New ideas in Model Building

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Epicycles over epicycles

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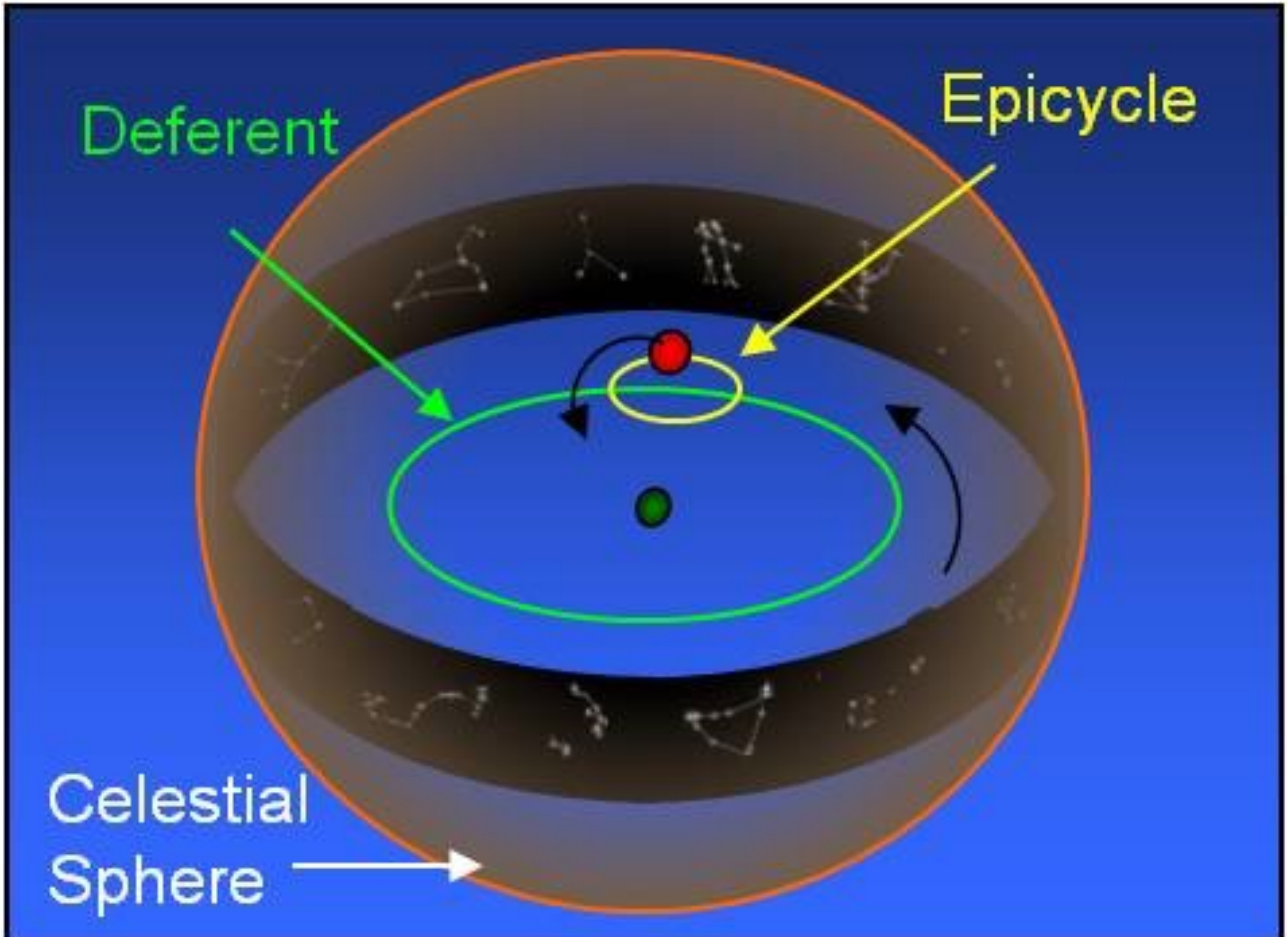

