COSMOLOGICAL NATURALNESS

Raffaele Tito D’Agnolo - IPhT Saclay

PASCOS 2021

Cosmological Constant

$$\Lambda^4$$

SIZE OF THE UNIVERSE

Higgs Mass Squared

$$m_h^2 |H|^2$$

WEAK FORCE, STRUCTURE OF NUCLEI, COMPLEX CHEMISTRY, …

SYMMETRY

$$m_h^2 \sim y_t^2 M_{\rm Pl}^2$$

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Selection Rules of
Spacetime Dilations

(assuming masses at
the Planck scale)

SYMMETRY

$$m_h^2 \sim y_t^2 M_{\rm Pl}^2$$

Selection Rules of the
Higher-Spin Symmetry
of Free Scalars

See R. Rattazzi @ GGI: https://www.ggi.infn.it/talkfiles/slides/slides5297.pdf

Cosmological Constant

$$\Lambda^4$$

Theory ~ 10^{120} Experiment

Higgs Mass Squared

$$m_h^2 |H|^2$$

Theory~10^{34} Experiment

Cosmological Constant

Higgs Mass Squared

This is not a well-posed problem
in the Standard Model EFT

Theory ~ 10^{120} Experiment

Theory~10^{34} Experiment

Cosmological Constant

Higgs Mass Squared

The two quantities are not calculable

Theory ~ 10^{120} Experiment

Theory~10^{34} Experiment

Cosmological Constant

Higgs Mass Squared

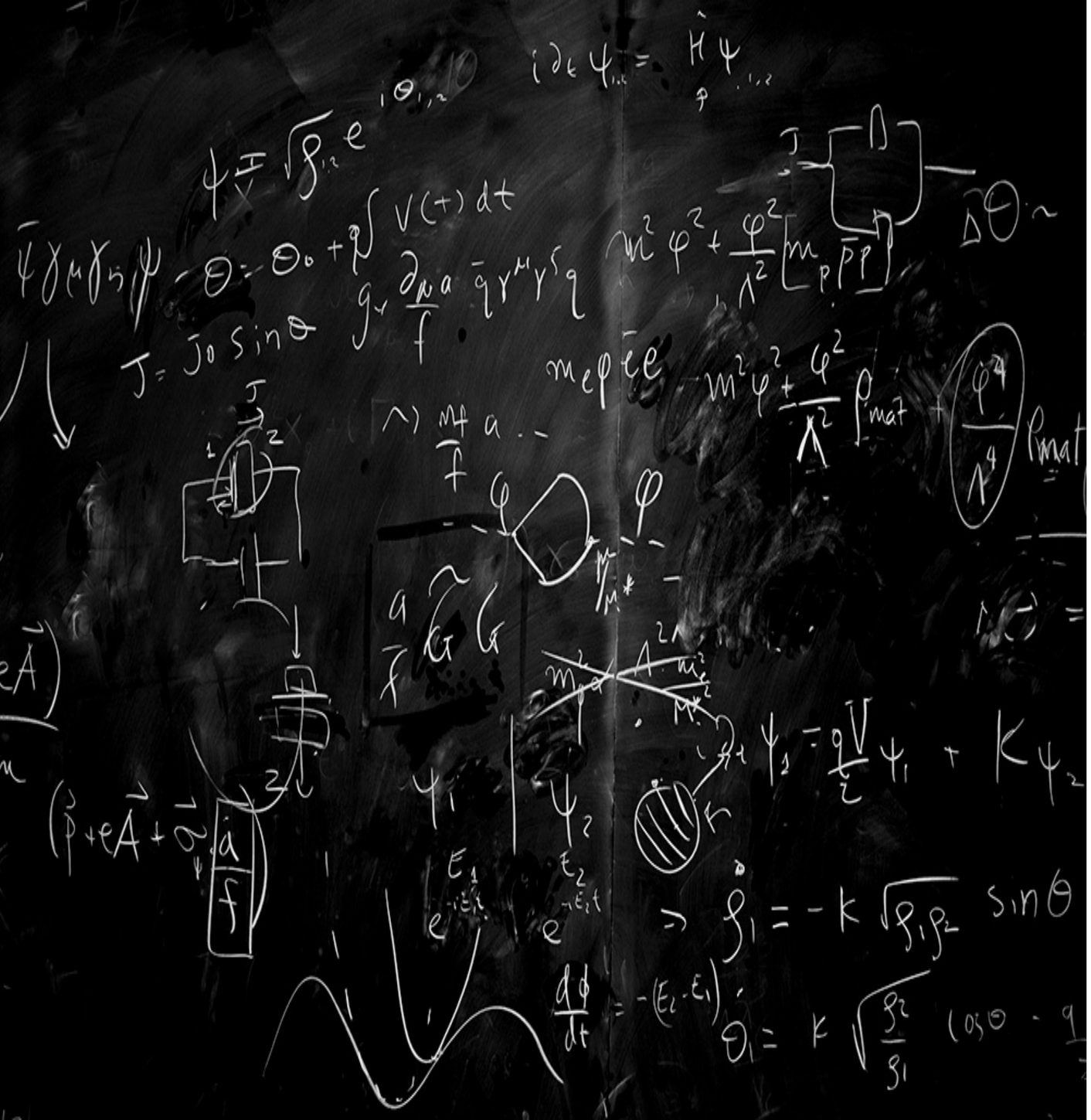
Precious clue about fundamental physics in the UV

