# Walking Technicolor and Techni-Dilaton

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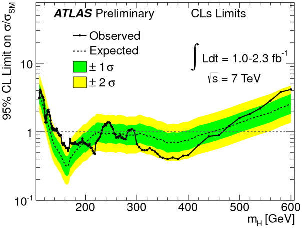
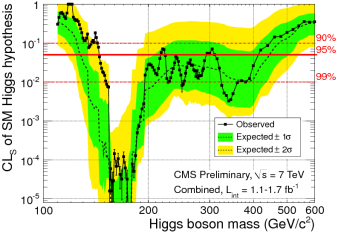
Based on arXiv:1101.5326 and arXiv:1112.xxxx
with K. Y. Choi and S. Matsuzaki

# Introduction

- Higgs holds a key to BSM, since it is sensitive to short distance phyics.
- But, we have not found Higgs yet. Current mass bound is

$$114 \text{ GeV} \lesssim m_H \lesssim 145 \text{ GeV}$$



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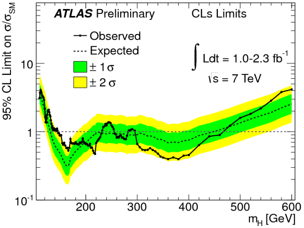


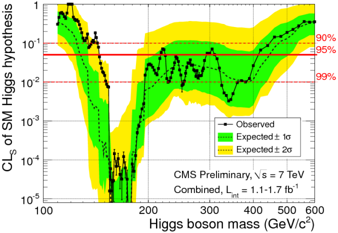

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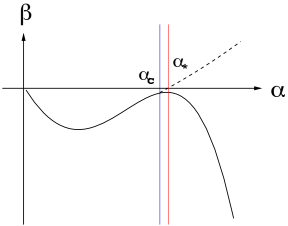
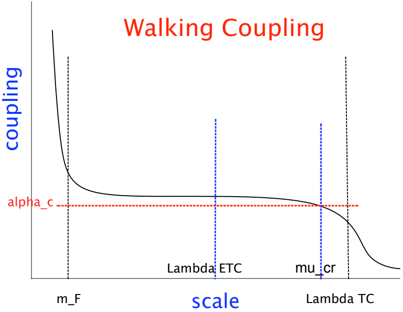
- Modern TC is called "Walking Technicolor" (Holdom '81, Yamawaki et al '86, Appelquist et al '86)



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- As a candidate for physics BSM, it will be nice if TC explains dark matter as well.
- Indeed, I will show that WTC can have a very light dilaton, techni-dilaton as a Nambu-Goldstone boson, associated with spontaneously broken (approximate) scale symmetry, which can be a good candidate for DM. (Cf. Techni-baryons)

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# Review of WTC

- Introduce new strong dynamics in addition to SM

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times G_{\mathrm{TC}}$$

- Introduce new particles, techniquarks, which transform as

$$Q_L^{\mathrm{TC}} \sim (*, 2, y_L, r),\ U_R^{\mathrm{TC}} \sim (*, 1, y_R, r),\ D_R^{\mathrm{TC}} \sim (*, 1, y_R', r)$$

- such that theory is anomaly-free, (asymptotically free) and has a (quasi) IR fixed point.
- Lattice simulation shows the conformal window exists when $8 < N_F < 12$ for $N_{TC} = 3$ for $SU(3)$ (AFN '09)

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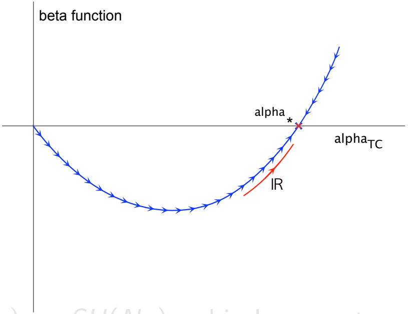


