

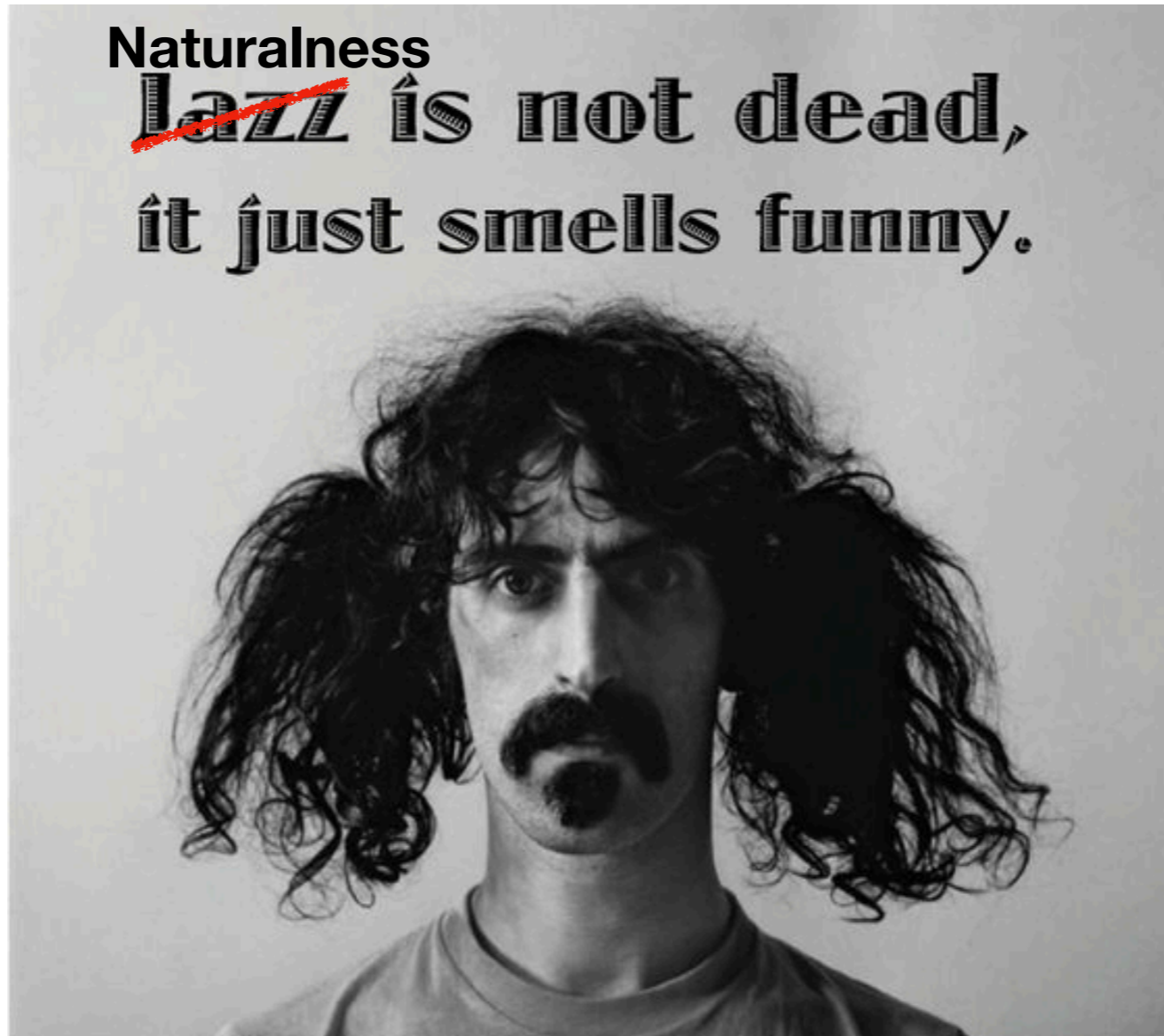
# Naturalness

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FCC physics workshop 2022

Naturalness

~~lazz~~ is not dead,  
it just smells funny.



# Intro

- For decades, Higgs naturalness has been a key motivation for theoretical and experimental progress in high energy physics.
- Naturalness is severely strained by the LHC data.
- Where do we go from here?

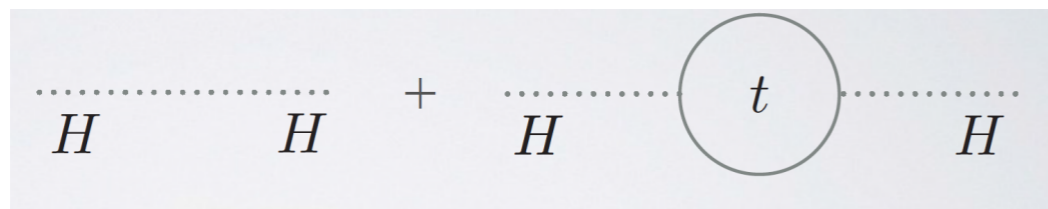
# What is Naturalness?

- The SM is a low energy limit of a more fundamental theory (EFT).
- At its core, naturalness is about the connection between the EFT and the UV-completion.
- EFT: natural theories, physical observables are compatible with order estimates for the loop corrections.
- UV completion: No “mysterious” fine-tuning of parameters are required.

# Higgs Naturalness

- In the SM: The Higgs mass parameter is sensitive to quantum corrections.

**EFT naturalness**



$$m_H^2 = m_{H0}^2 + \frac{\lambda_t^2}{16\pi^2} \Lambda^2$$

- In any UV completion we know: if the scale of new physics is high, a mysterious tuning of parameters is required.

