Beyond Standard Model Theory

Anson Hook

University of Maryland

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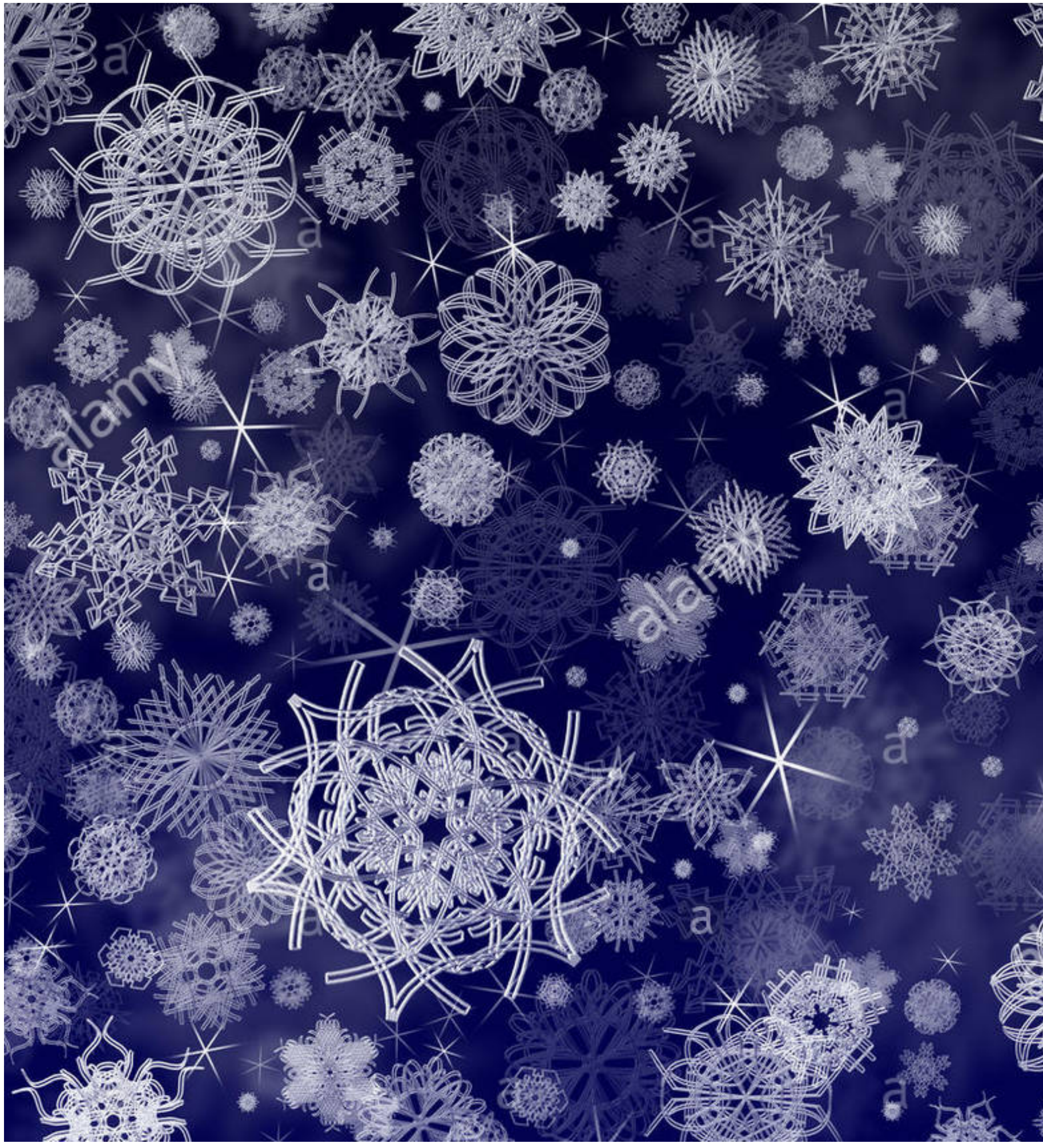
Naturalness

Naturalness is like a snowflake

No two people have the same definition of naturalness



This talk : Naturalness

Naturalness : Using dimensional analysis to predict a new scale (sometimes this is the mass of a new particle)

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Useful : Predicts where you should look to find something qualitatively new

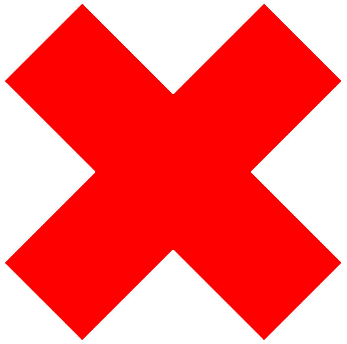
This talk : Naturalness

Naturalness : Using dimensional analysis to predict a new scale (sometimes this is the mass of a new particle)

