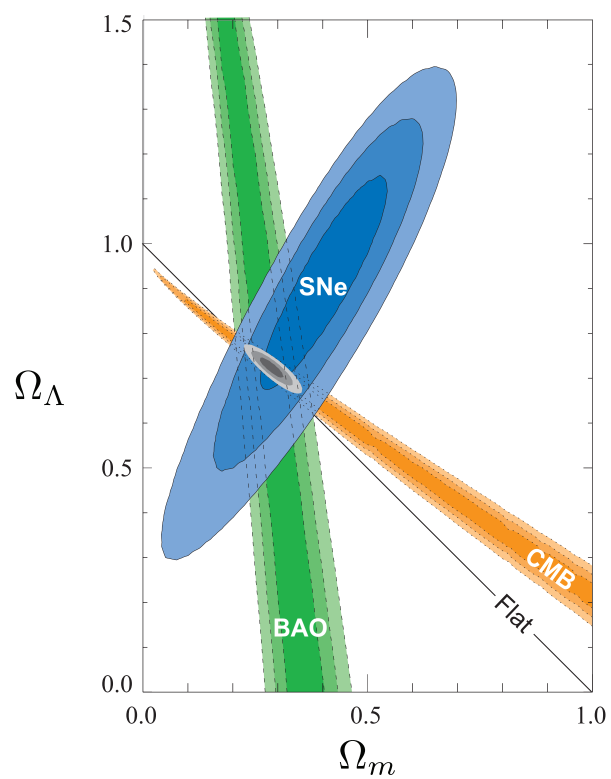
Radiation domination	Matter domination	CC domination
$\rho(a) \sim a^{-4}$	$\rho(a) \sim a^{-3}$	$\rho(a) \sim a^{0}$
$a(t) \sim t^{1/2}$	$a(t) \sim t^{2/3}$	$a(t) \sim e^{Ht}$

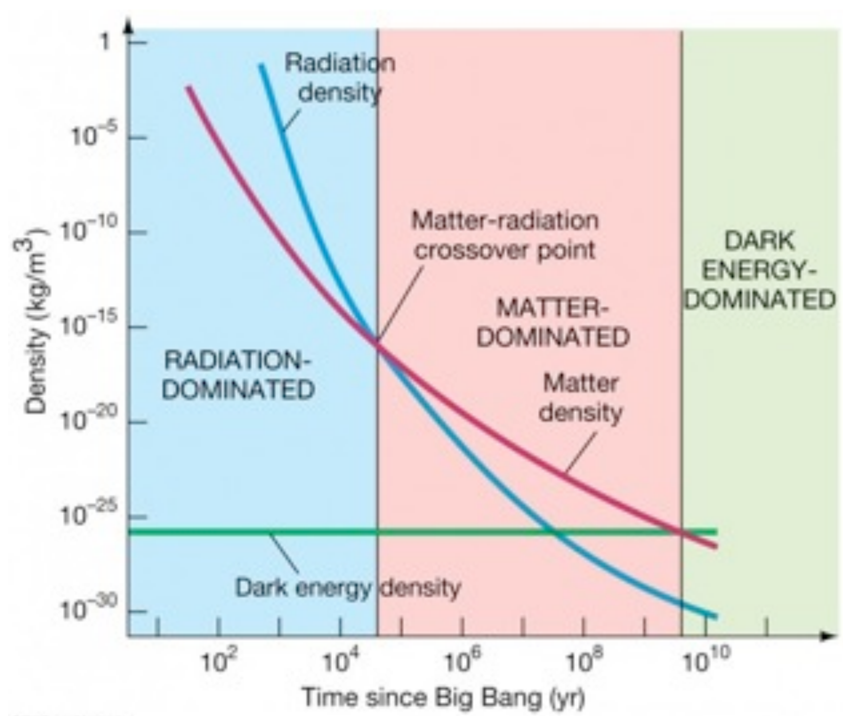
Homogeneous & isotropic (flat) Universe

$$ds^2 = -dt^2 + a^2(t)dx_i^2$$

Einstein equations $G_{\mu\nu} = T_{\mu\nu}$

By measuring energy densities today,
we obtain a beautiful picture for the hot early Universe