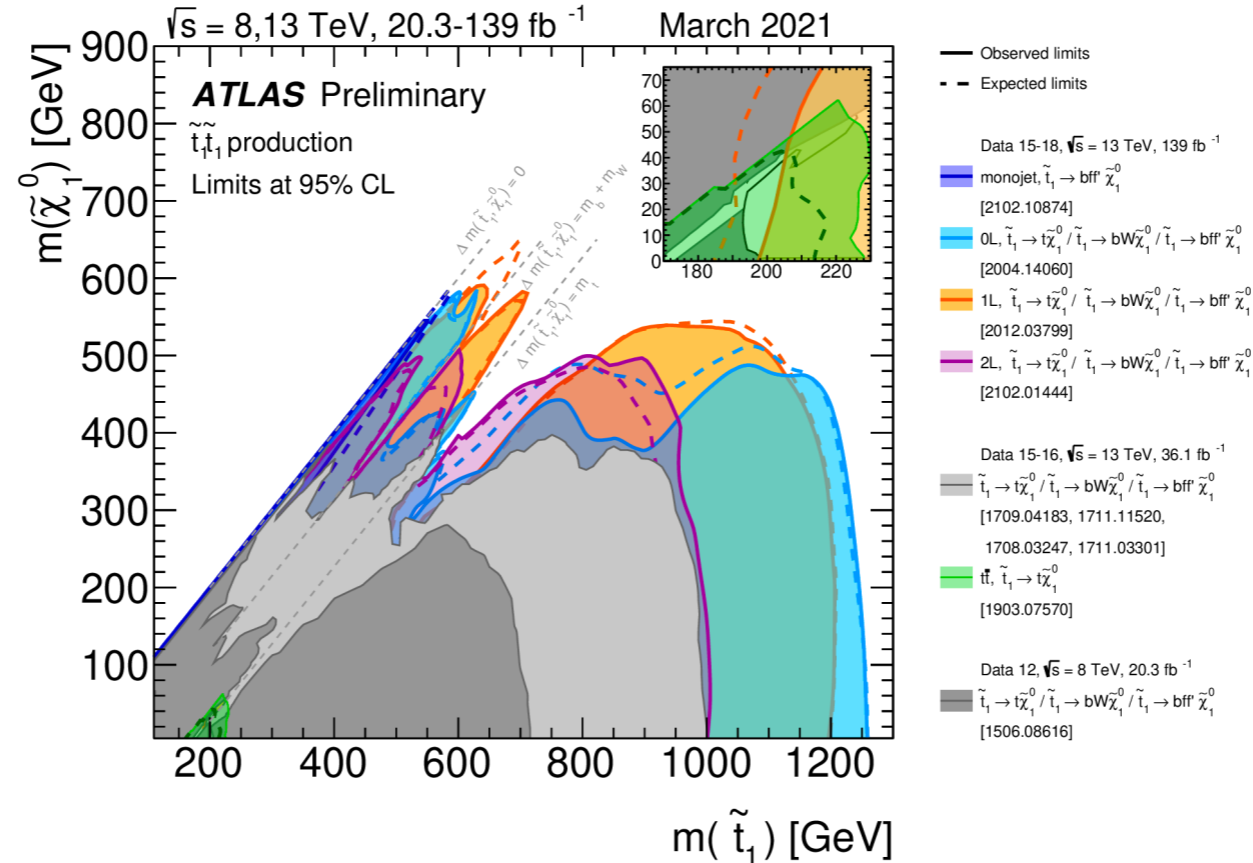


# Natural Theories

- In past decades, “natural” extensions of the SM were studied extensively:
  - SUSY
  - Composite Higgs
- Symmetries are introduced ensuring cancelation of the loop contributions.
- New particles - symmetry partners, notably “top partners”.
- The unnaturalness of the SM EFT: “Tuning” scales as  $m_H^2/m_{tp}^2$ .

# Naturalness vs Data

**Scalar  
Top Partners  
(Stops):**



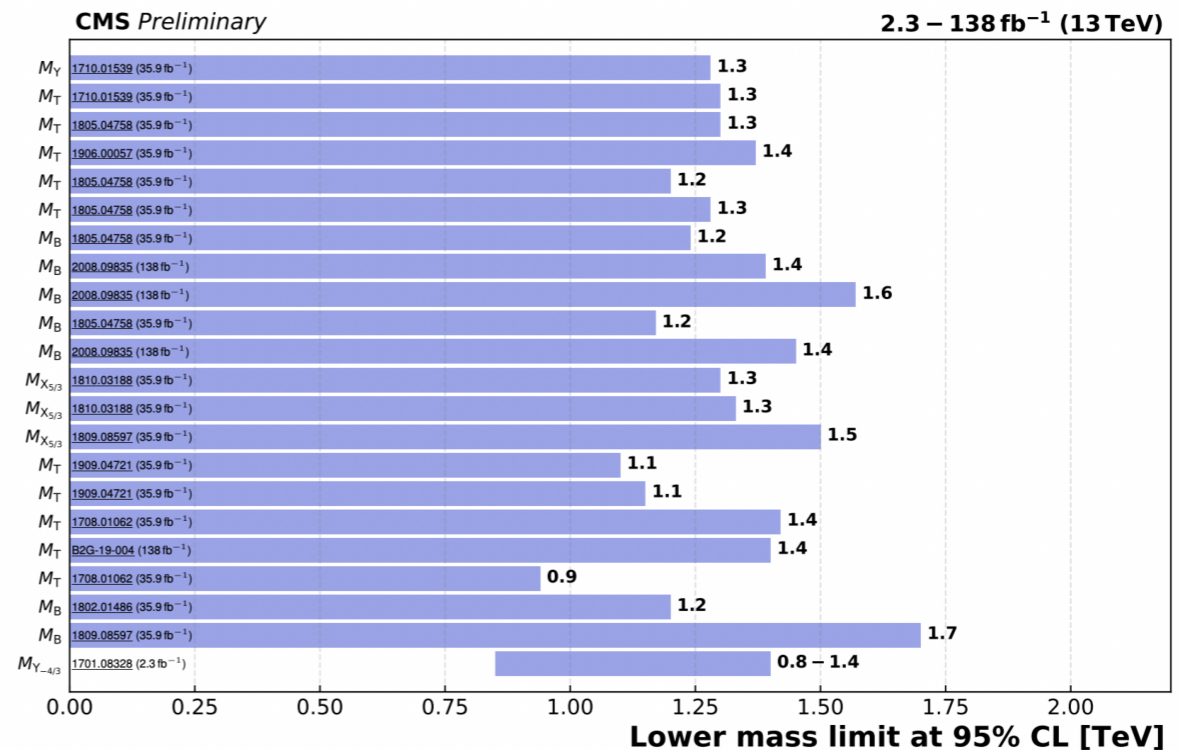
**Fermionic  
Top Partners  
(VLQs):**

**Very heavy fermions**

- YY→bWbW
- TT→bWbW
- TT→tZtZ
- TT→tHtH
- TT (Singlet)
- TT (Doublet)
- BB→tWtW
- BB→bZbZ
- BB→bHbH
- BB (Singlet)
- BB (Doublet)
- $X_{5/3}X_{5/3} \rightarrow tWtW$  (Singlet)
- $X_{5/3}X_{5/3} \rightarrow tWtW$  (Doublet)
- $X_{5/3} \rightarrow tW$  (Singlet,  $\Gamma/M_B=30\%$ )
- T→tH (Singlet,  $\Gamma/M_T=10\%$ )
- T→tH (Singlet,  $\Gamma/M_T=30\%$ )
- T→tZ (Singlet,  $\Gamma/M_T=10\%$ )
- T→tZ (Singlet,  $\Gamma/M_T=30\%$ )
- T→tZ (Doublet,  $\Gamma/M_T=10\%$ )
- B→bH (Doublet,  $\Gamma/M_B=30\%$ )
- B→tW (Doublet,  $\Gamma/M_B=30\%$ )
- $Y_{-4/3} \rightarrow bW$