Believe : Experimental evidence indicates dimensional analysis always works

Just like Occam's Razor

Physics 

Math 

Naturalness examples

Simple Example

Drop a ball

Time when you hear a noise

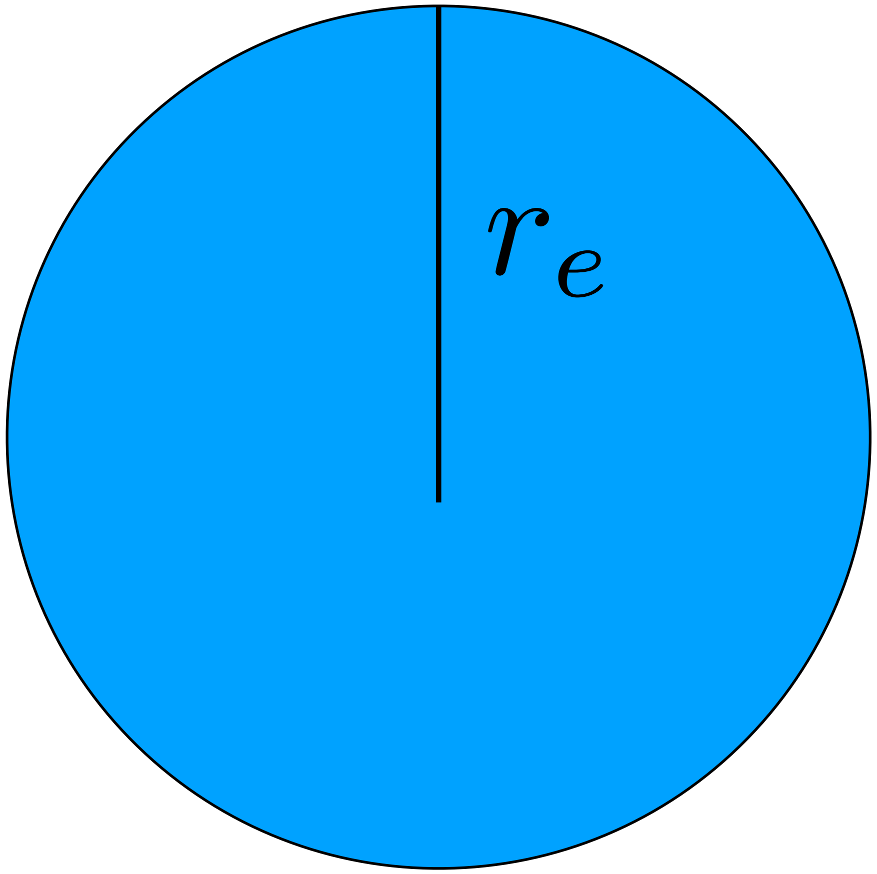
$$d \sim g\, t^2$$

Predict distance to new physics

Naturalness examples

Classic Examples

Classical Radius of the electron



$$V_{E+M} \sim \frac{\alpha}{r_e} \sim m_e$$

"Anticipated" Quantum Mechanics

Naturalness examples

Classic Examples

Charged pion mass

Diagrams enforce dimensional analysis

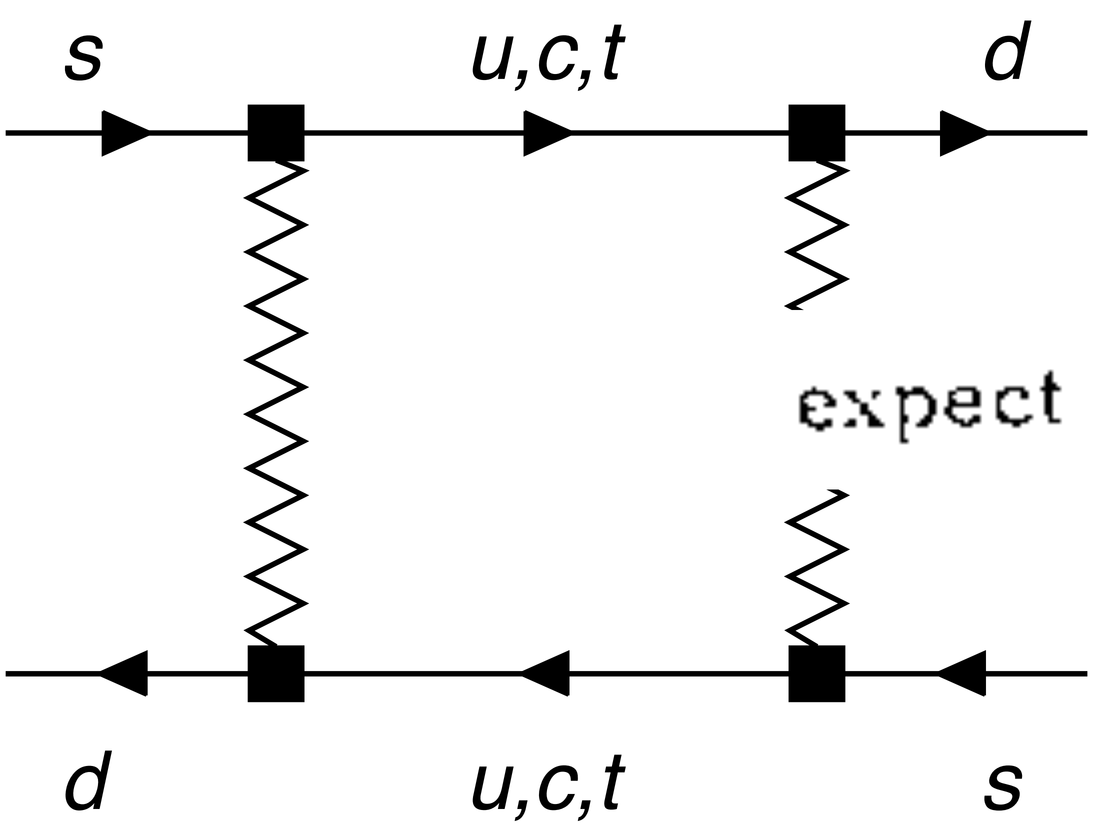
$$m_{\pi^\pm}^2 - m_{\pi^0}^2 \sim \alpha\Lambda^2$$

"Anticipated" Rho meson

Naturalness examples

Classic Examples

Charm quark



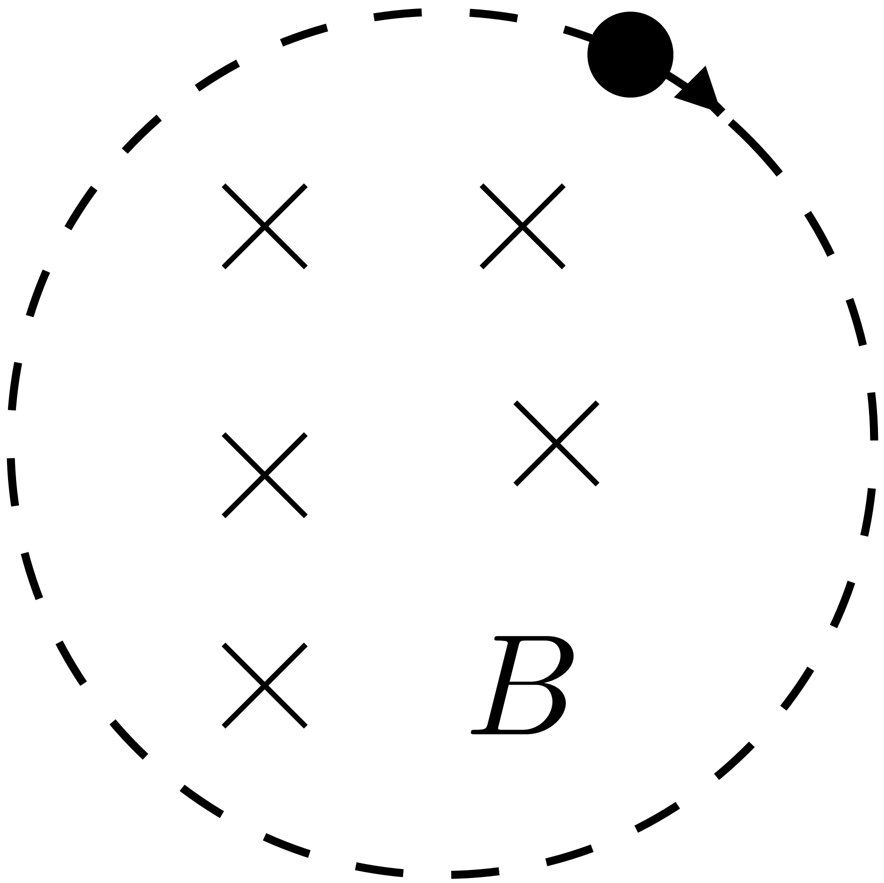
Prediction of charm quark

expect m_c to be less than, say, 10 GeV.

M.K. Gaillard and B. Lee, Phys.Rev.D 10 (1974) 897

Naturalness examples

Fermi in 1922 predicted (stimulated) Schwinger pair-production



Larmor Radiation

$$\omega_\gamma \sim \gamma^2 \frac{eB}{m} \sim \gamma m$$

Something happens when

$$\gamma e B \sim m^2$$

Elephant in the Room

Naturalness meets the Higgs

$$\Lambda_{\text{top yukawa}} \sim 500\,\text{GeV}$$

$$\Lambda_{\text{gauge}} \sim 1\,\text{TeV}$$

$$m_H^2 \sim g^2 \Lambda_{\text{gauge}}^2$$

$$\Lambda_{\text{quartic}} \sim 1.3\,\text{TeV}$$

Elephant in the Room

What does this scale mean?

$$\Lambda_{\text{top yukawa}} \sim 500\,\text{GeV}$$

Obtained by dimensional analysis

Correspond to anything with dimensions GeV

Tradition

New particles are at these energy scales

1. SUSY — Colored scalars
2. Colored particles — Little Higgs, Extra dimensions
3. Twin Higgs — Particles

What's going on?

Where is the 500 GeV new Physics????

*Could be very carefully hidden from the LHC

To the extent that there is nothing there, we must be missing something important!