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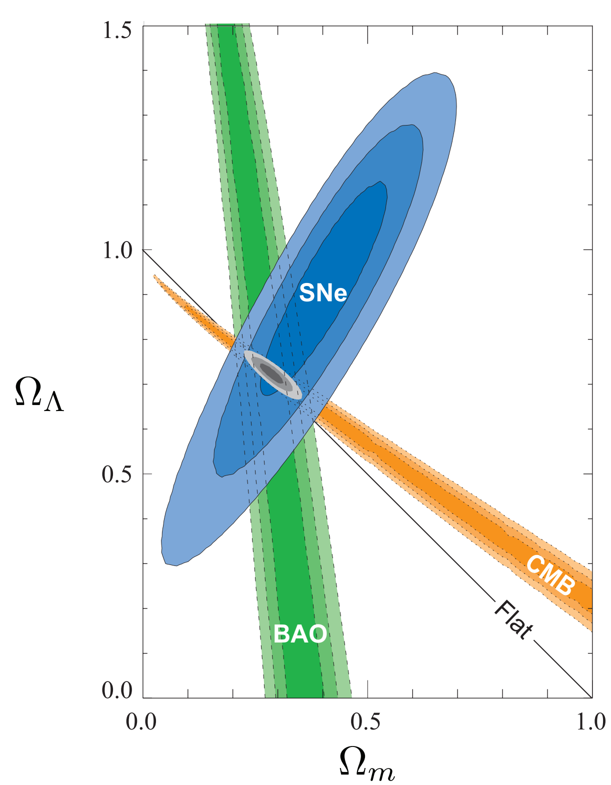
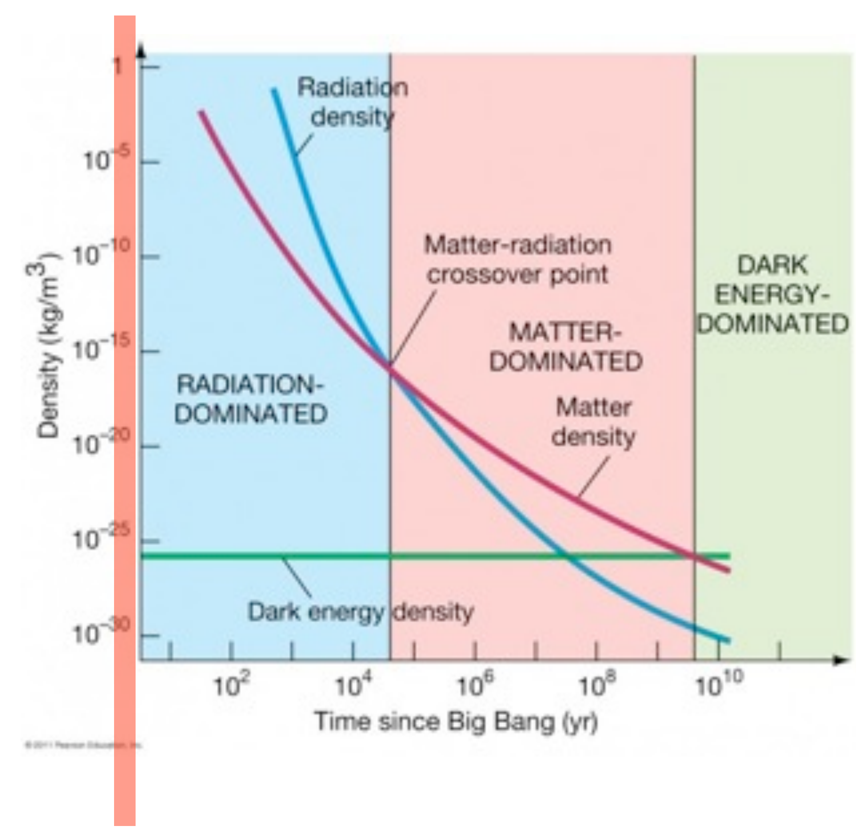
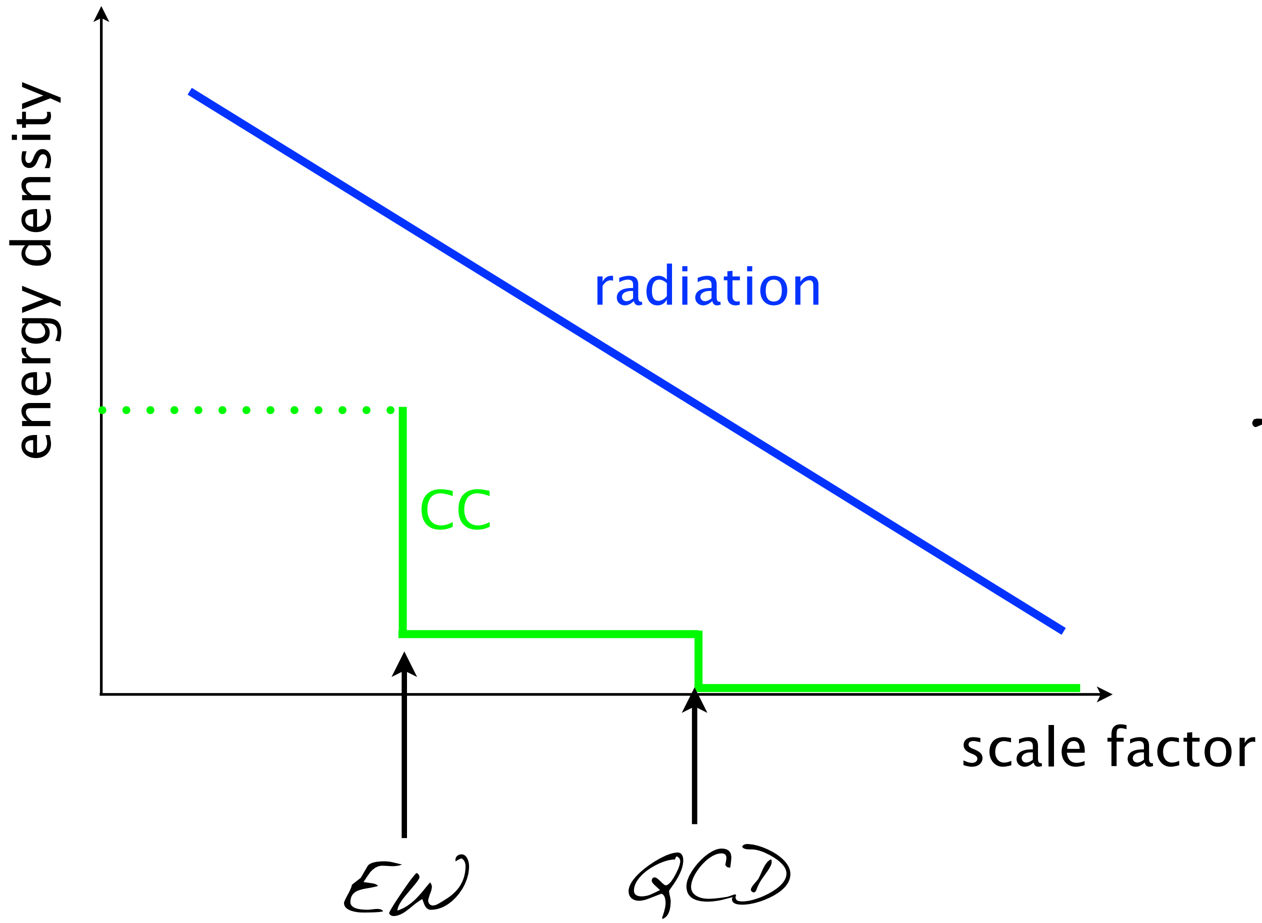