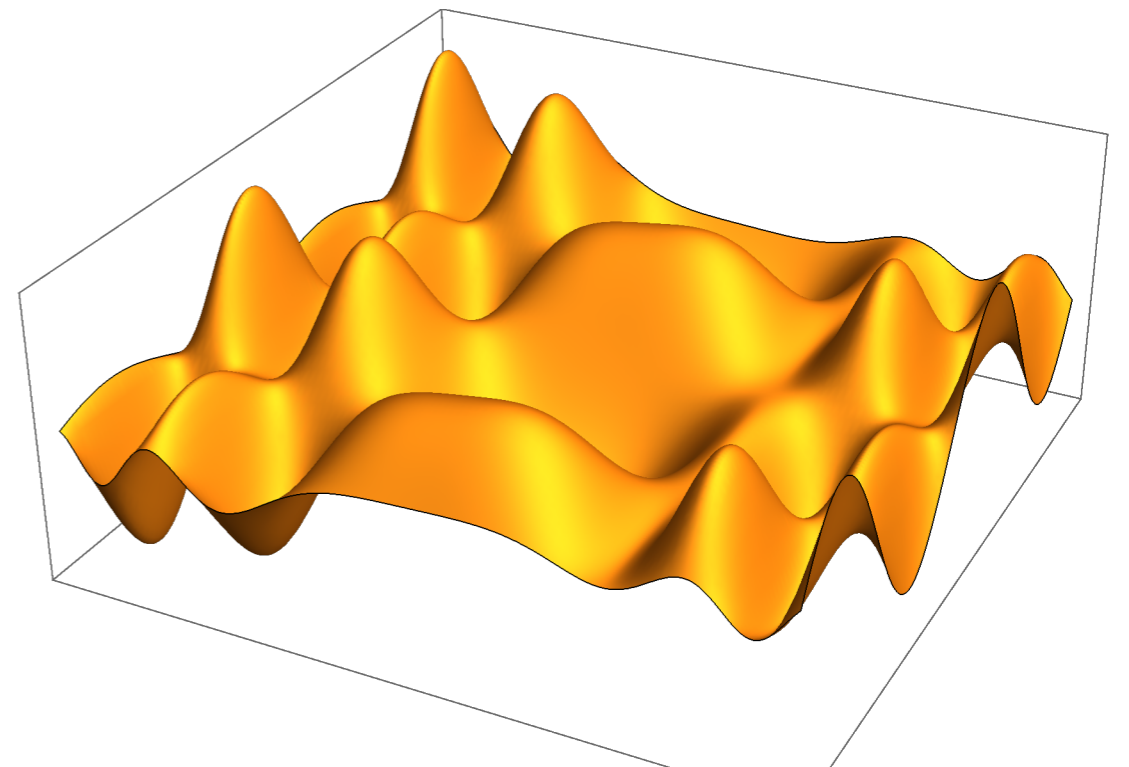
## Overview of CMS B2G Results

November 2021



# What may be wrong?

- Could still be around the corner!
- Naturalness holds an implicit assumption - that the LHC probes the ground state of the theory.
- Doesn't have to be true! We might well be in a metastable minimum among many others
- Or even not a minimum, but a flat slope



# Anthropics or “Dead Naturalness”

- Assuming a landscape is often posed as a dead-end.
- But, it doesn't have to be. It's just physics - have to study mechanisms, models, dynamics, predictions.
- Even throwing away naturalness may lead to radical implications - see Amin et. al. 1802.00444

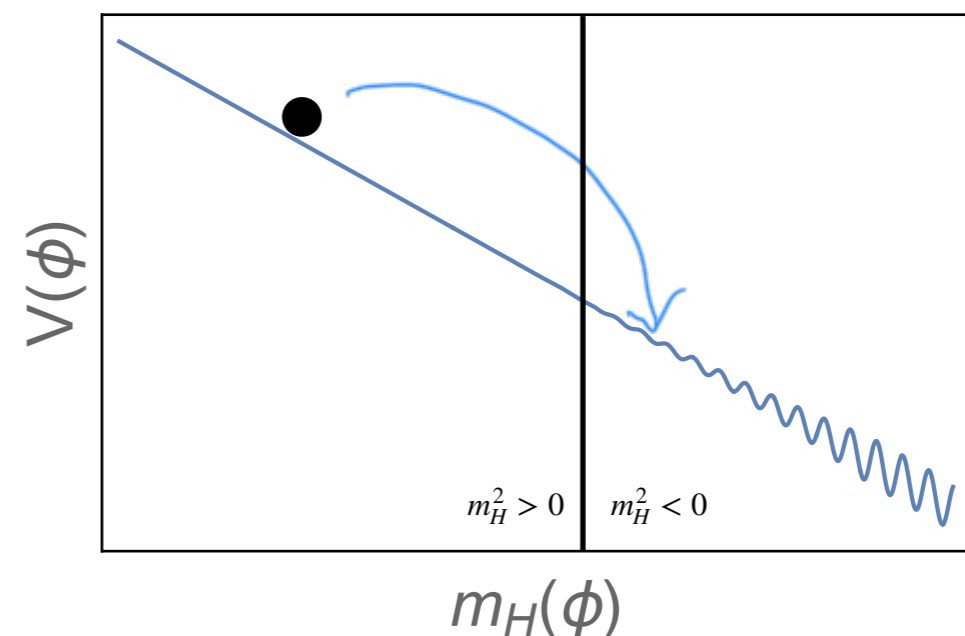
# Cosmological Dynamics

- New ideas have been proposed
- In these ideas the **physical** Higgs mass back-reacts on some cosmic dynamics
- The backreaction predicts **new physics**, but not where naive naturalness expects them.
- Can be broadly classified according to their mechanisms:
  1. Classical Rolling
  2. Quantum diffusion and inflationary equilibrium
  3. Landscape selection

# Rolling Dynamics

Graham et. al. 1504.07551

- Relaxion: the physical Higgs mass back-reacts on the rolling of a scalar field during inflation - by generating “wiggles”.
- The scalar field couples to the Higgs mass and “scans” it.
- The rolling stops in the first minimum - very close to the crossover.