What we could be missing

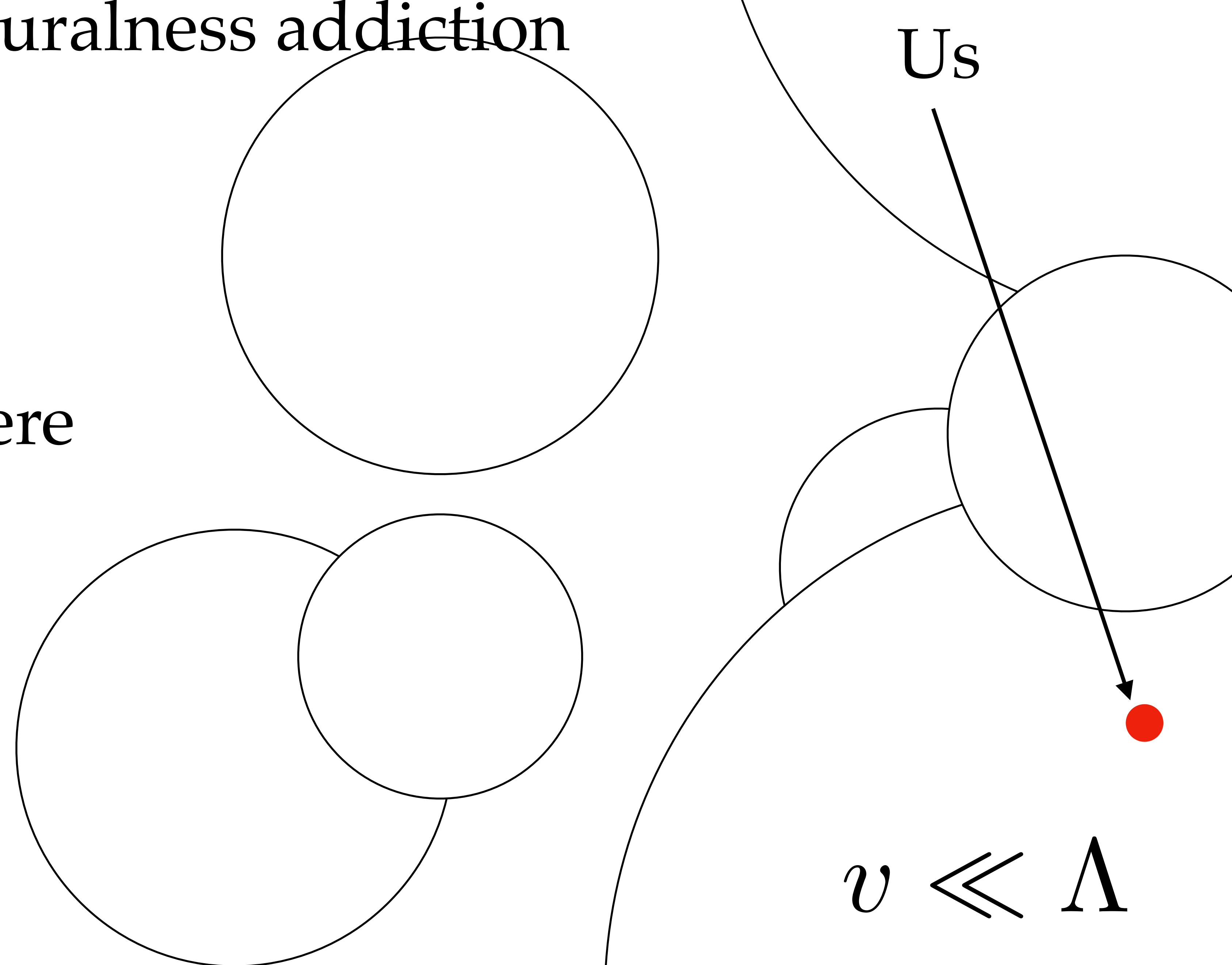
2 Step plan to help you quit your naturalness addiction

1. Different parts of the universe have different Higgs masses
   - Multiverse, brute force via number of vacua
   - Scalar scanning the Higgs mass

What we could be missing

2 Step plan to help you quit your naturalness addiction

2. We live in a non-generic location where Higgs mass is small



What we could be missing

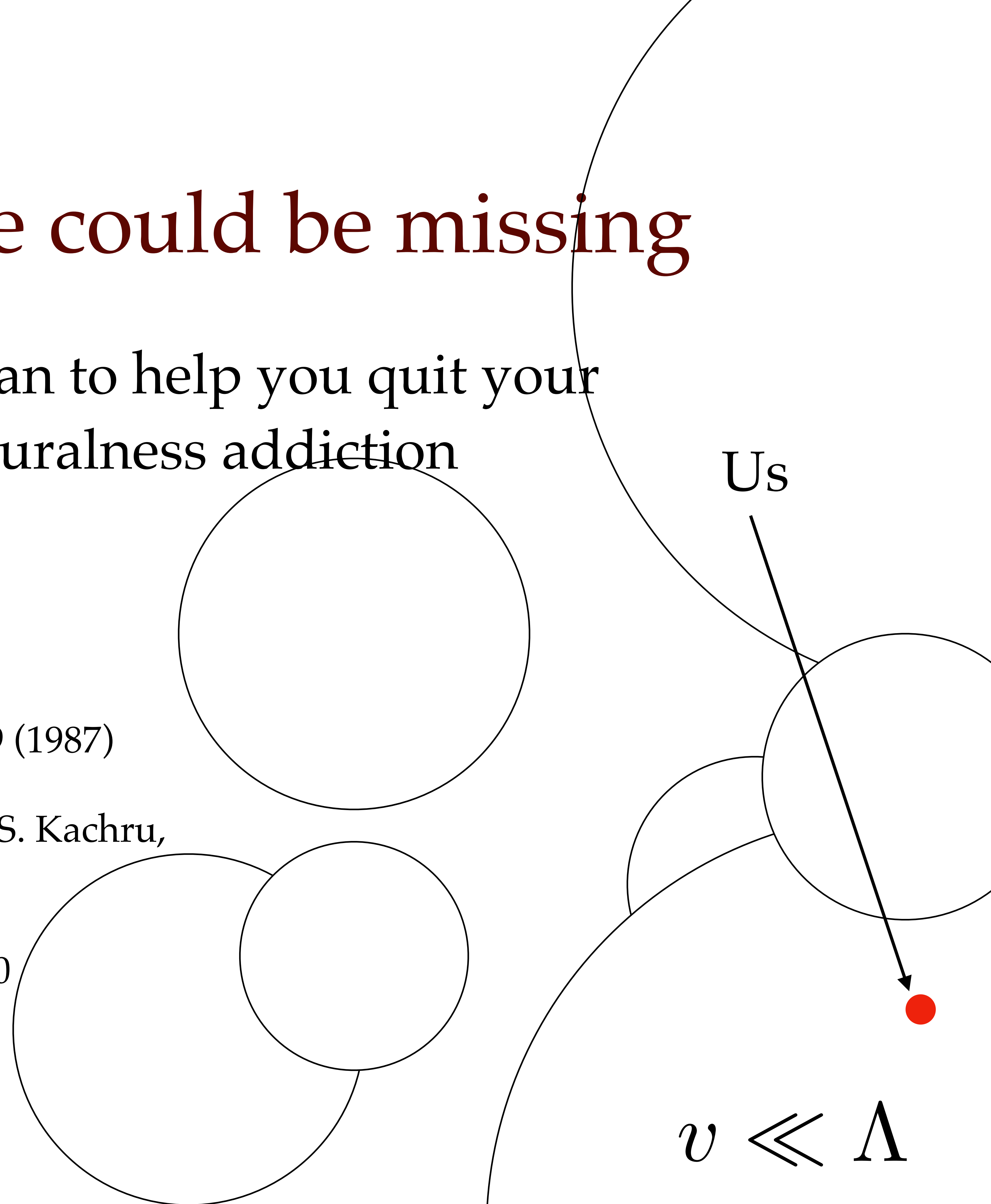
2 Step plan to help you quit your naturalness addiction