But we are interested in what happens outside here!

Actually, what happens in the very early Universe is similar to this:



The CC jumps at each phase transition!

To end up at the very small value we observe today

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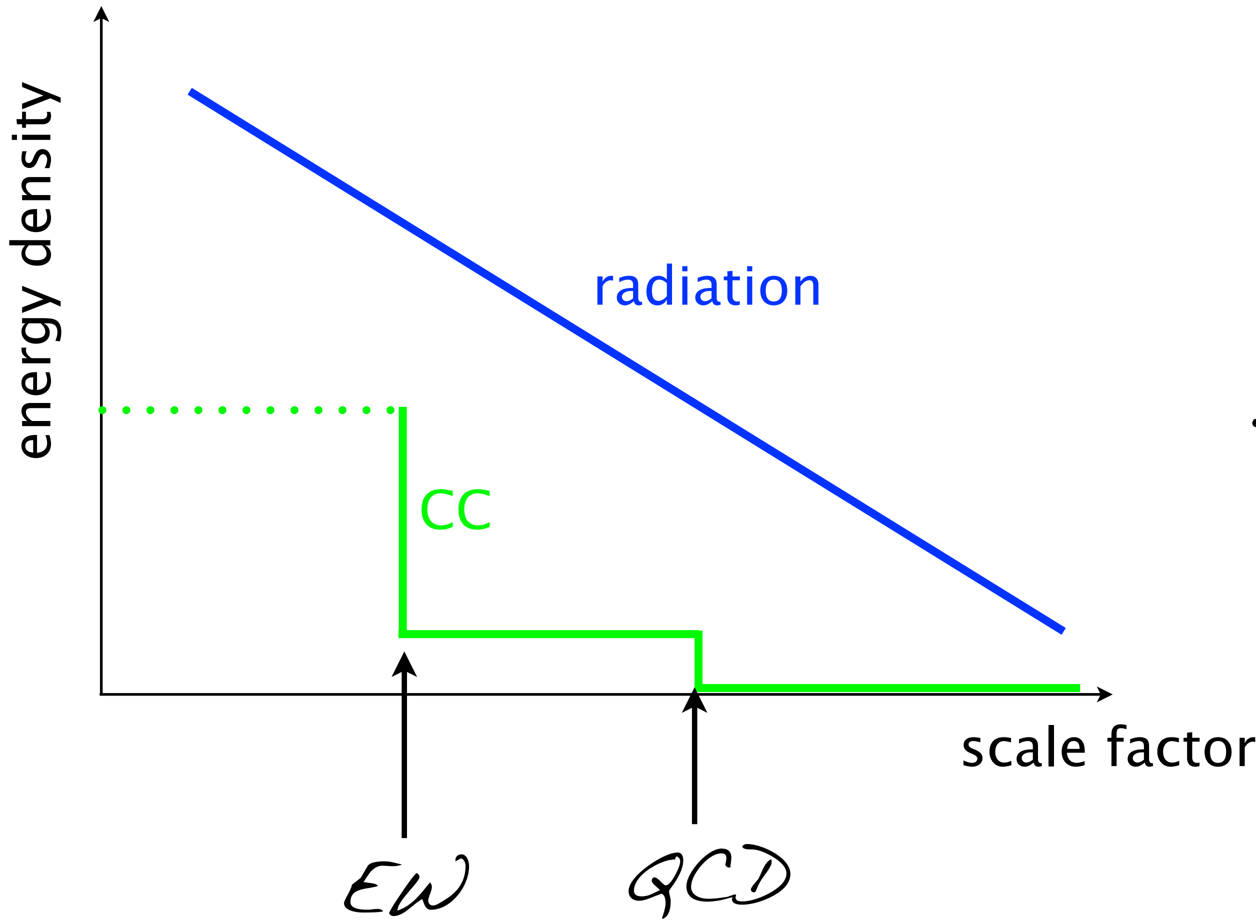