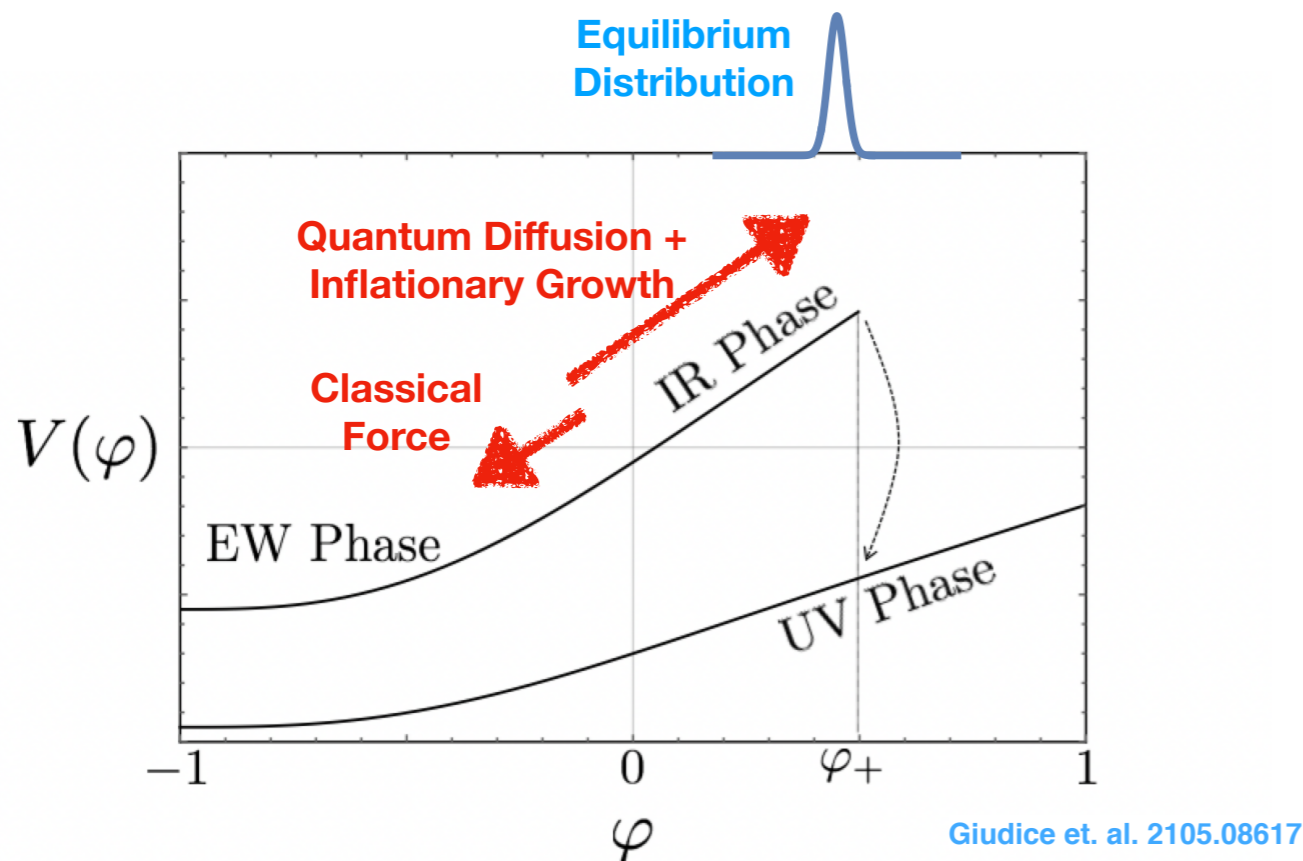


# Quantum Diffusion

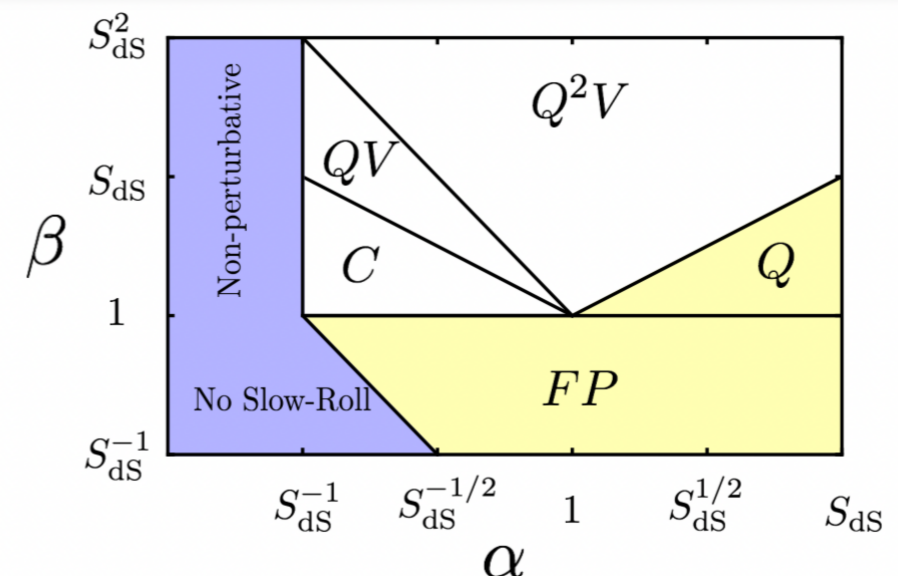
Geller et. al. 1809.07338

Giudice et. al. 2105.08617

- Self Organized Criticality (see Giudice et. al. 2105.08617 )
  - Predictive statistical behavior during (eternal) inflation.
  - Drives light fields to critical “unnatural” points



$$\frac{\alpha}{2} \frac{\partial^2 P}{\partial \varphi^2} + \frac{\partial(\omega' P)}{\partial \varphi} + \beta \omega P = \frac{\partial P}{\partial T}$$