- Anthropics

S. Weinberg, Phys.Rev.Lett. 59 (1987)

N. Arkani-hamed, S. Dimopoulos, S. Kachru, hep-th/0501082

G. Giudice, A. Riotto 1907.05370



What we could be missing

2 Step plan to help you quit your naturalness addiction

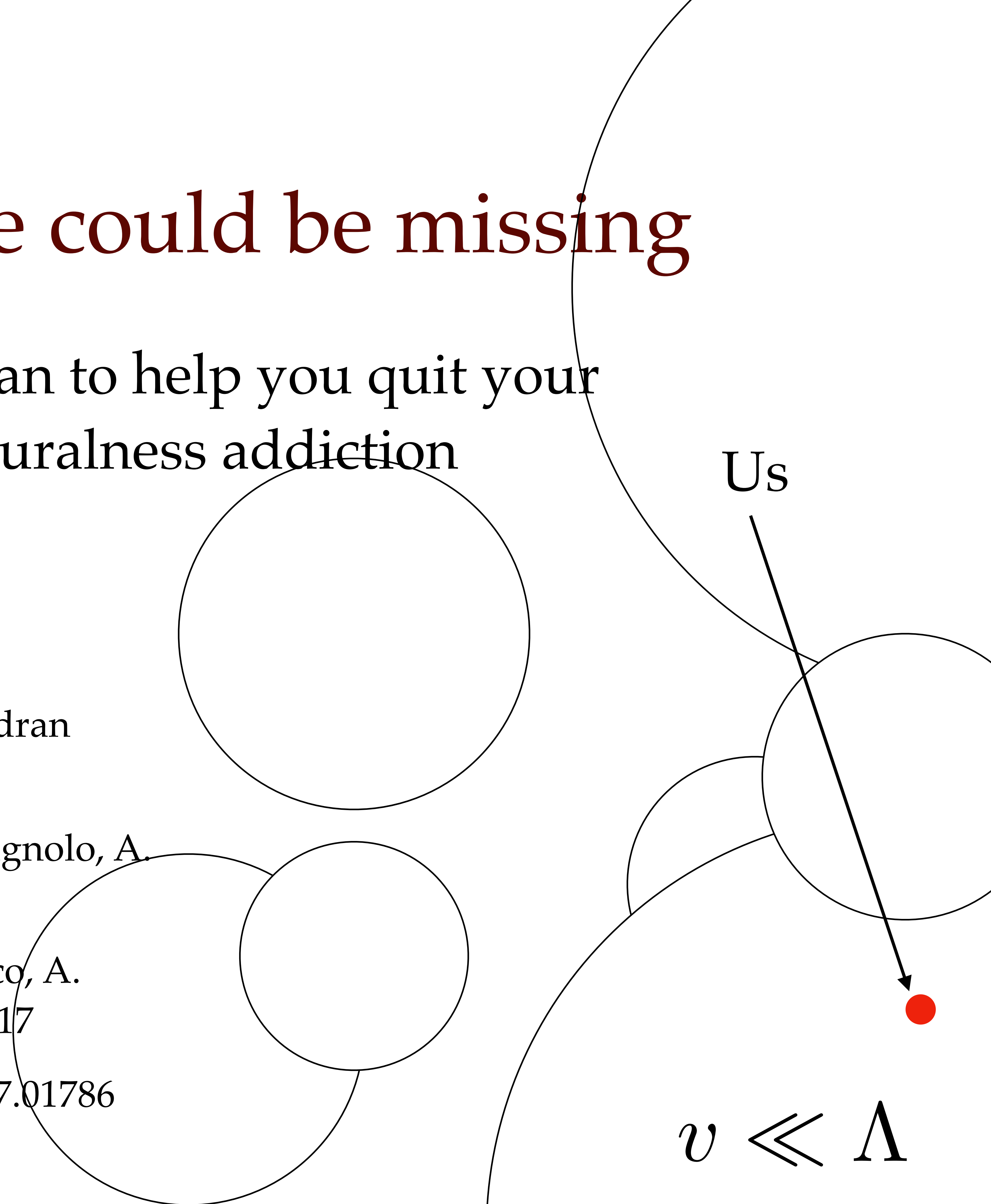
- History

P. Graham, D. Kaplan, S. Rajendran 1504.07551

N. Arkani-Hamed, T. Cohen, R. D'Agnolo, A. Hook, H. Kim 1607.06821

J. Espinosa, C. Grojean, G. Panico, A. Pomerol, O. Pujolas 1506.09217

A. Hook, G. Marques-Taveres 1607.01786



What we could be missing

2 Step plan to help you quit your naturalness addiction

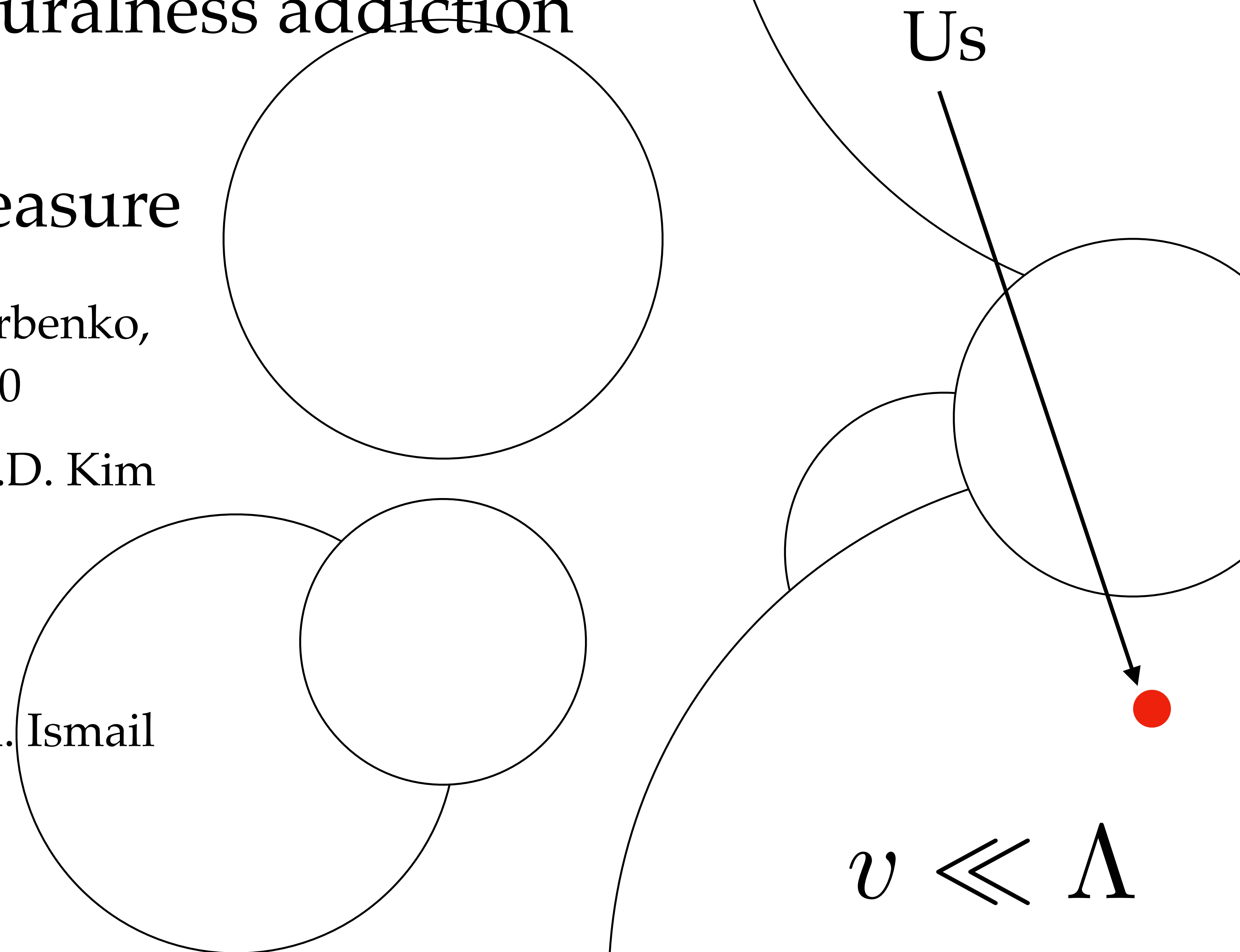
- Messing with the measure

A. Arvanitaki, S. Dimopoulos, V. Gorbenko, J. Huang, K. Tilburg 1609.06320

A. Arkani-Hamed, R.T. D'Agnolo, H.D. Kim 2012.04652

M. Geller, Y. Hocherg, Kuflik 1809.07338

C. Csaki, R.T. D'Agnolo, M. Geller, A. Ismail 2007.14396



Oddity in Solutions

An underlying assumption of physics is typicality

Common problems have common solutions

What is responsible for the Higgs' mass?

Should have a common solution!

Oddity in Solutions

- Symmetry based solutions
  - Composite Higgs
  - SUSY
  - Little Higgs,
  - XXX Higgs
- Naturalness Anonymous
  - Anthropics, Measure
  - Historical

Oddity in Solutions

- Symmetry based solutions
  - Composite Higgs
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Never seen before solutions!

Oddity in Solutions

- Symmetry based solutions
  - Composite Higgs
  - SUSY
  - Little Higgs
  - XXX Higgs
- Naturalness Anonymous
  - Anthropics, Measure
  - Historical

Solutions we have seen before

New Old solutions

Why invent new solutions?

Learn from previous solutions!