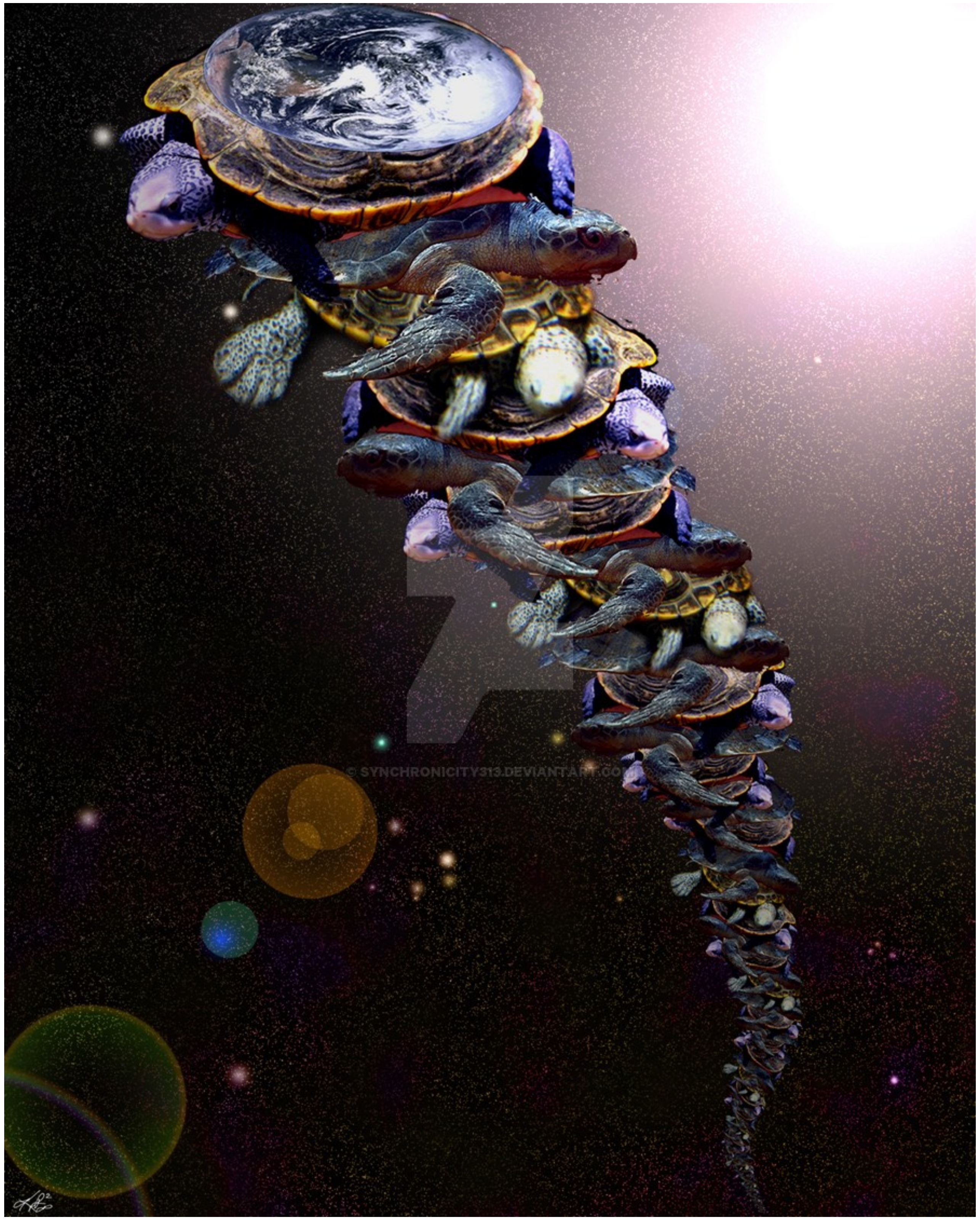

Turtles over turtles

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    - Naturalness

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  - Naturalness
  - DM

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    - Naturalness

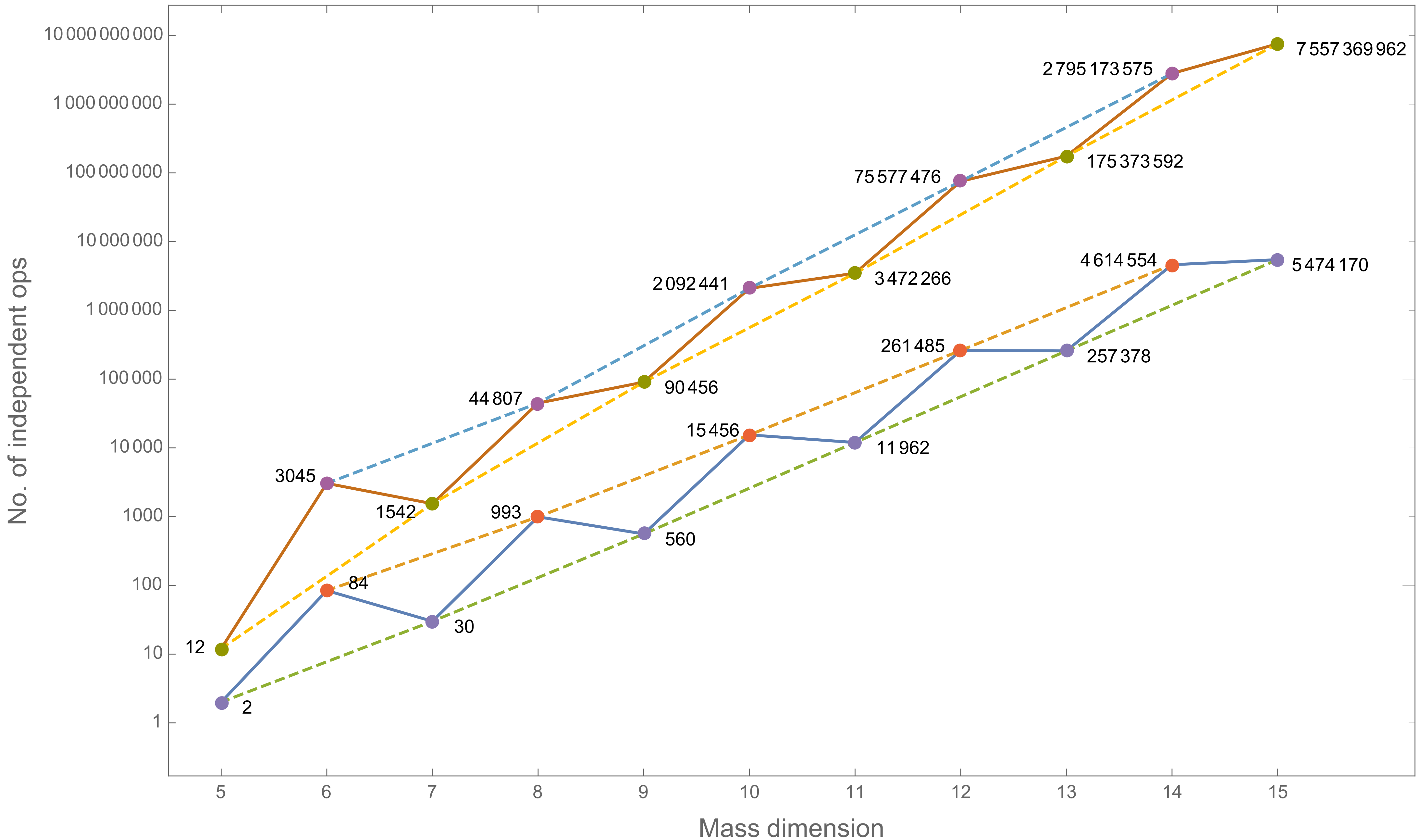
    - DM

    - Flavour?

- Since the discovery of the Higgs in 2012 there has been lots of attention and work on the SMEFT

- It allows to include Dim 5,6,7,8,…. operators to the renormalizable lagrangian of the SM without any prejudice on the possible new physics that causes those deviations from the SM prediction.

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_{k=5}^{\infty} \Sigma_{i=1}^{n} \frac{\mathcal{C}_i^k}{\Lambda^{k-4}} O_i^k$$



Number of operators in the SMEFT as a function of the dimension

(Henning, Lu, Melia, Murayama)

Also: Lehman, Martin

- Dim 5 is just the Weinberg operator.
- All odd dimensions violate L or B
- Dim 6 was first studied by Buchmüller and Wyler in 1986 and then completed by Grzadkowski et al. in 2010.