The CC jumps at each phase transition!

To end up at the very small value we observe today

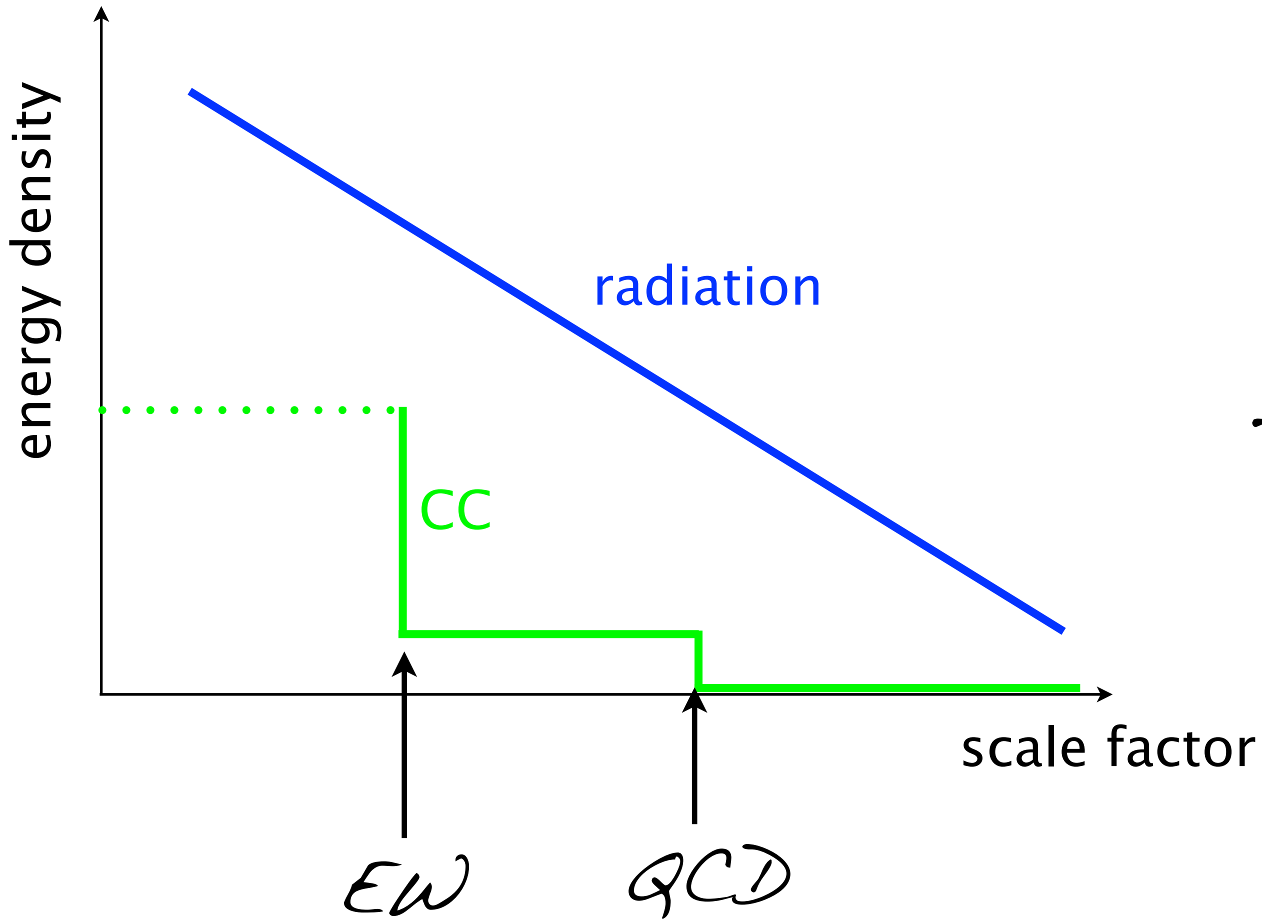
$$V(\phi) = V_0 - m^2\phi^2 + \lambda\phi^4$$