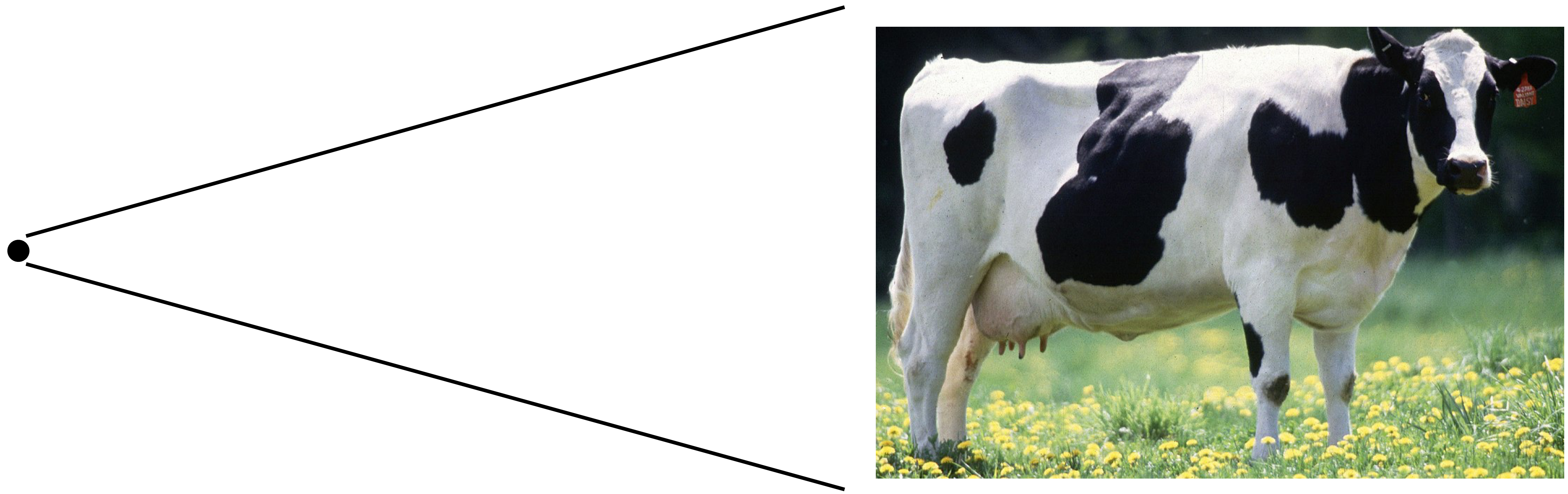
Remainder of talk will be discussing progress in this direction

2 well known solutions

2 not so well known solutions

Compositeness

One of the earliest solution to naturalness problems



Cows are not spherical point like objects

Compositeness

Pro :

Very common solution

Very predictive

Con :

Too predictive - not seen

Historical

The history of an object is important

Extremely fine tuned until one discovers that a person is trying to set a world record

Even then, depends on how skilled the person is, if the air conditioning is on, …

Historical

Recent trend started by the relaxion

Historical solutions are real solutions that have been seen before

Pro :

Can explain why we haven't seen anything at colliders yet

Historical

Recent trend started by the relaxion

Depends critically on assumptions about quantum gravity

Con :