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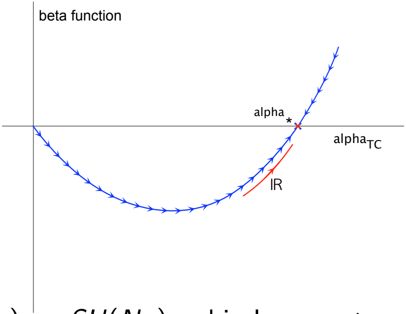


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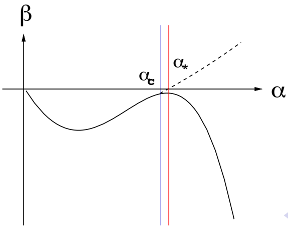
- Once techni-fermions get dynamical mass, they decouple for $E < m_F$ and coupling runs quickly and confines technicolor.



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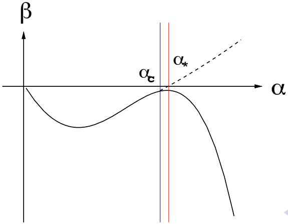

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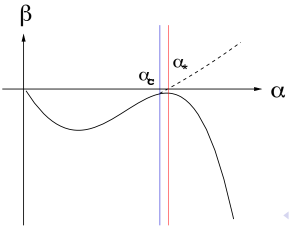

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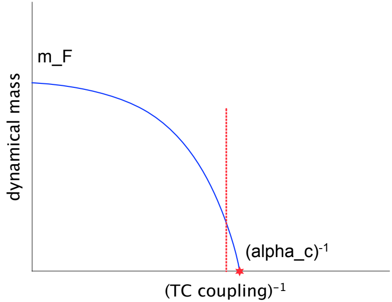


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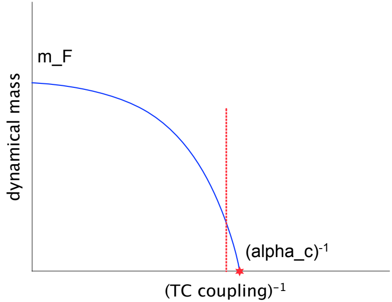


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# Very light techni-dilaton

- Physics of Miransky scaling: In the walking region we have approximate scale invariance and ladder approximation is good. The BS equation for the bound state then becomes

$$\left[P^2 + \partial^2 + \frac{\alpha/\alpha_c}{r^2}\right]\chi_P(x) = 0.$$

- Since the potential is singular, we need to regularize it:

$$V(r) = \begin{cases} -\frac{\alpha/\alpha_c}{r^2} & \text{if } r \geq a, \\ -\frac{\alpha/\alpha_c}{a^2} & \text{if } r \leq a. \end{cases}$$

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- For bound states to be the cutoff-independent, we require the coupling to depend on the cutoff. (DKH+Rajeev '90)

$$\alpha(a) = \alpha_c + \alpha_c \frac{\pi^2}{[\ln(a\mu)]^2} \, .$$

- The non-perturbative beta function is then

$$\beta^{\rm np}(\alpha) = a\frac{\partial}{\partial a}\alpha(a) = -\frac{1}{\pi}(\alpha - \alpha_c)^{3/2}$$

- The gap equation has a nontrivial solution with this beta function for $\alpha \geq \alpha_c$. (Bardeen et al '86):

$$m_F \simeq \Lambda(\alpha_0) \exp\left[\int_{\alpha_0}^{\alpha} \frac{d\alpha}{\beta^{\rm np}(\alpha)}\right] = \Lambda_{TC}\, e^{-\frac{\pi}{\sqrt{\alpha/\alpha_c - 1}}} \, .$$

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- In the walking region $\gamma_{\bar{Q}Q} \simeq 1$ new marginal operator emerges and therefore generates a new scale, $m_F \ll \Lambda_{TC}$:

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- If $\alpha_* \approx \alpha_c$, theory exhibits walking behavior and is almost scale-invariant.
- Dilation current, $D^\mu = x_\nu \theta^{\mu\nu}$, is conserved up to scale-anomaly:

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- At some scale $\mu_{cr} \ll \Lambda_{TC}$, the coupling walks to cross the critical coupling $\alpha(\mu_{cr}) = \alpha_c$ and the theory undergoes a chiral phase transition:

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$$\langle \partial_\mu D^\mu \rangle = F_{TD} m_{TD}^2 \langle \sigma \rangle = F_{TD}^2 m_{TD}^2 \,. \tag{2}$$

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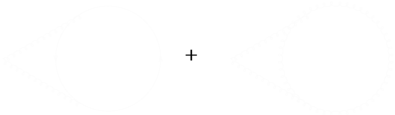

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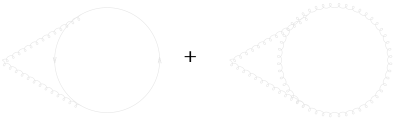

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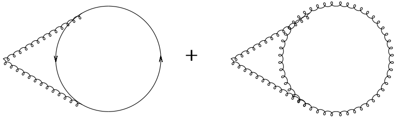

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$$F_{TD}^2 m_{TD}^2 \approx \frac{16 N_{TC} N_F}{\pi^4} m_F^4 \,.$$

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$$\frac{m_F}{F_{TD}} \to 0 \,.$$

- Since $\left(\frac{m_{TD}}{m_F}\right)^2 \sim \left(\frac{m_F}{F_{TD}}\right)^2$, TD is very light and decoupled:

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- Composite Higgs and Light TD ($v = 247 \text{ GeV}/\sqrt{N_F}$):

$$\lim_{y \to x} Q_{TC}(x)\bar{Q}_{TC}(y) = (\mu\,|x-y|)^{\gamma_{\bar{Q}Q}}\, Q_{TC}\bar{Q}_{TC}(x)$$

$$Q_{TC}\bar{Q}_{TC}(x) \sim e^{i\pi_{TC}/F_{TC}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} .$$

- Higgs mass is finite near the conformal phase transition (cf. D. Kutasov)

$$\frac{m_H}{m_V} \approx 0.2 \quad (m_V \sim m_F)$$

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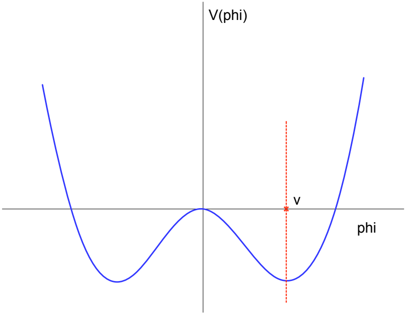


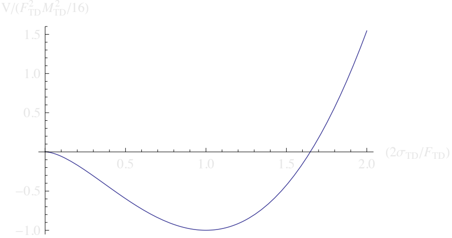

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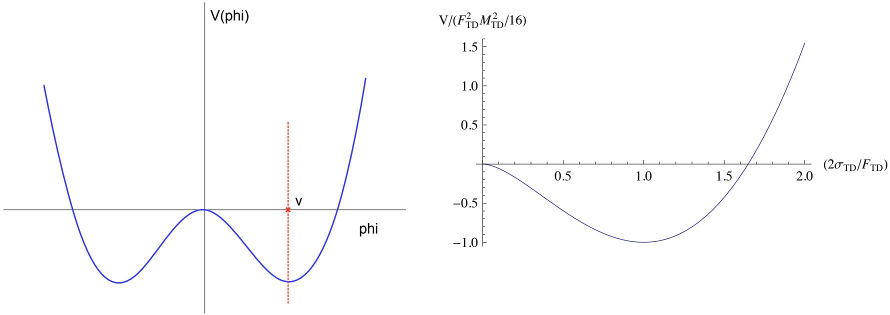

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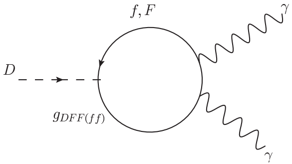


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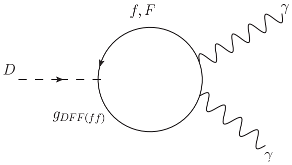