# Landscape Selection

Csaki et. al. 2007.14396

D'Agnolo and Teresi 2109.13249

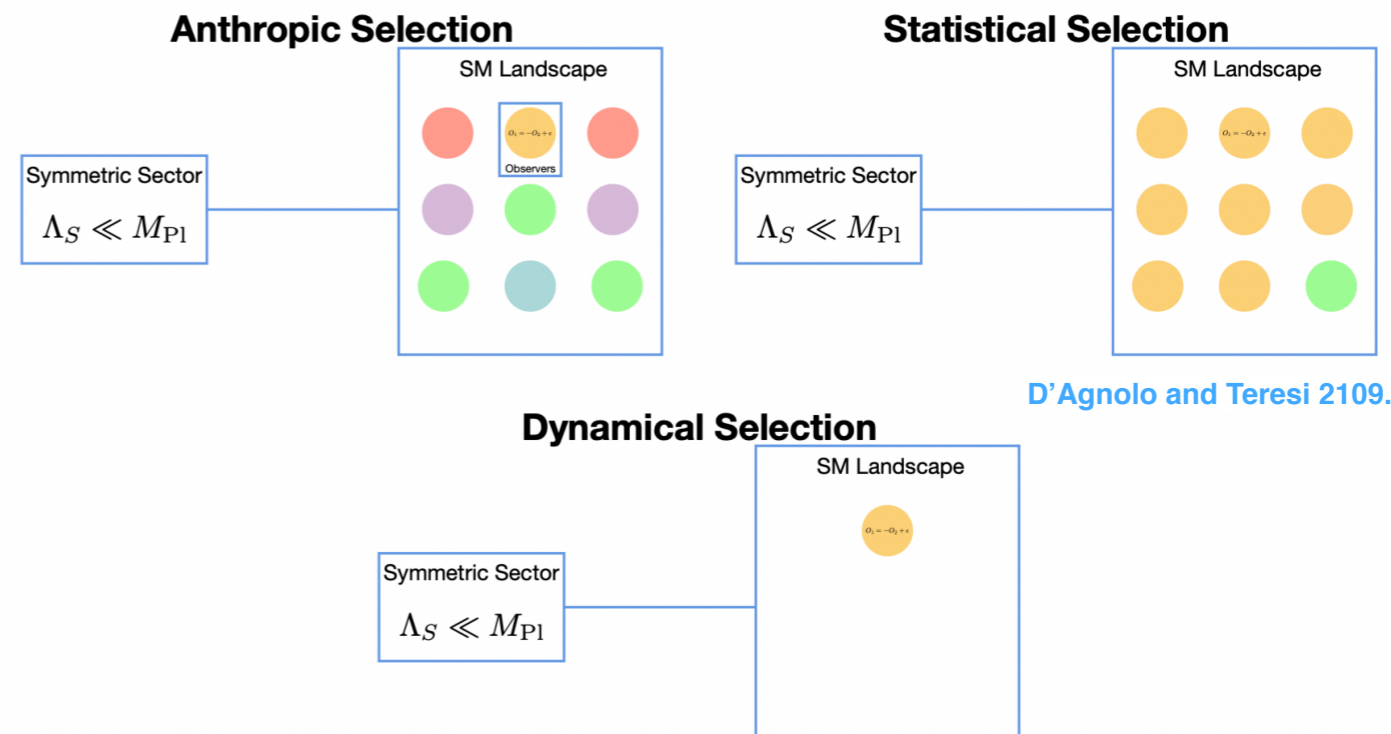
D'Agnolo and Teresi 2106.04591

Arkani-Hamed et. al. 2012.04652

- Assume a landscape of Higgs masses.
- Instead of speculating that life selects the Higgs mass - create a selection mechanism.

- Possible Selection Mechanism: No expansion/long-lived universe if  $|m_H^2| > EW^2$

- Other ideas:  
Connect the Higgs selection to the CC selection.