Extremely hard / Impossible to test

The most common solution

Naturalness questions appear all of the time in classical mechanics

There is a solution which is extremely common

Can see it in CO_2

Classic Problem : Dipole moment of CO_2

Carbon Dioxide

Composite particle

Made of a positively charged object and 2 negatively charged ones

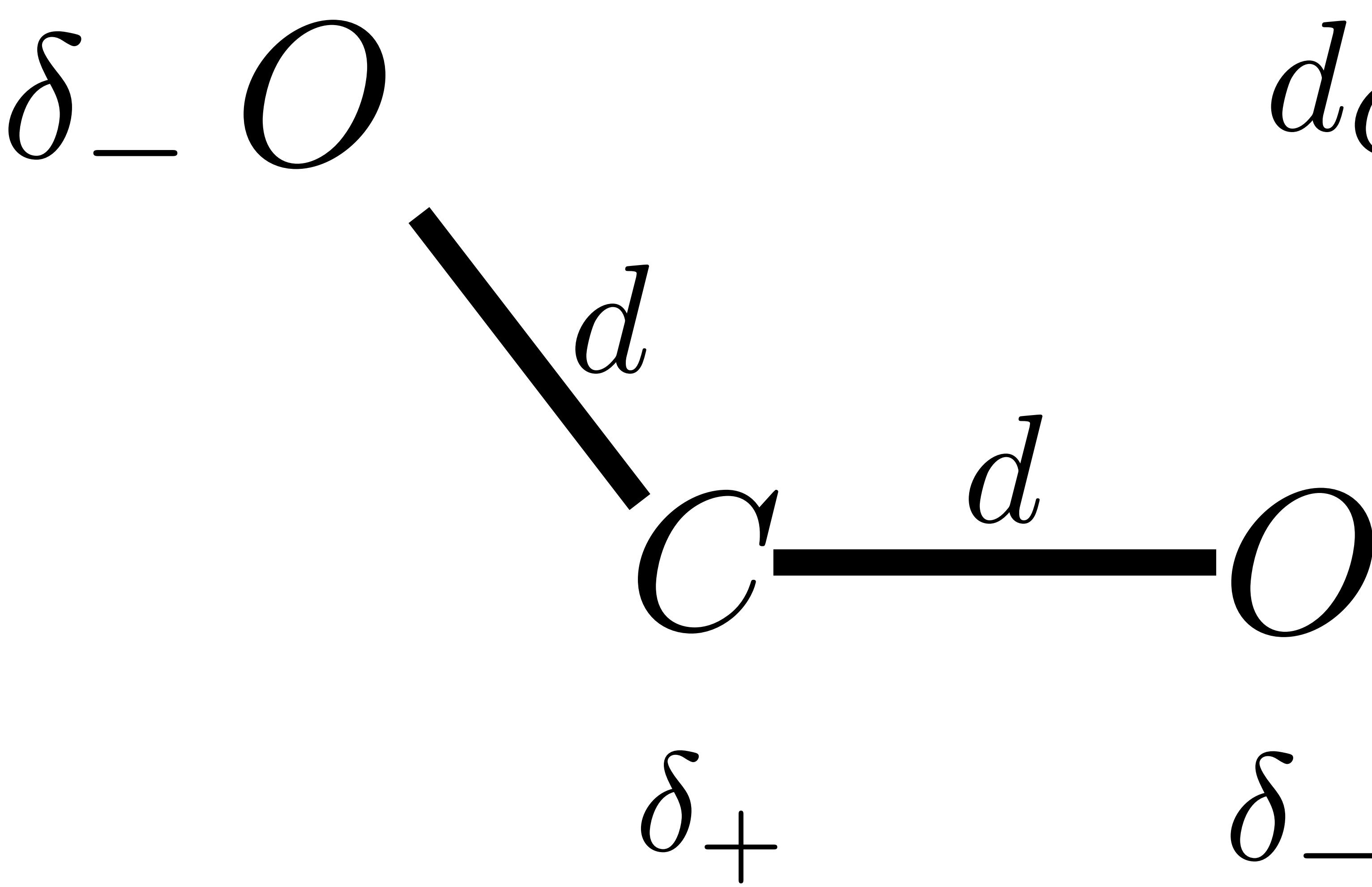
O δ_-

C δ_+

O δ_-

Classic Problem : Dipole moment of CO_2

Generic configuration



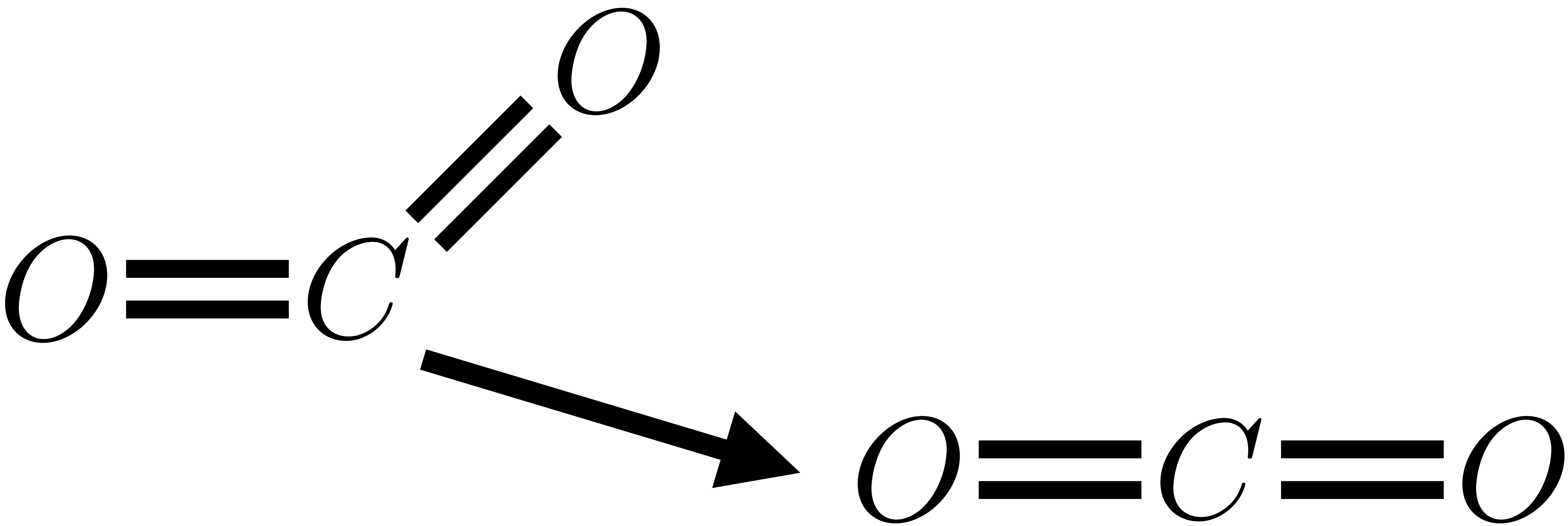
$$d_{CO_2} \approx \delta_+ d$$

Classic Problem : Dipole moment of CO_2

CO_2 dipole problem : measured dipole is zero!

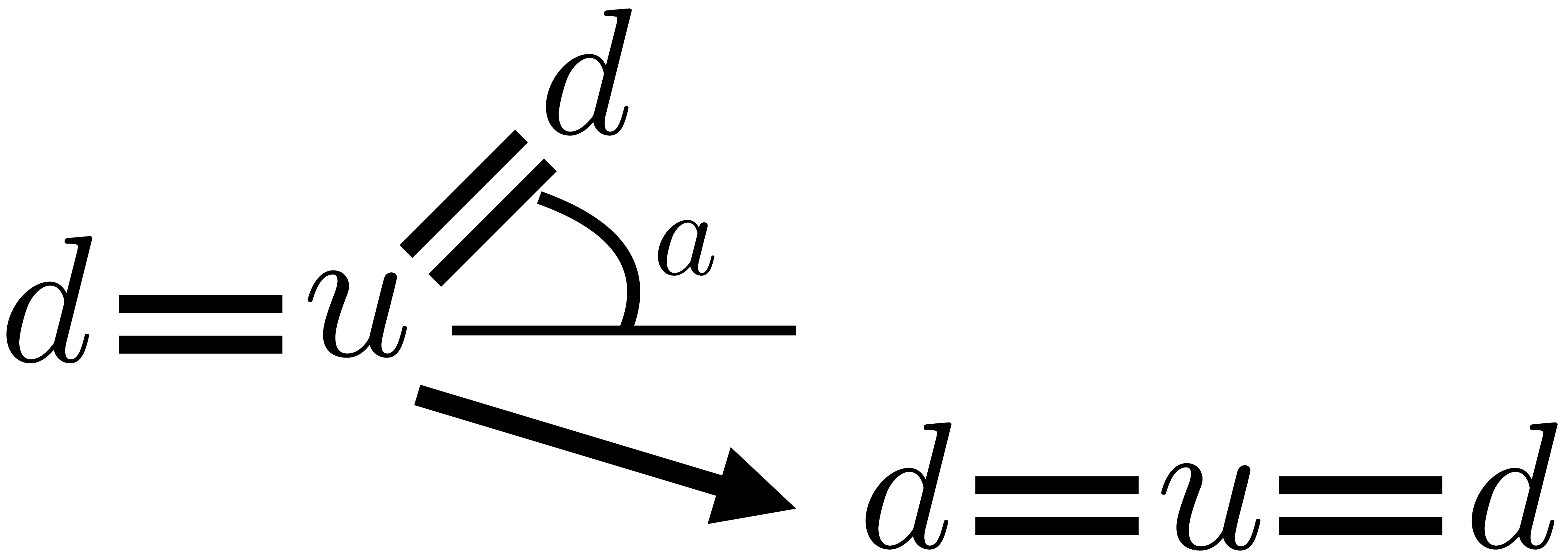
$$O = C = O$$

Classic Solution : Dipole moment of CO_2



Angle relaxes itself to zero!

Strong CP problem and the axion



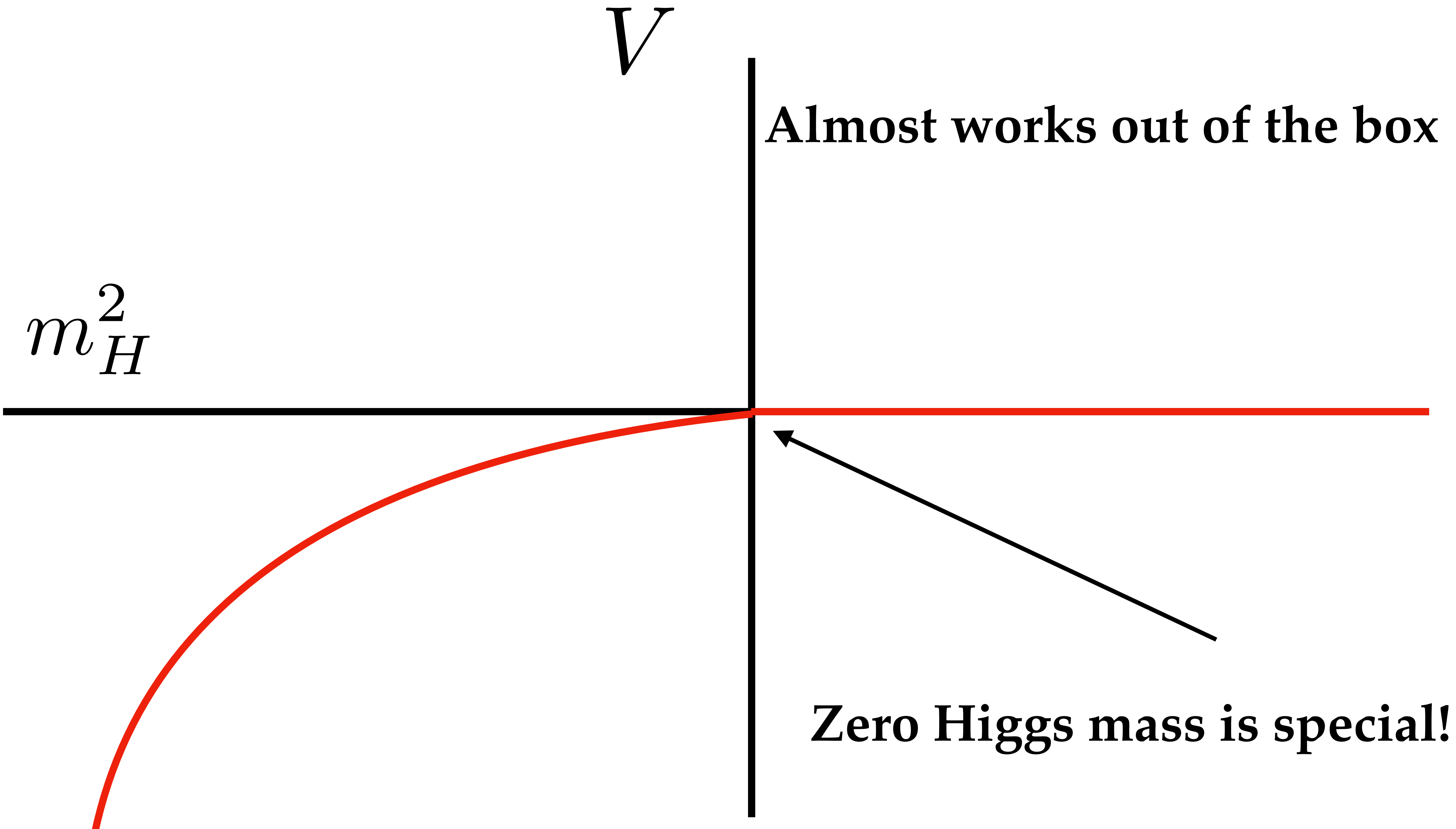
Axion relaxes angle to zero!