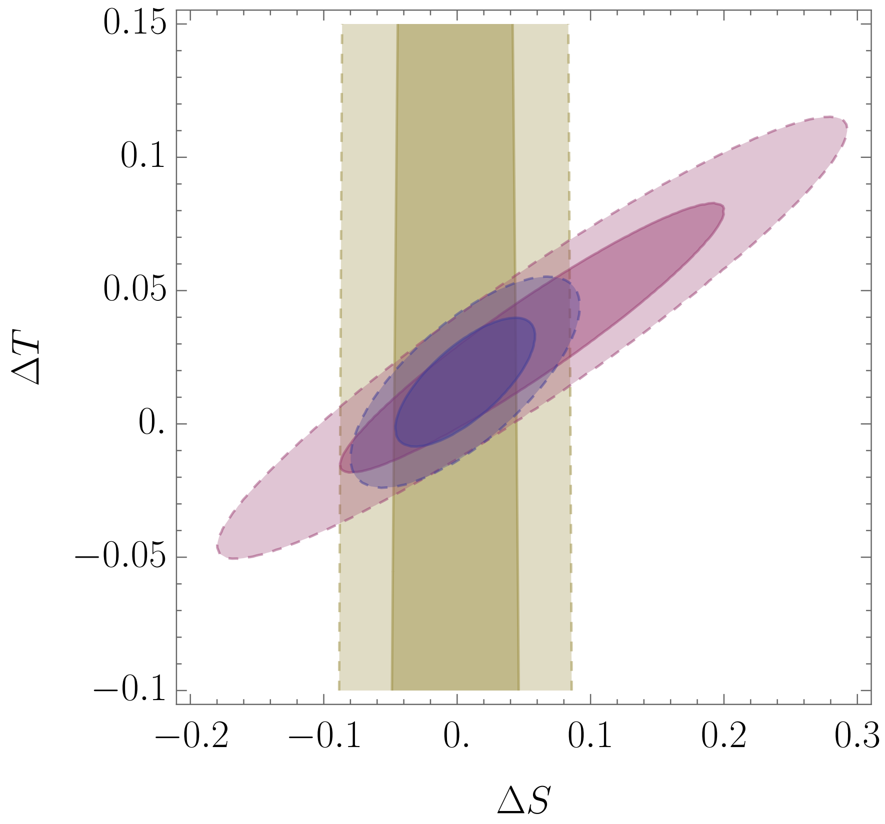
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Dim 6 operators with bosons

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

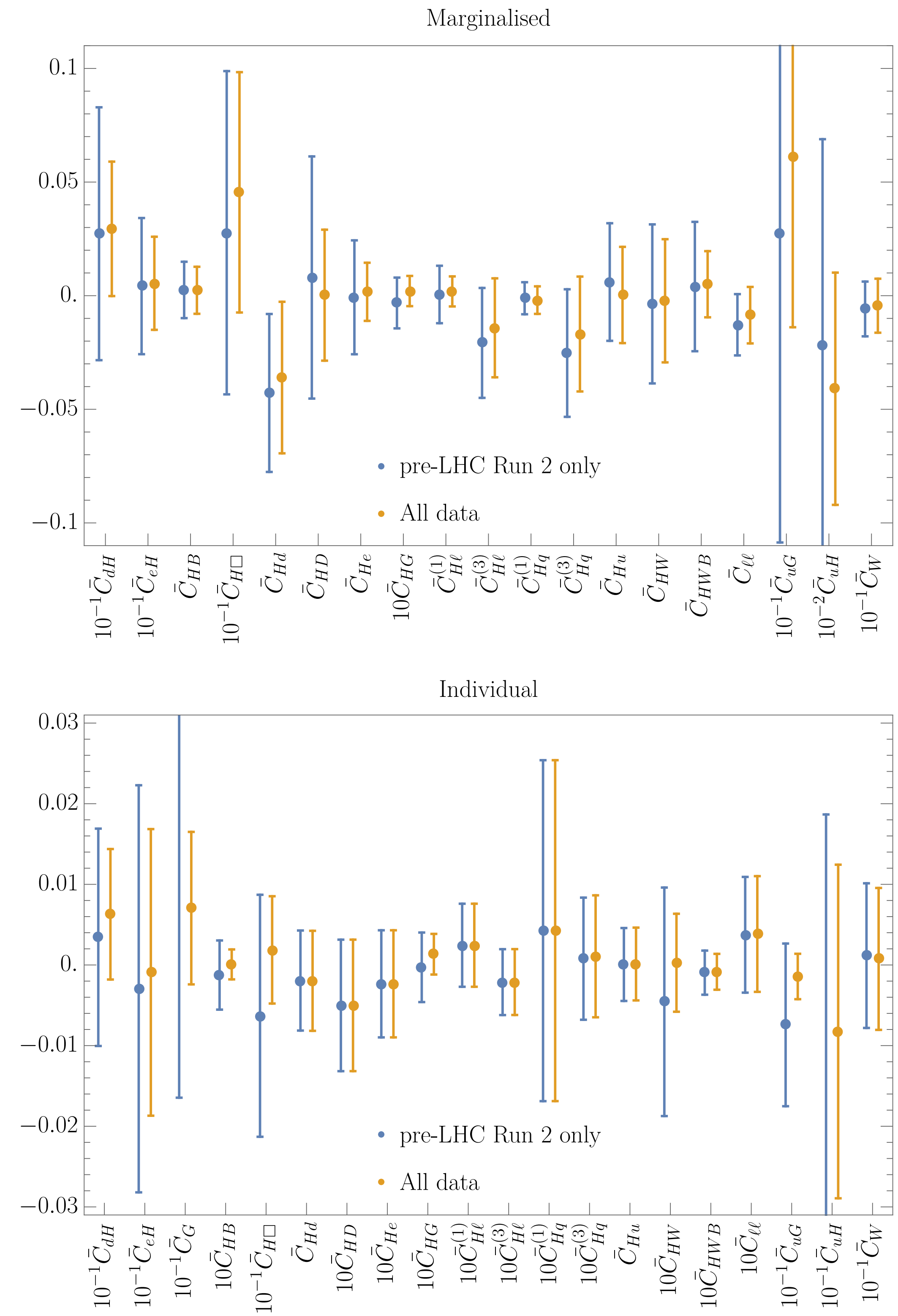
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

4-fermion operators



S and T

Warsaw base coeff. after LHC Run 2



Ellis, Murphy, Sanz & You

- There are equivalent parametrizations, i.e. SILH, and similar bounds and fits can and have been done.