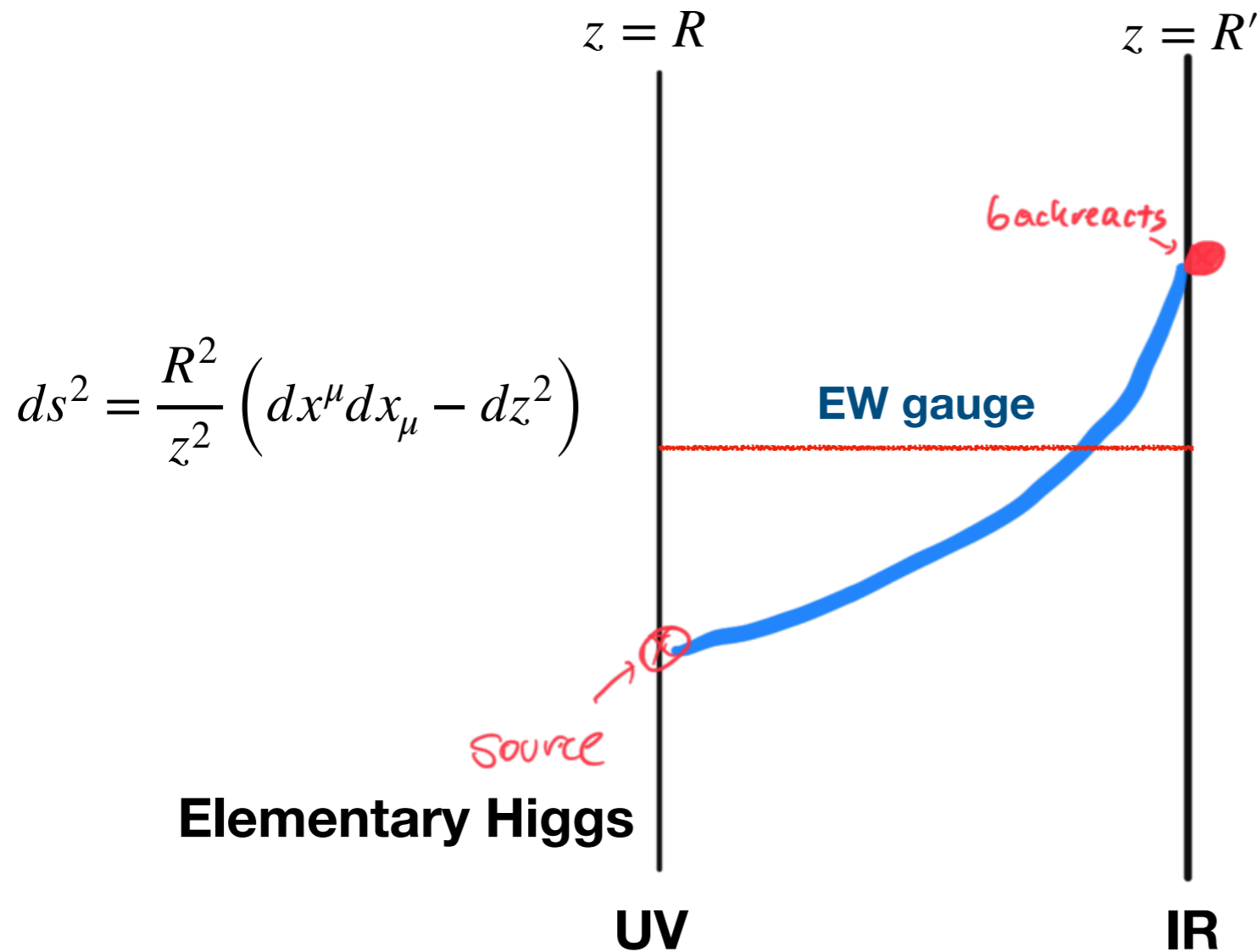
D'Agnolo and Teresi 2109.13249



# Landscape Selection

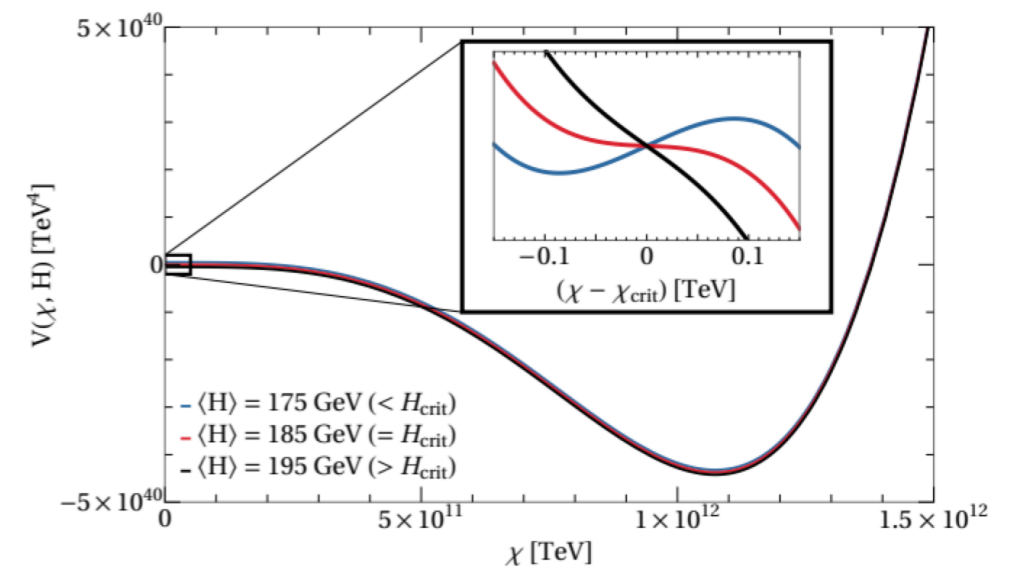
Csaki et. al. 2007.14396

- The Model:



The position of the IR brane:  
dilaton

$$\chi \sim \frac{1}{R'}$$

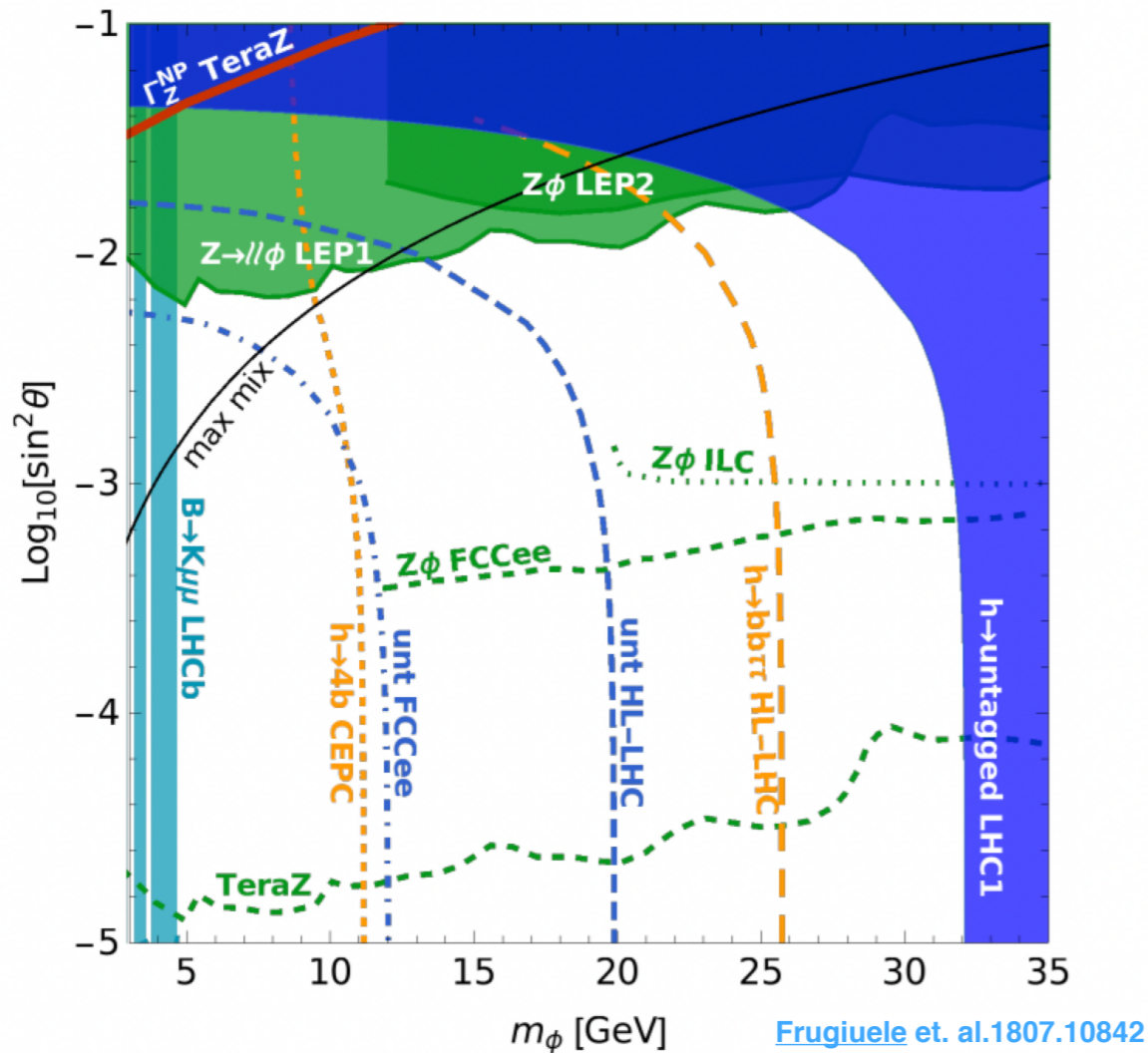


# Predictions

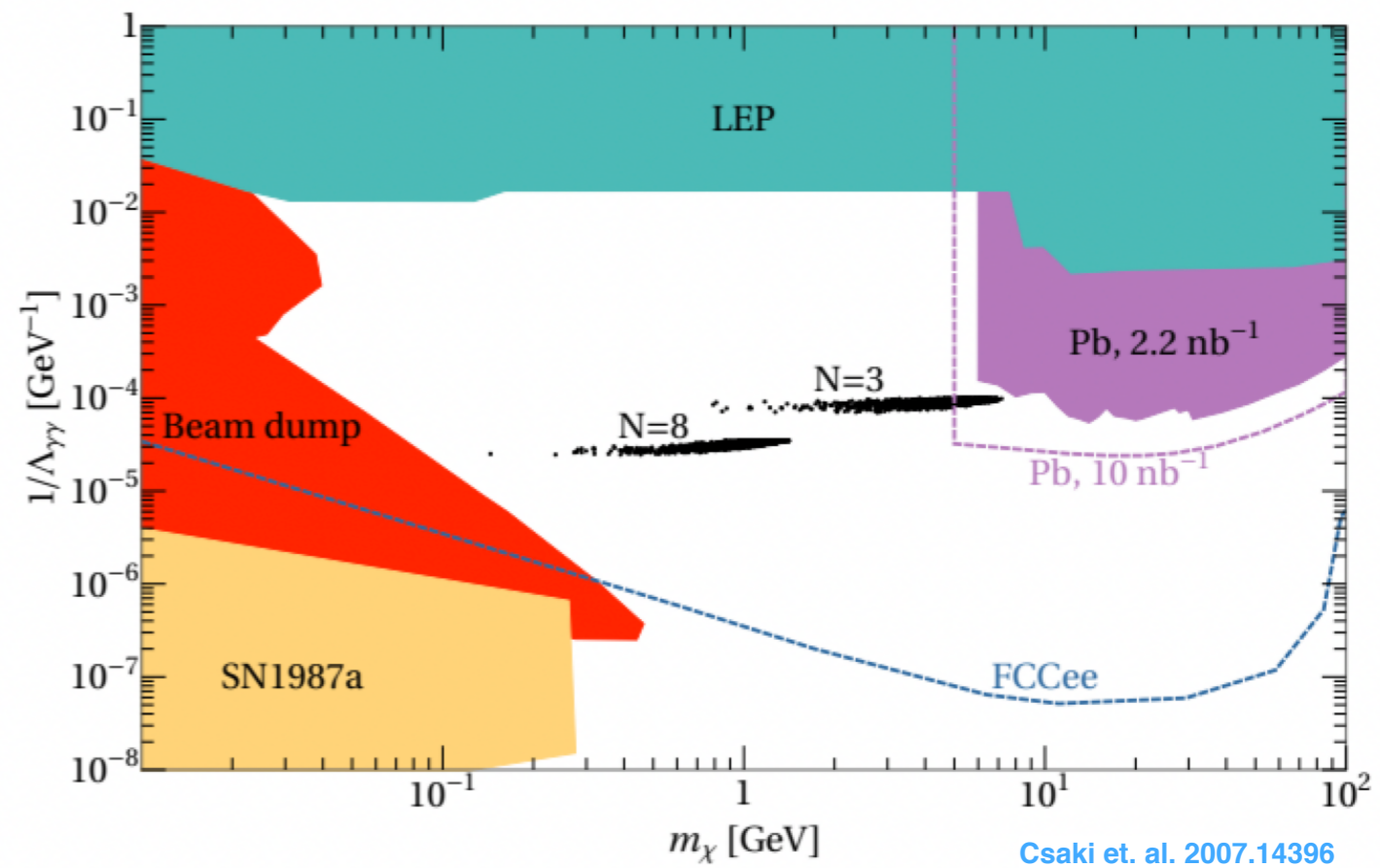
- Higgs backreaction requires new d.o.f close or lighter than the Higgs mass.
- These new particles are potentially discoverable at future colliders.
- Other implications include: luminosity and precision frontier, cosmology, astrophysics.