$$T_{PT} \sim -\langle\phi\rangle \sim \frac{m}{\sqrt{g}} \quad \text{and} \quad V(\langle\phi\rangle) \sim 0 \Rightarrow V_0 \sim \frac{m^4}{g}$$

At the PT, radiation and CC are closest

$$\rho_{cc} \sim V_0 \lesssim \rho_{radiation} \sim T_{PT}^4 \sim \frac{m^4}{g^2}$$

Actually, what happens in the very early Universe is similar to this:



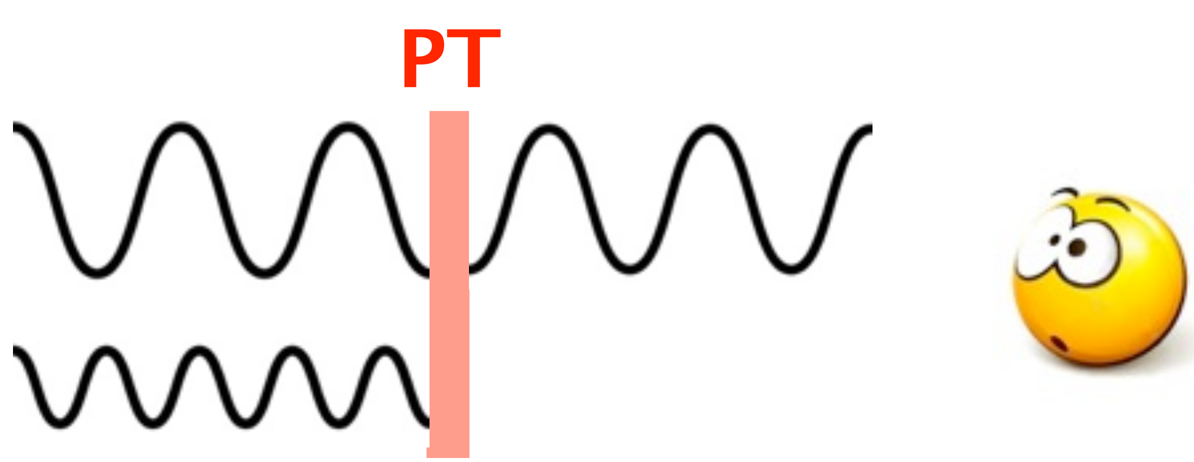
The CC jumps at each phase transition!

To end up at the very small value we observe today

$V(\langle\phi\rangle) \sim V_0 \sim 0$

How could we tell if there has been a jump or NOT?

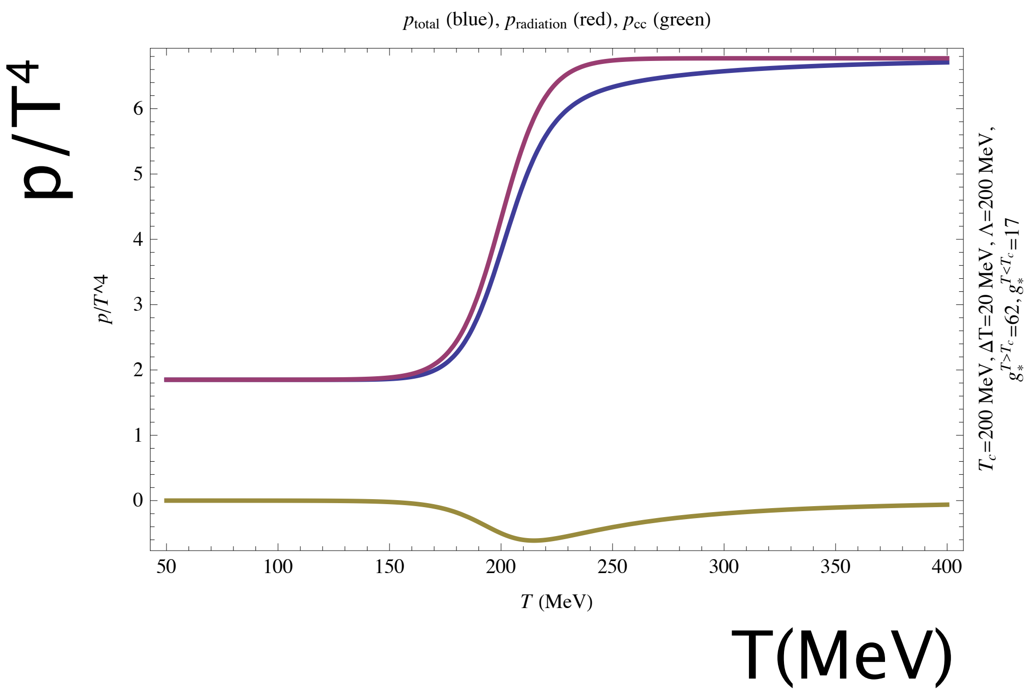
Certainly gravitational waves will be affected and will reach us later