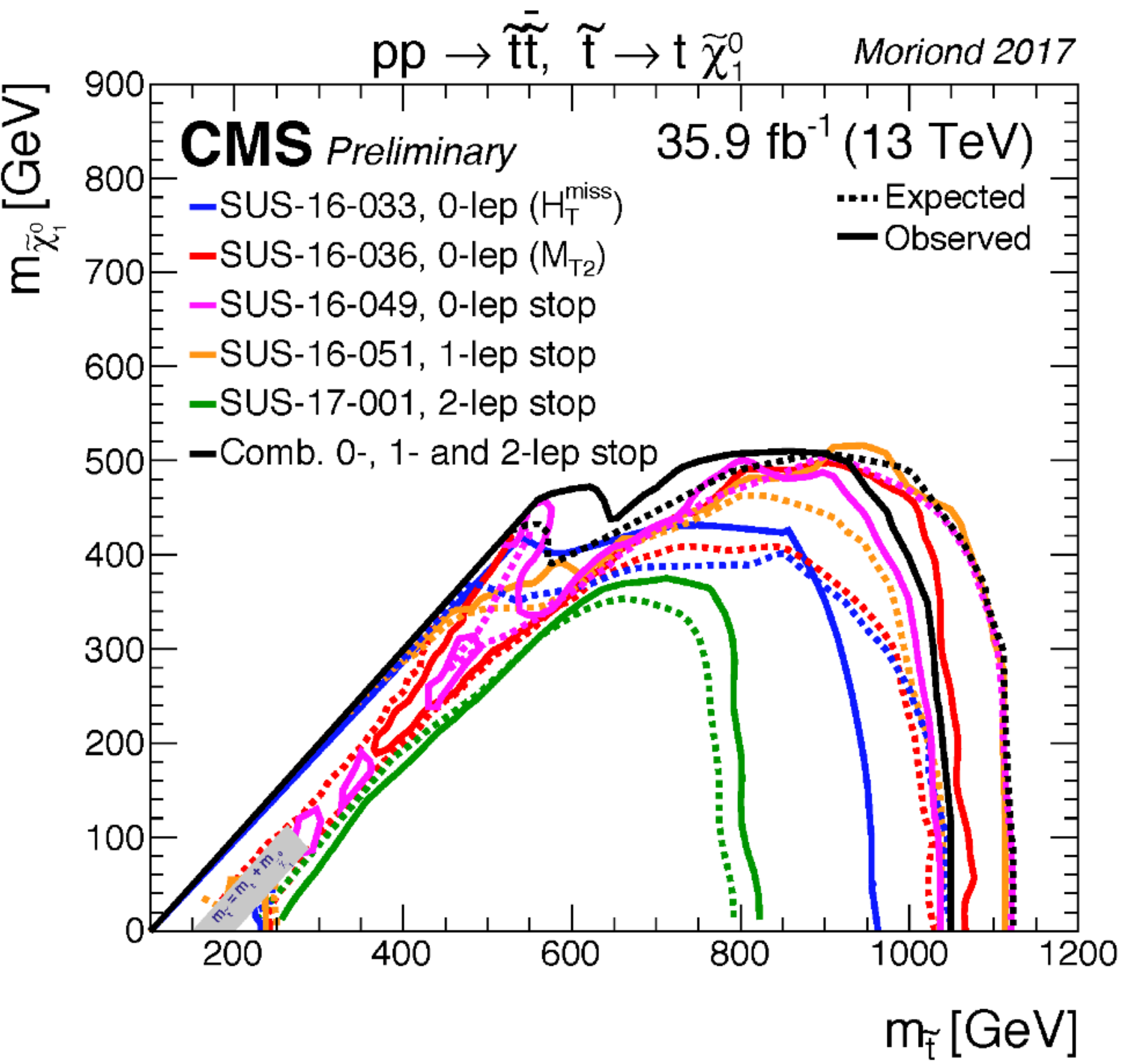
- A lot of experimental effort is happening and will happen in the future to measure deviations on the triple gauge couplings and higgs potential parameters as smoking guns for new physics.