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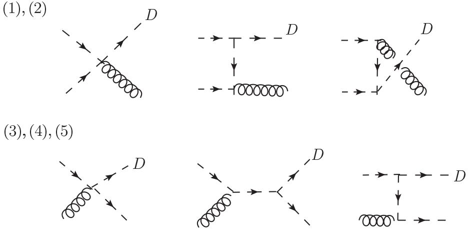
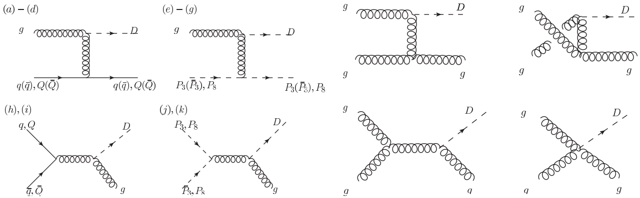
- Thermal production of TD




(l)



# Dark matter TD

- The Boltzmann equation for the TD number density $n_{\mathrm{TD}}$

$$\frac{dn_{\mathrm{TD}}}{dt} + 3Hn_{\mathrm{TD}} = \sum_{i,j} \langle \sigma(i+j \to D + \cdots)v \rangle n_i n_j$$

where $H$ is the Hubble parameter $H(T) = (\frac{\pi^2}{30} g_* T^4 / 3M_P^2)^{1/2}$.

$$\Omega^{\mathrm{tp}}_{\mathrm{TD}} h^2 \simeq \left(\frac{\mu_{\mathrm{cr}}}{10^8 \mathrm{GeV}}\right) \left(\frac{M_{\mathrm{TD}}}{\mathrm{keV}}\right) \left(\frac{200}{g_*(\mu_{\mathrm{cr}})}\right)^{3/2} \left(\frac{10^{11}\mathrm{GeV}}{F_{\mathrm{TD}}}\right)^2 \times \begin{cases} 4.4 \times 10^{-1} & \mathrm{for} \quad N_{\mathrm{TC}} = 2 \\ 2.6 \times 10^{-2} & \mathrm{for} \quad N_{\mathrm{TC}} = 3 \end{cases},$$

# Dark matter TD

Contour plot of $\Omega_{TD}^{tp} h^2$ for $\mu_{cr} = 10^{-3} F_{TD}$.

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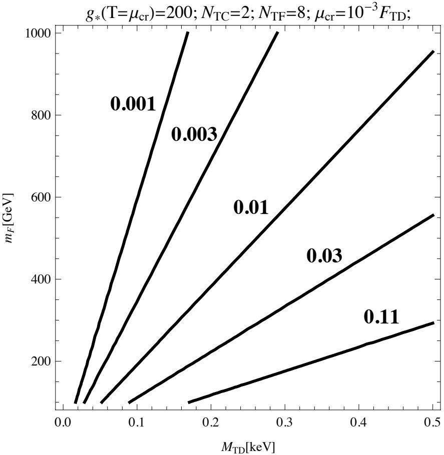
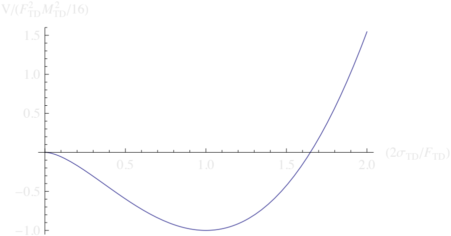


# Dark matter TD

- Non-thermal production of TD due to mis-alignment. TD potential is determined by scale anomaly (Schechter '80):

$$\frac{V(\sigma_D)}{F_{\rm TD}^2 m_{\rm TD}^2} \simeq \left(\frac{\sigma_D}{2F_{\rm TD}}\right)^2 \left[\log\left(\frac{2\sigma_D}{F_{\rm TD}}\right)^2 - 1\right]$$




$$\Omega_{\rm TD}^{\rm ntp} h^2 \simeq 11 \times \left(\frac{\theta_{\rm os}}{0.1}\right)^2 \left(\frac{200}{g_*(T_{\rm os})}\right) \left(\frac{m_F}{10^3{\rm GeV}}\right)^4 \left(\frac{10^5{\rm GeV}}{T_{\rm os}}\right)^3$$