The Free energy is continuous (decreasing) & $\mathcal{F} = p$

Pressure ansatz:

Matches well lattice simulations



The number of degrees of freedom changes

The CC disappears

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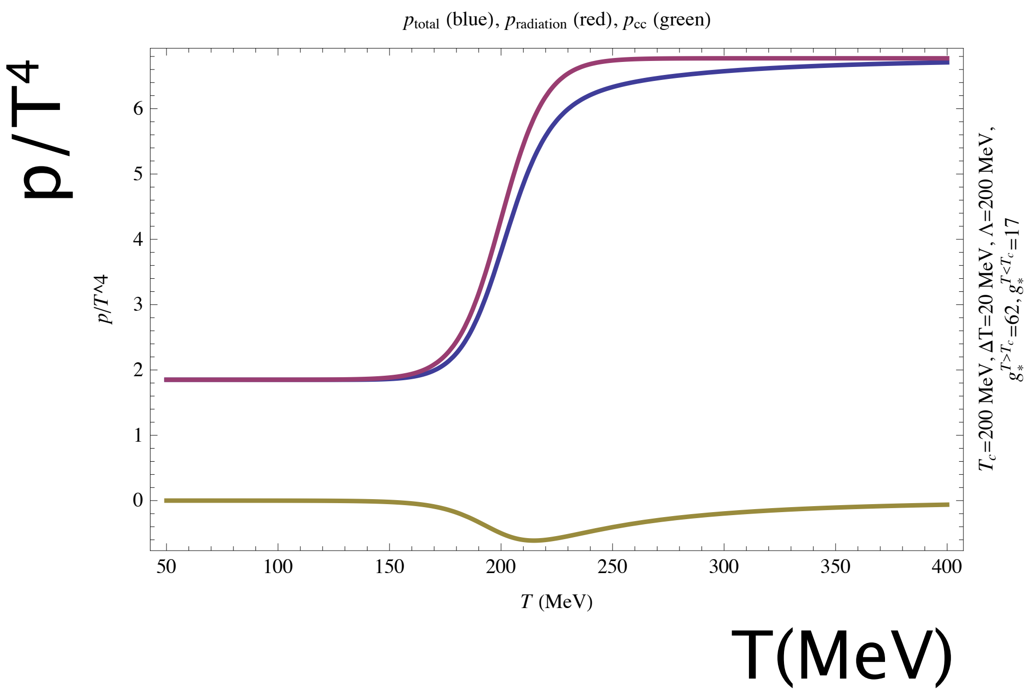
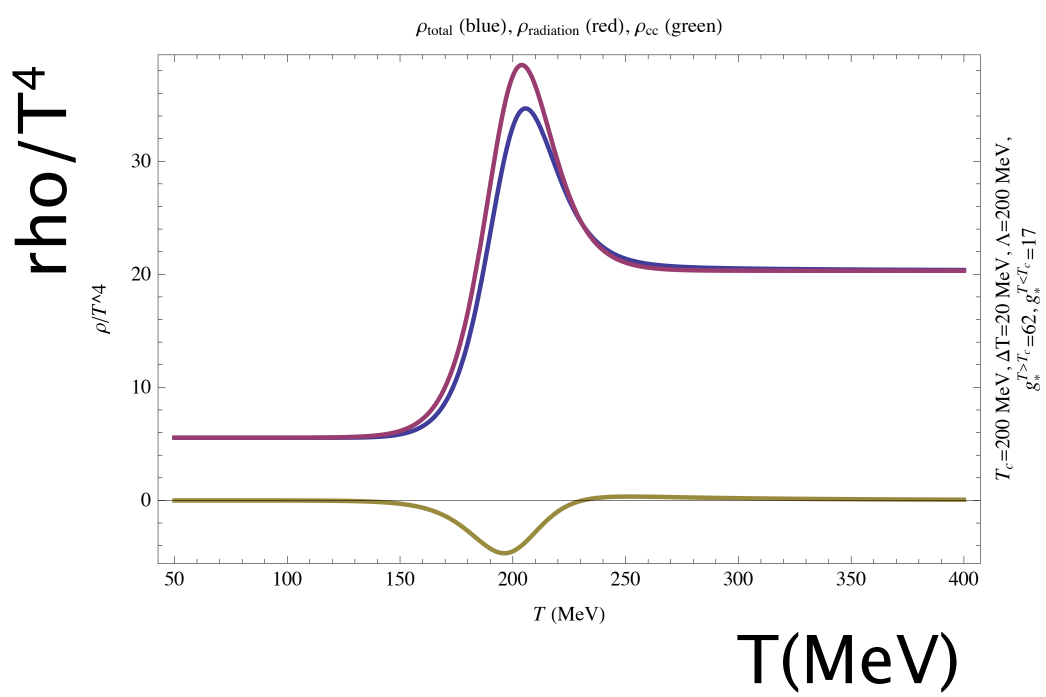