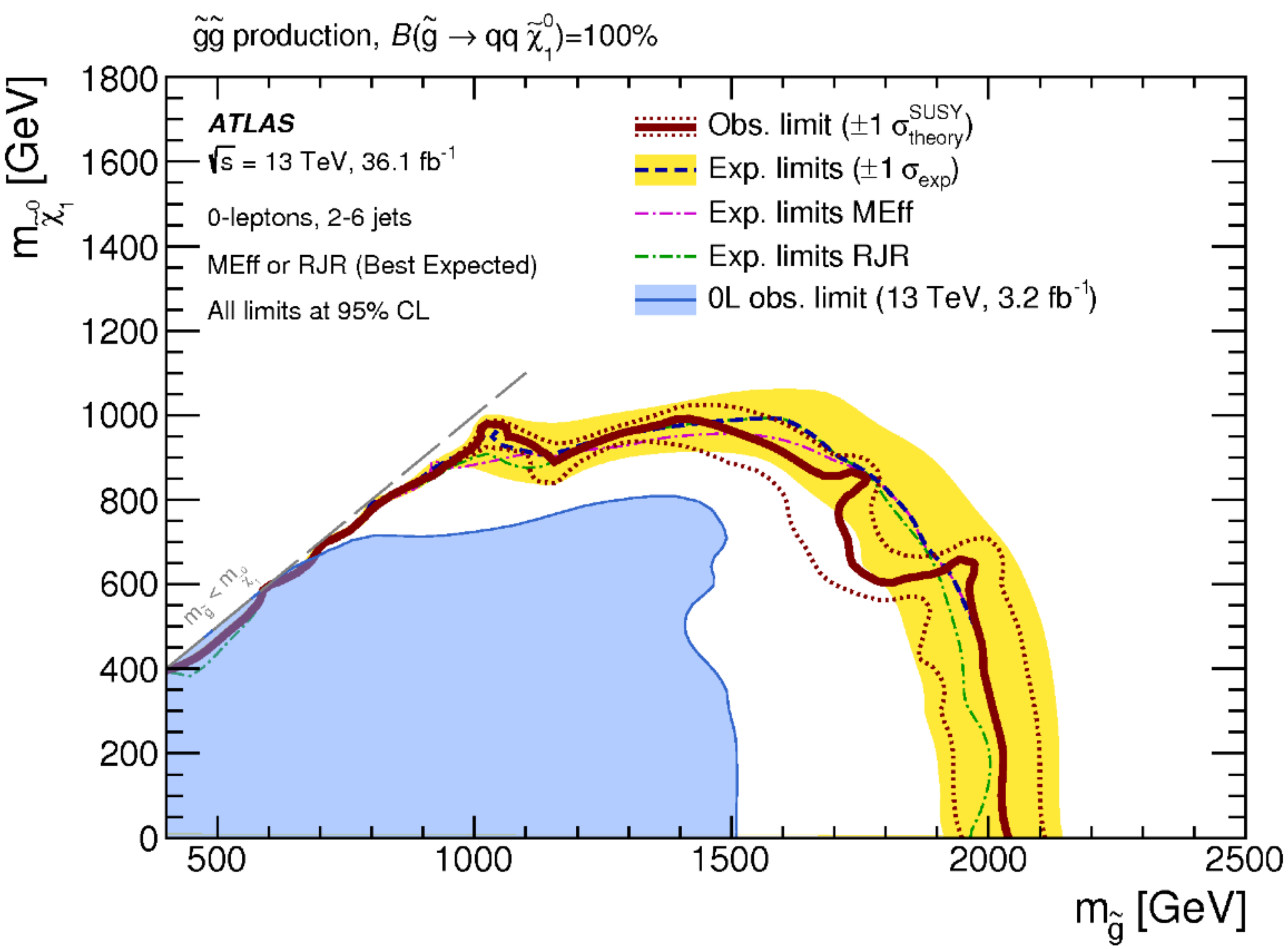
- A similar approach has been applied to ALP's. Generalization of the QCD axion which could be the DM.

- In this same category one can mention simplified models for SUSY or DM. Modifications to the SM lagrangian with few degrees of freedom to ease the experimental interpretation.

- Naturalness continue to be a guiding principle in model building……

- but faces the verdict of the LHC.





- In order to avoid those bounds one can try to build a model where the lightest states are uncoloured but with the model remaining natural.
- That means that the states that provide with a cut-off to the top loop, contributing to the quadratic sensitivity of the Higgs mass parameter have to be uncoloured but with the right multiplicity (6) and coupling (y_{top}).
- There are several ways…….

FOLDED SUSY

$H_{u,d}$

$$SU(2)_W \times SU(1)_Y \times SU(3)_c \times SU(3)_f$$

$$\left(Q,\, U,\, D,\, L,\, E\right)_i$$

$$\left(Q_f,\, U_f,\, D_f,\, L_f,\, E_f\right)_i$$

$y = 0$ $y = \pi R$

5D model implementing Folded SUSY

Upon compactification the first KK stop has the wrong color

(Cohen, Craig, Lou, Pinner)

TWIN HIGGS

$$\lambda_t \, Q_A \overset{\text{Higgs}}{\overset{\downarrow}{H_A}} U_A + \lambda_t \, Q_B \overset{\text{Twin Higgs}}{\overset{\downarrow}{H_B}} U_B$$

Standard Model Quarks (Q_A, U_A) — Twin Quarks (Q_B, U_B)

Chacko, Goh, Harnik

- The model has an approximate SU(4) global symmetry which protects the Higgs mass parameter.

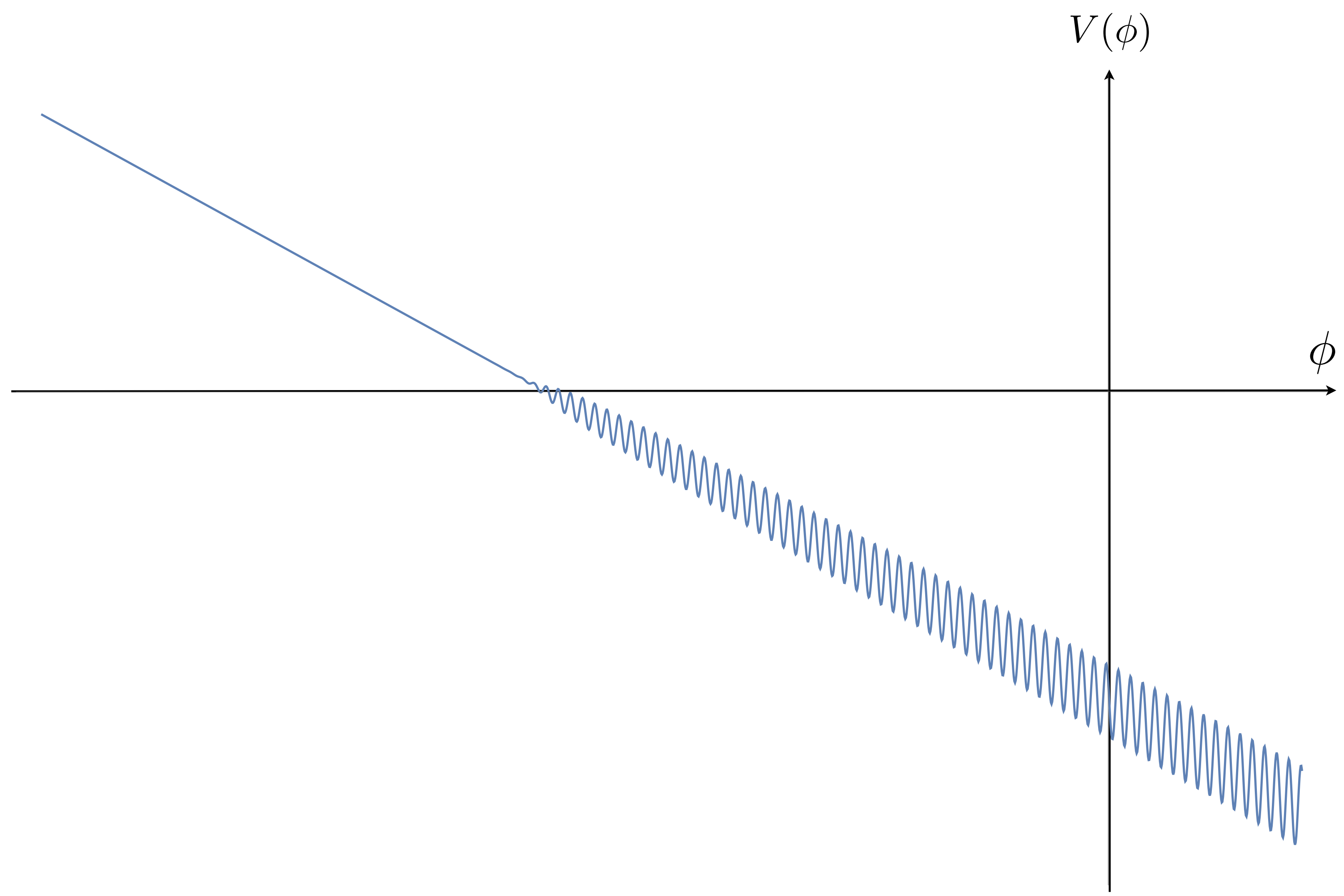
- Both of this models present some challenges in the model building since they need lots of extra structure and also they face a low cut-off since secretly they are strongly coupled theories.