Theory ~ 10^{120} Experiment

Theory~10^{34} Experiment

WHAT KIND OF PHYSICIST ARE YOU?

The Theorist



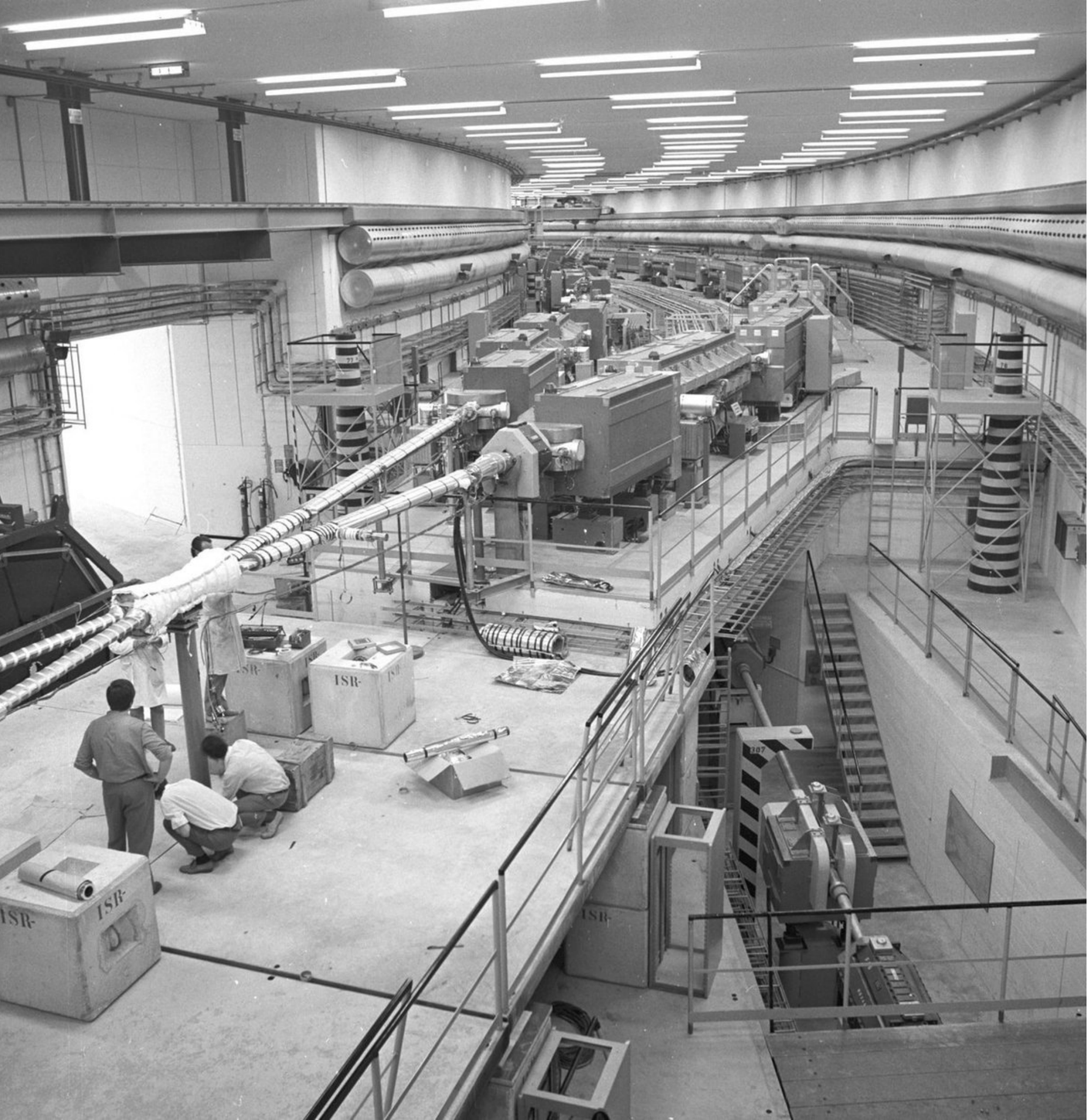
The Theorist

Planck