“Axion” approach to the Higgs

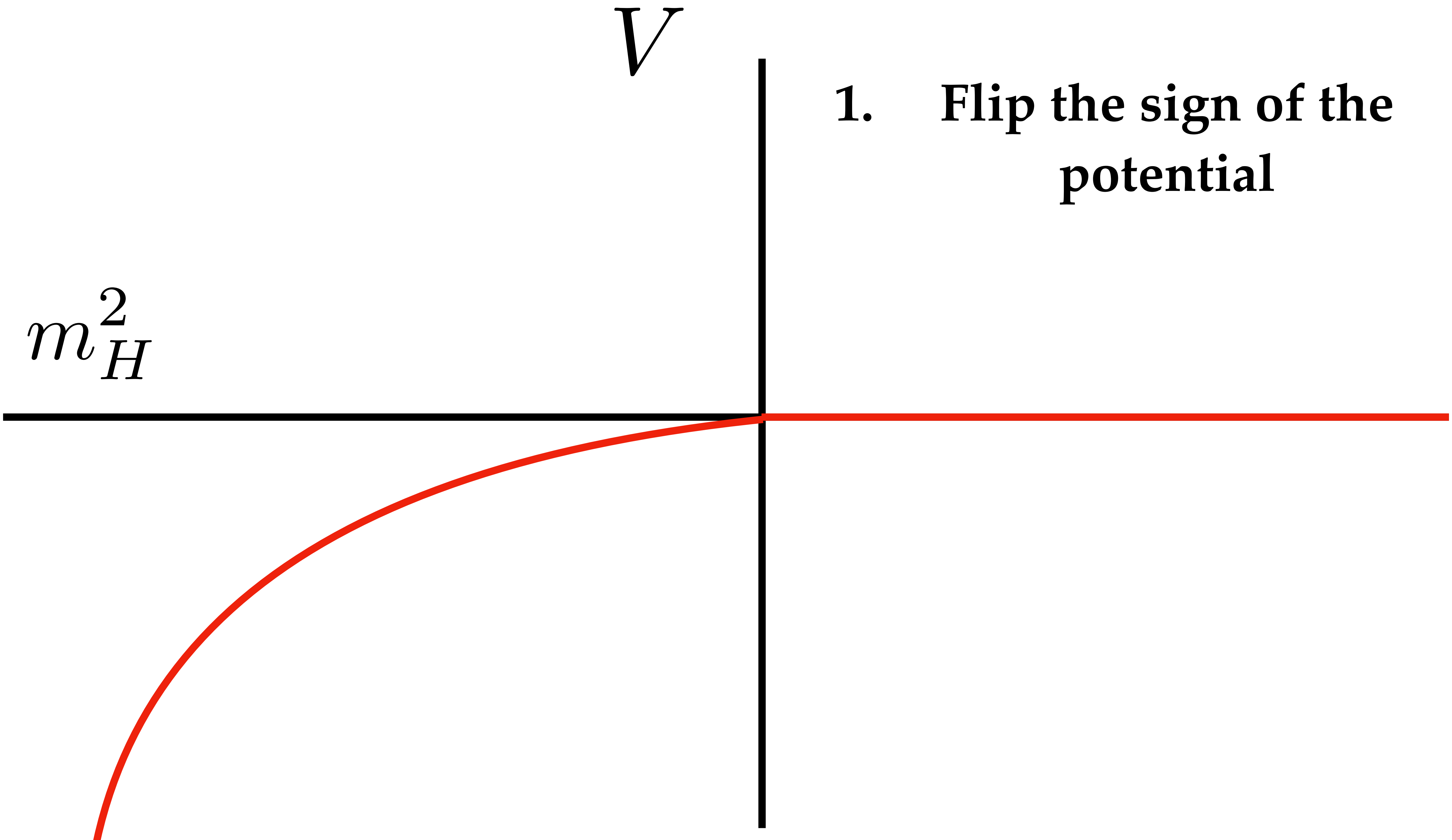
What if Higgs mass is dynamical, what happens?