- From the experimental point of view since the lightest new particles are colourless their production cross-section are generally small and direct production is difficult.

- These models predict deviations in the Higgs potential and therefore measurements of di-Higgs production and self coupling could provide with handles to these scenarios.

- A more dramatic approach by Graham, Kaplan & Rajendram suggests that the EW scale is a consequence of the cosmological evolution of our universe.

- The Higgs begins with a zero vev and it is coupled to a field that relaxes from big field values to smaller ones in an inflationary phase.



$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4 \cos(\phi/f)$$

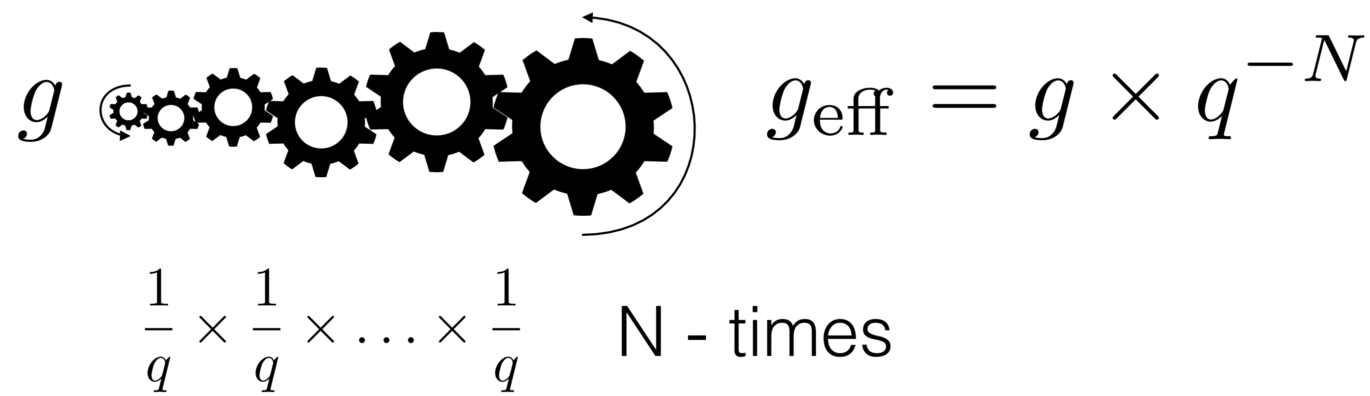
g is dimensionfull and very tiny

- There has been several realizations of this idea with different flavours.
- In general all of them require an exponential number of e-folds.
- There are very few signals at the LHC for this kind of models.
- There are potential issues between these scenarios and the weak gravity conjecture.

- The final idea I will discuss on the hierarchy problem is the one introduced by Giudice and McCullough.

- The ‘clockwork' is a proposal to generate a hierarchy of scales via a product of charges.

- It can be viewed as a deconstructed extra-dimension where there is a decrease in the vev of the link fields.