The number of degrees of freedom changes

The CC disappears

Entropy is conserved: $$\frac{dp}{dT} = \frac{p+\rho}{T}$$

Energy density:



We wish to compute the power spectrum

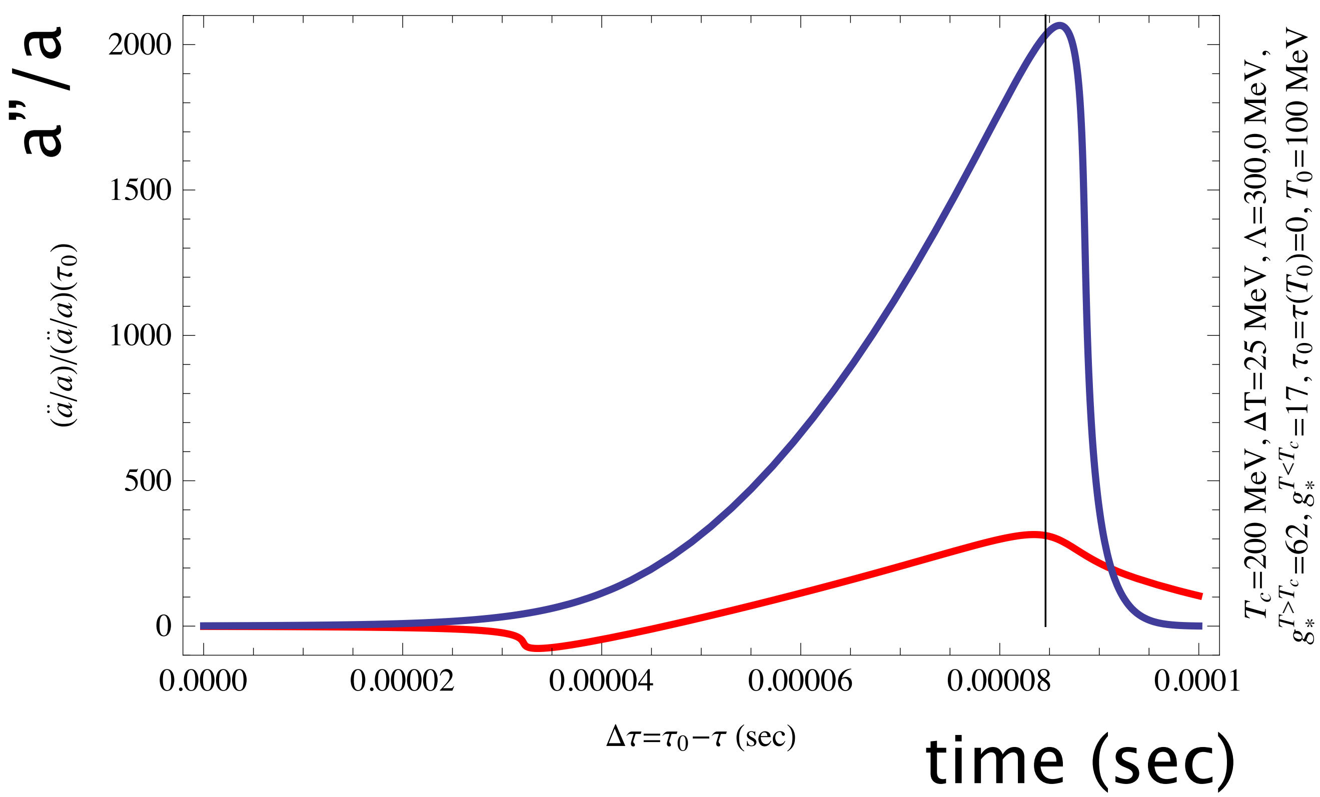
$$\Delta_t^2(\tau, k) = \frac{2k^3}{2\pi^2} \langle |h_k(\tau)|^2 \rangle$$