# Examples - FCC physics

## Relaxion

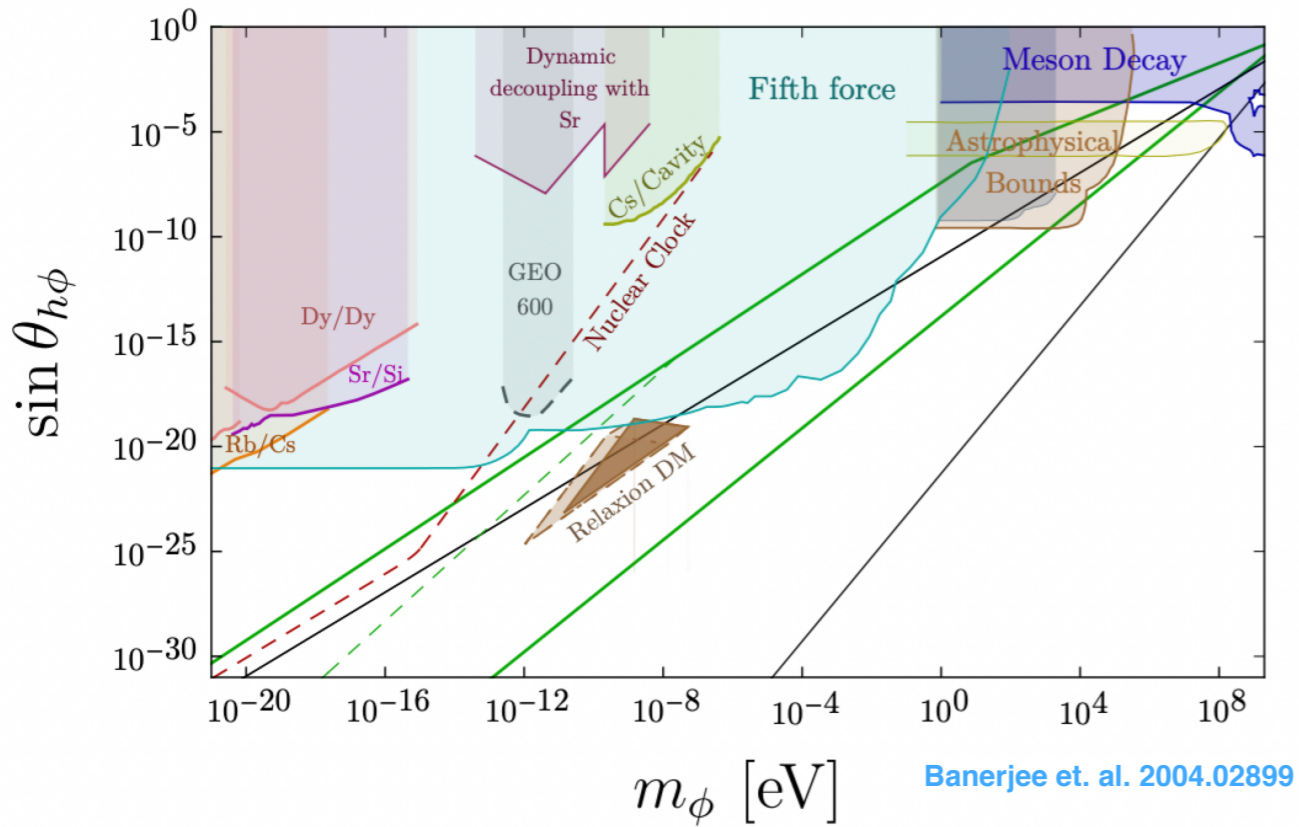


## Light Dilaton in Crunching Naturalness

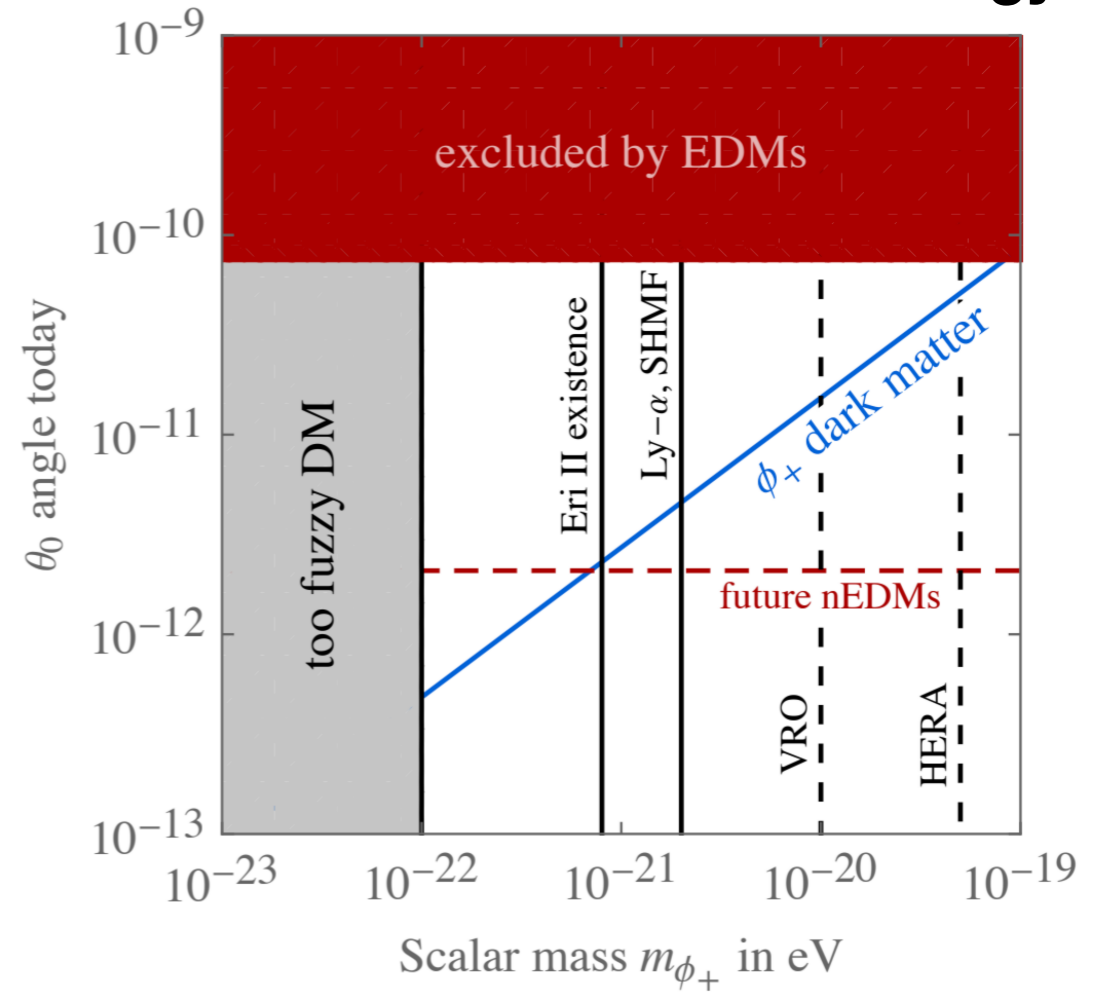


# Other Examples

## Precision Physics



## Dark Matter and Cosmology



# Discussion

- Just started thinking beyond naive naturalness.
- New ideas, but still major theoretical problems:
  - Models are still quite ugly - flat scalars, little-hierarchy problems.
  - Require understanding eternal inflation.
  - Dynamics in “toy landscapes” don’t have to be representative of dynamics in the string landscape. Don’t have a “landscape decoupling limit”.
- Have clear predictions - don’t have to wait!

**Thank you! Stay Safe!**