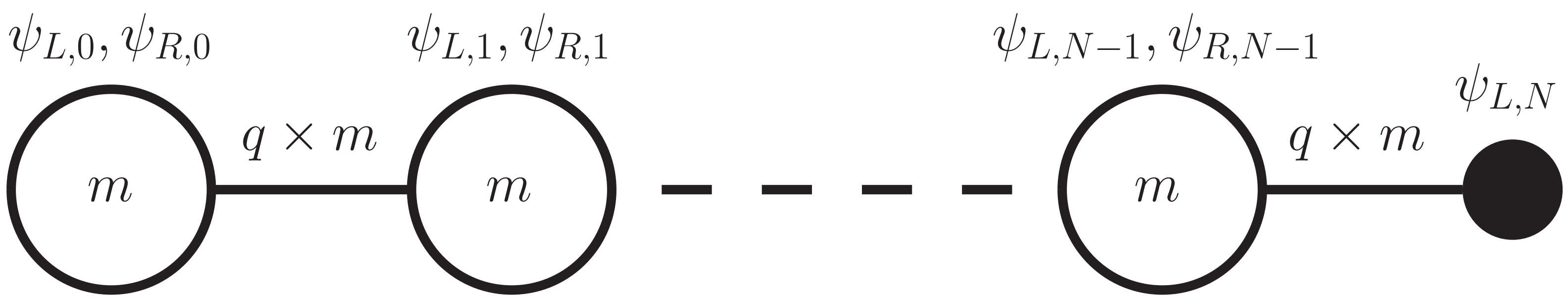
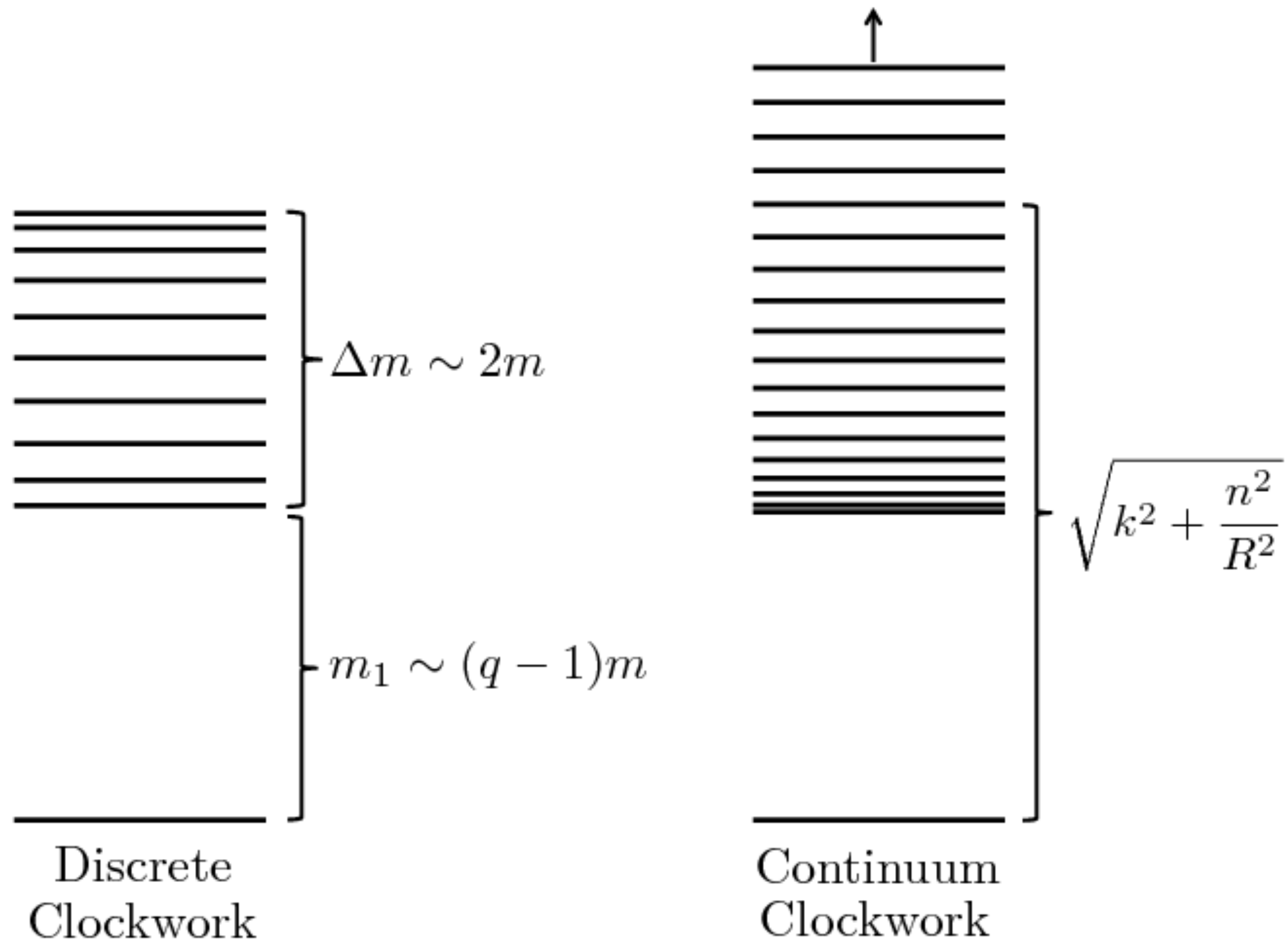