$$V = -m_H^2 H H^\dagger + \frac{\lambda}{4}(H H^\dagger)^2$$

“Axion” approach to the Higgs

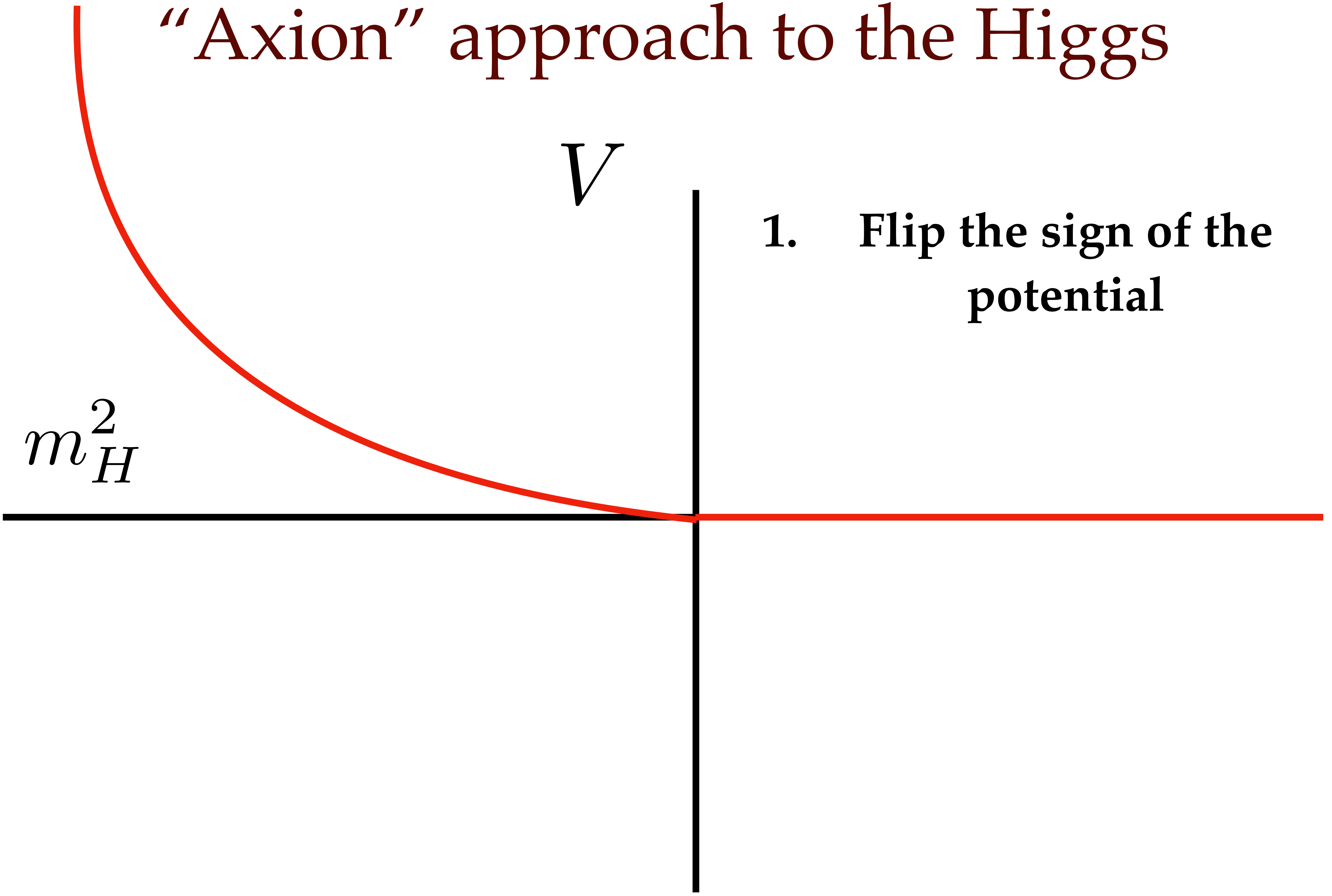


“Axion” approach to the Higgs



1. Flip the sign of the potential

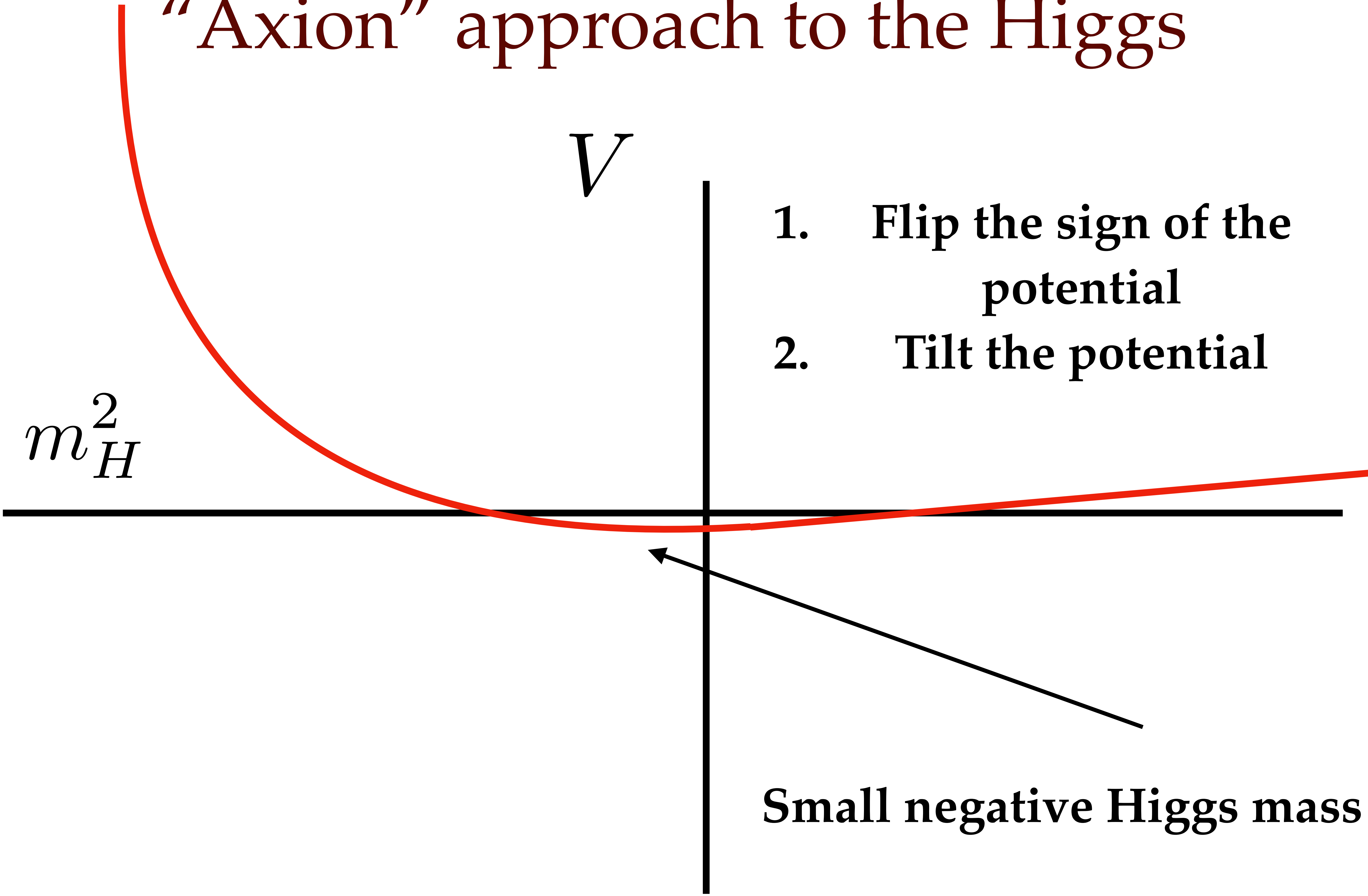
"Axion" approach to the Higgs



1. **Flip the sign of the potential**

“Axion” approach to the Higgs

1. **Flip the sign of the potential**
2. **Tilt the potential**



“Axion” approach to the Higgs

1. **Scan the Higgs mass**
2. **Flip the sign of the potential**
3. **Tilt the potential**

Possible in a N>2 Higgs doublet model!

Proof of principle that axion approach to the Higgs mass is viable

A. Hook 1802.10093

“Axion” approach to the Higgs

Phenomenology requires minimal model input

$$\mathcal{L} \supset \epsilon^2 \sin\left(\frac{\phi}{f}\right) H H^\dagger$$

Small f - LHC

Large f - 5th force

“Axion” approach to the Higgs

Pro :

The most common solution

Fairly predictive

Con :

Not developed enough to say for certain

Fermi was right

Second example : Fermi predicted field value where new physics occurs

Is it possible that we are mis-interpreting the results of dimensional analysis?

Fermi predicted field value where new physics occurs not distance/energy scale

Toy model

There is a toy model which shows that this is possible!

Axion without gluon coupling

$$\mathcal{L} = f^2|\Phi|^2 - |\Phi|^4 + \frac{\Phi^n}{M_{pl}^{n-4}}$$

Theory of a scalar with charge 1 under a Z_n symmetry

Toy model

Integrate out the radial mode $m_{\text{radial}} \sim f$

$$V \sim \frac{f^n}{M_{pl}^{n-4}} \cos\frac{n\phi}{f} \equiv \epsilon^4 \cos\frac{n\phi}{f}$$

$$\sim \frac{n^2\epsilon^4}{f^2}\phi^2 + \frac{n^4\epsilon^4}{f^4}\phi^4 + \cdots$$

Toy model

$$V \sim \frac{n^2 \epsilon^4}{f^2} \phi^2 + \frac{n^4 \epsilon^4}{f^4} \phi^4 + \cdots$$

Compare this to our naturalness estimate

$$\Lambda_{NP,\mathrm{guess}} \sim \frac{m}{\sqrt{\lambda}} \sim \frac{f}{n} = \frac{m_{\mathrm{radial}}}{n}$$

Guessed the wrong scale for new physics!

Toy model

$$\Lambda_{NP,\text{guess}} \sim \frac{m}{\sqrt{\lambda}} \sim \frac{f}{n} = \frac{m_{\text{radial}}}{n}$$

Guessed the wrong scale for new physics!

$$V \sim \epsilon^4 \cos\frac{n\phi}{f}$$

Instead we got the field value where the theory behaves qualitatively differently

A. Hook 1902.06758

Toy model

$$V \sim \epsilon^4 \cos \frac{n\phi}{f}$$

Phenomenology of new behavior in field space

Higher dimensional operators

High density/intensity environments

A. Hook 1902.06758

Toy model

For Yukawa couplings, you can break this relationship even more badly

A. Hook, M. Luty, R. Rattazzi XXXX.XXXX

Discrete shift symmetries can give Yukawa couplings non-trivial transformations

$$m^2 \propto y^n \Lambda^2$$

A. Hook 1802.10093

S. Das, A. Hook 2006.10767

L. Luzio, B. Gavela, P. Quilez, A. Ringwald
2102.00012 + 2102.01082

Keep tuned

Fermi was right

Pro : A solution that has been seen before

Con : Not developed enough to say for certain

Conclusion

Dimensional Analysis (naturalness) works so we must take it seriously

Just like Occam's razor

For the Higgs boson, it identifies the TeV scale

Traditionally this is the scale at where new particles appear

Conclusion

Age old solutions to age old problems

Compositeness **Historical**

“Axion” approach can relax the Higgs mass small

Find via axion type experiments

Maybe TeV scale is not the mass scale of new particles but instead the field value of new physics

Find via high precision/density/intensity experiments