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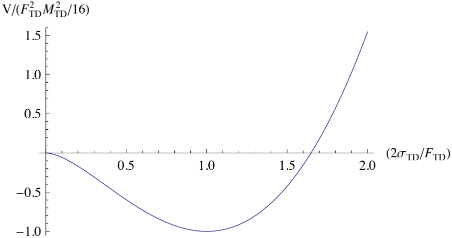


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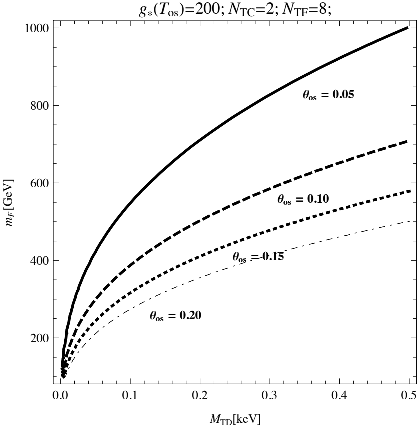

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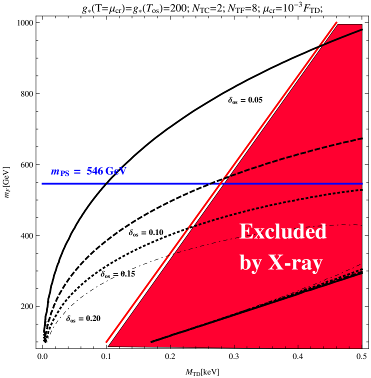


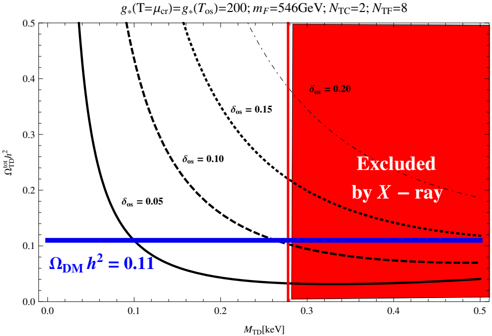

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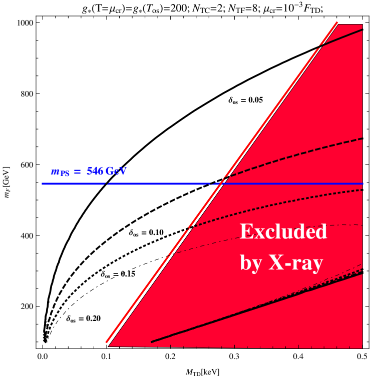


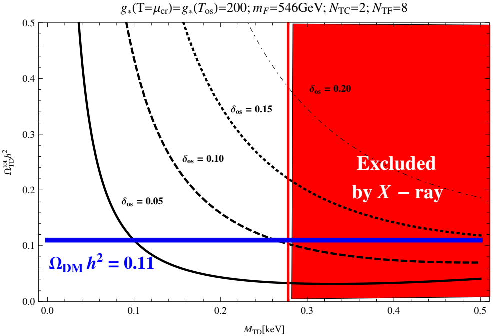

# Conclusion

- WTC predicts very light technidilaton (TD) due to spontaneously broken (approximate) scale symmetry.
- If the critical coupling for chiral symmetry breaking is very close to the (quasi) Banks-Zaks IR fixed point of WTC, large hierarchy is dynamically generated:

$$m_F \approx \Lambda_{TC}\, e^{-\frac{\pi}{\sqrt{\alpha/\alpha_c - 1}}}\,.$$

- By PCDC we have $m_{TD} \ll m_F \ll F_{TD}$ .
- TD can be a good candidate for dark matter.
- Cosmological and astrophysical constraints require

$$0.01\ \mathrm{eV} \lesssim m_{TD} \lesssim 500\ \mathrm{eV}$$

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