Diagram of a clockwork fermion

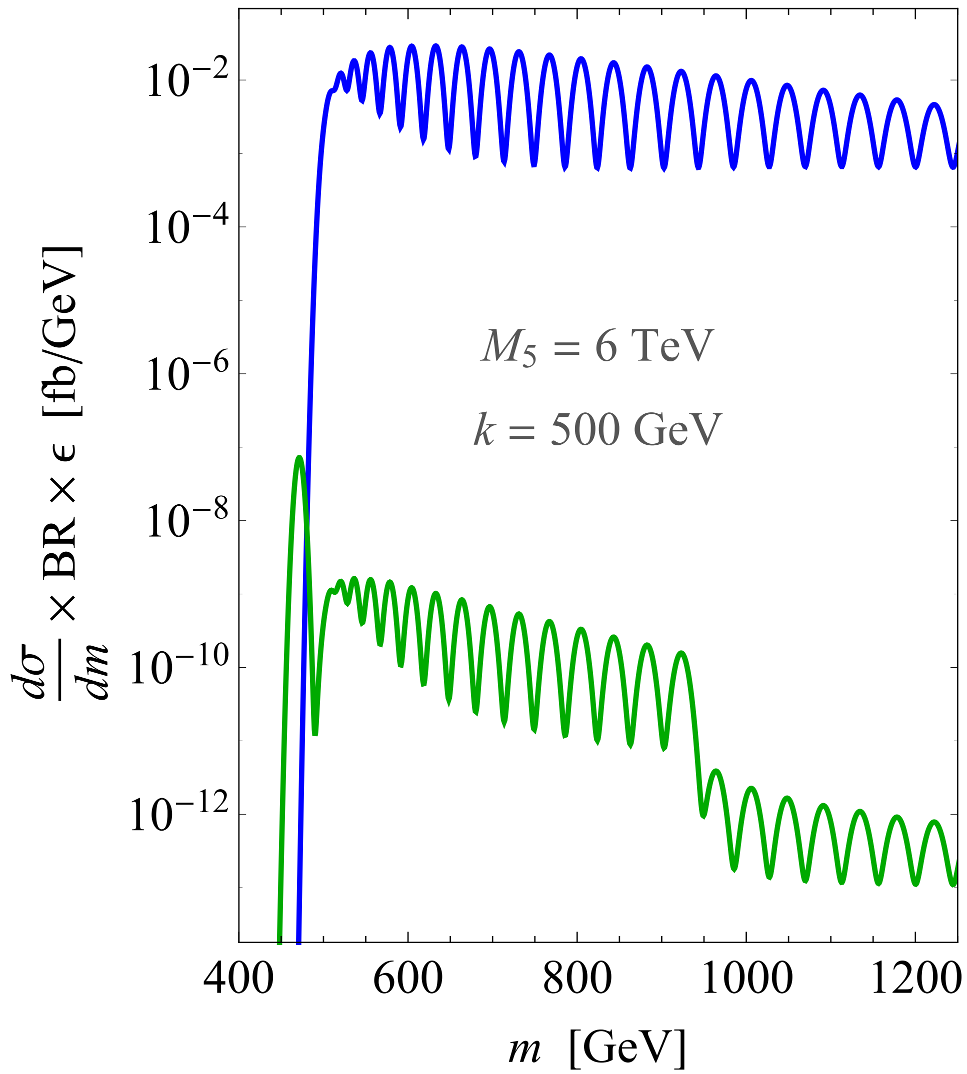


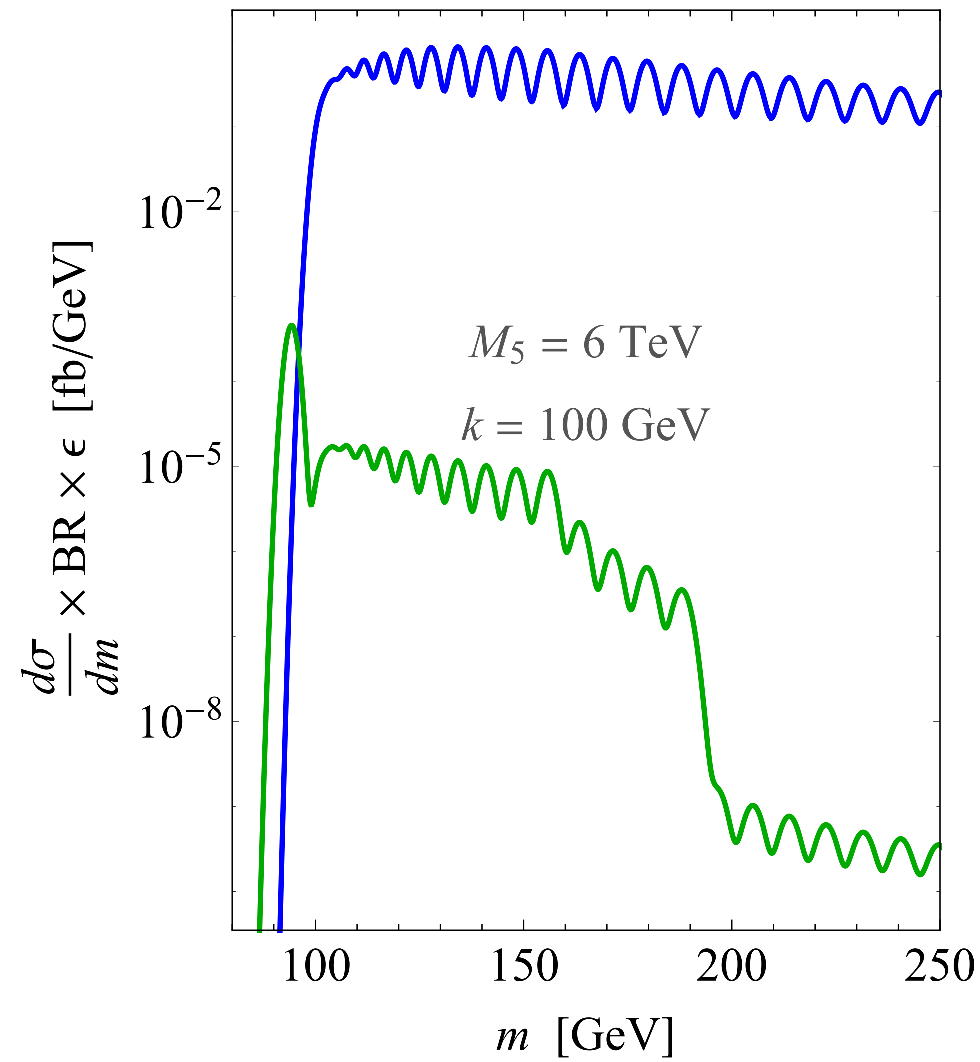
Spectrum of the clockwork model

$$ds^2 = e^{-\frac{2}{3}\alpha|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right)$$

- The clockwork in the continuum limit can be understood in the context of the linear dilaton model.

- A particular realization of little string theory (a construction where gravity decouples, so the apparent weakness of gravity is due to an ultra small coupling) introduced by Antoniadis, Dimopoulos and Giveon.





Diphoton signal for KK-gravitons and KK-dilatons

- This scenario can be extracted from D=5 N=1 SUGRA. (Antoniadis, AD, Markou, Pokorski)

- It needs a theory with pure SUGRA in 5D plus an extra gauge multiplet that contains the dilaton.

- Upon the inclusion of the linear dilaton background half of the supersymetries get broken.

- It solves the hierarchy problem supposing the fundamental scale is around the TeV and M_{Pl} is large due to a very small string scale and not because of a large volume like in ADD.

Conclusions
(or apologies again)

- I have not talked about flavour models due to lack of time.
  - There are interesting anomalies from Belle and LHCb that could point out to new physics.
  - Neutrinos are massive and there are a lot of model building around them.

- Model building is still an active part of the research program in theoretical particle physics beyond the SM.
- It still tries to understand the origin of the EW scale.
- The expectation is still that there is a ‘reason' for that value (as opposed to fine-tuning or anthropicity).
- One way to describe the new physics is through EFTs or simplified models. LHC data constrain the deviations from the SM.

- Facing the lack of signals from the LHC ‘neutral naturalness’ appears as a possibility although the models tend to be rather baroque.

- A more dramatic approach is taken in the relaxion idea where the EW scale is generated cosmologically.

- Finally the ‘clockwork' is another way of generating the hierarchy via a carefully chosen ratios of charges which can be viewed as a deconstructed extra dimension in a particular background.

“Look deep into Nature, and then you will understand everything better”

–Albert Einstein