Wave equation

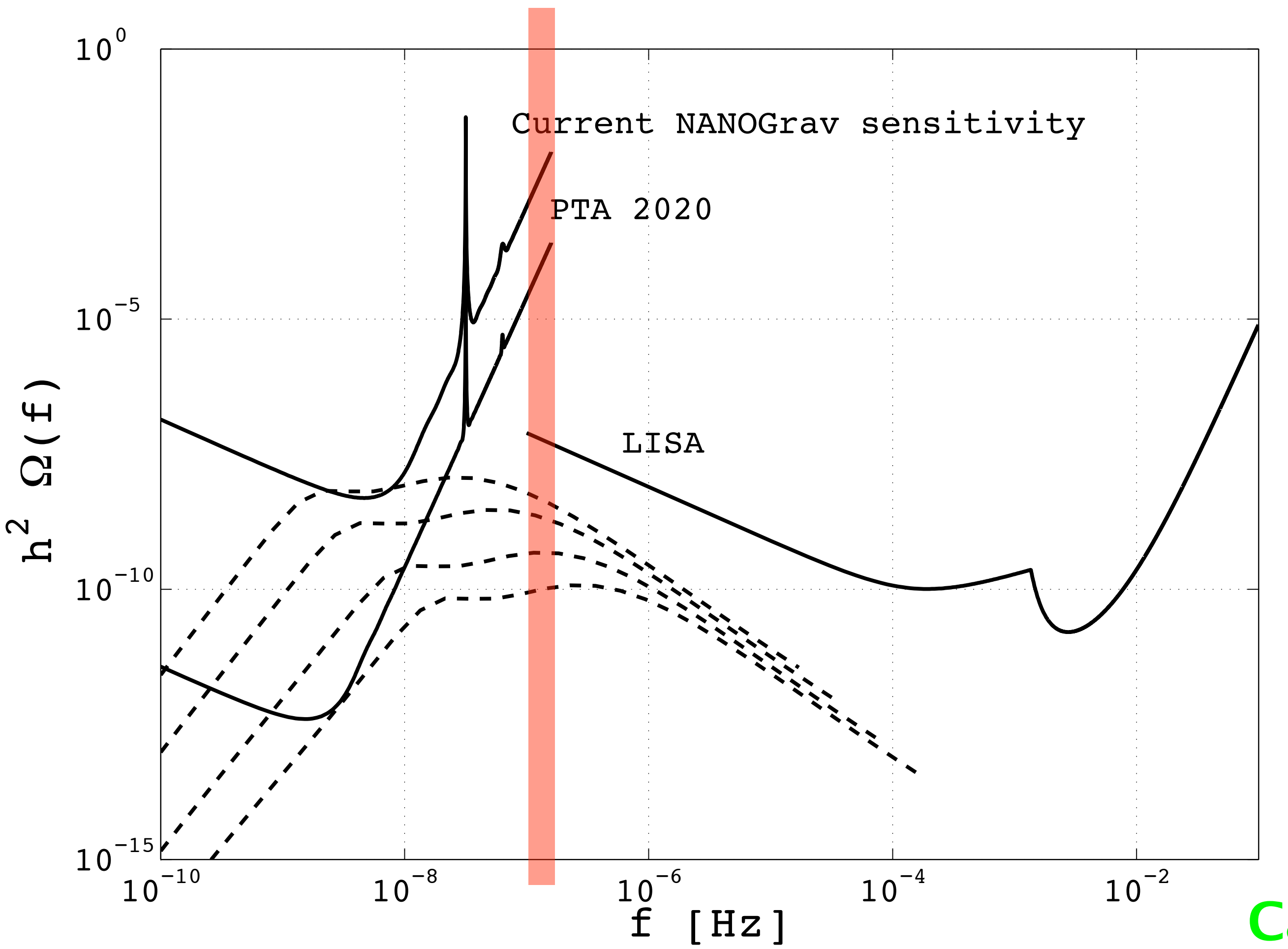
$$(ah_k)'' + \left(k^2 - \frac{a''}{a}\right)(ah_k) = 0$$

de Sitter space

$$a''/a = 2/\tau^2$$



Unfortunately, for the QCD phase transition, experiments are not very sensitive



Caprini et al ’10

But who knows in the future?! Or other PT’s?!

Approximate spontaneous breaking of scale invariance offers a NATURAL way to obtain a light scalar

and to suppress the Cosmological Constant

Is this possibility realized in Nature?

A Higgs-like Dilaton
Dilaton in Phase Transitions
QCD?
...

We just have to wait and see

Thank you for your attention