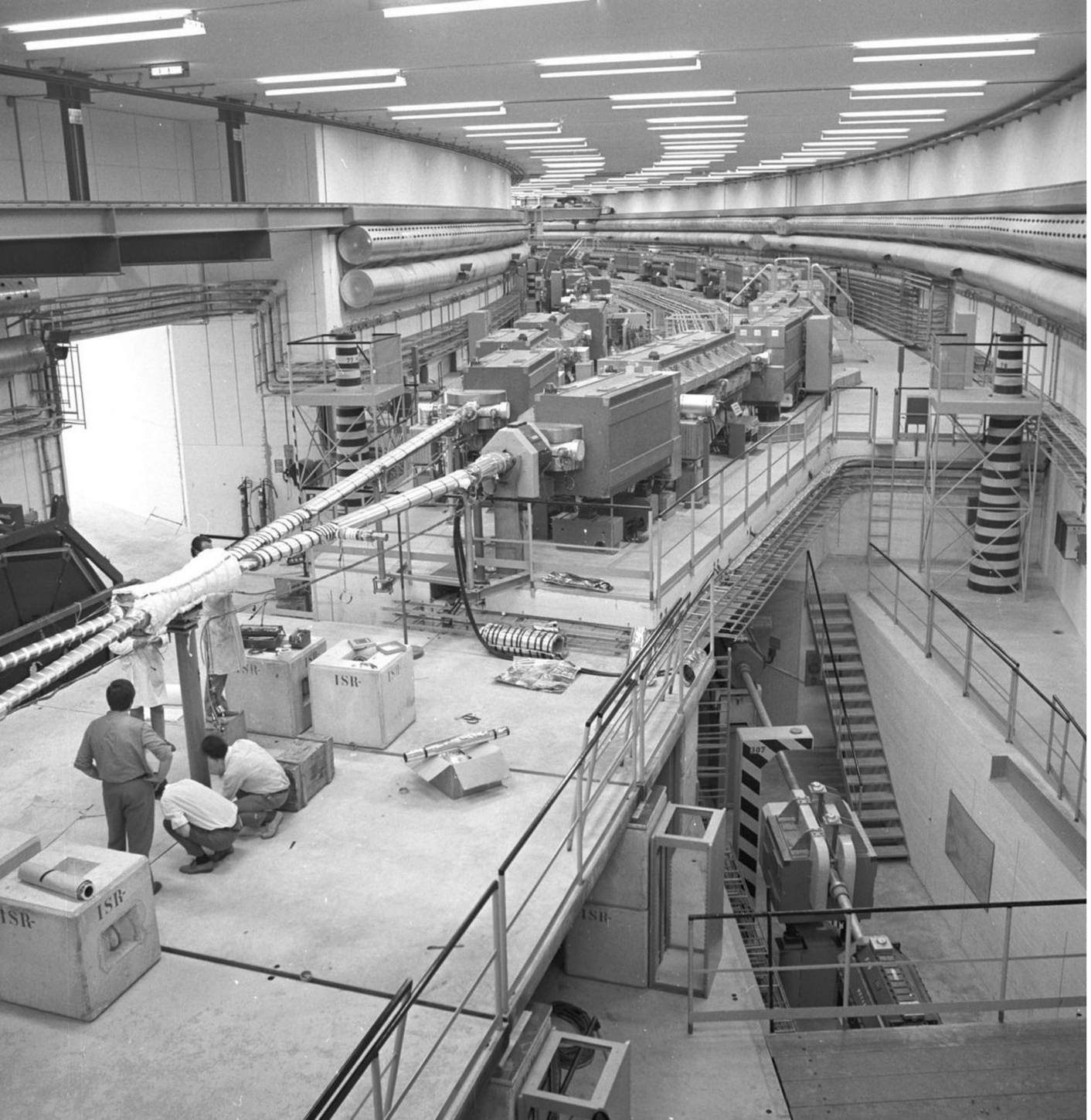
String

SUSY

SM



The Experimentalist



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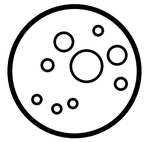
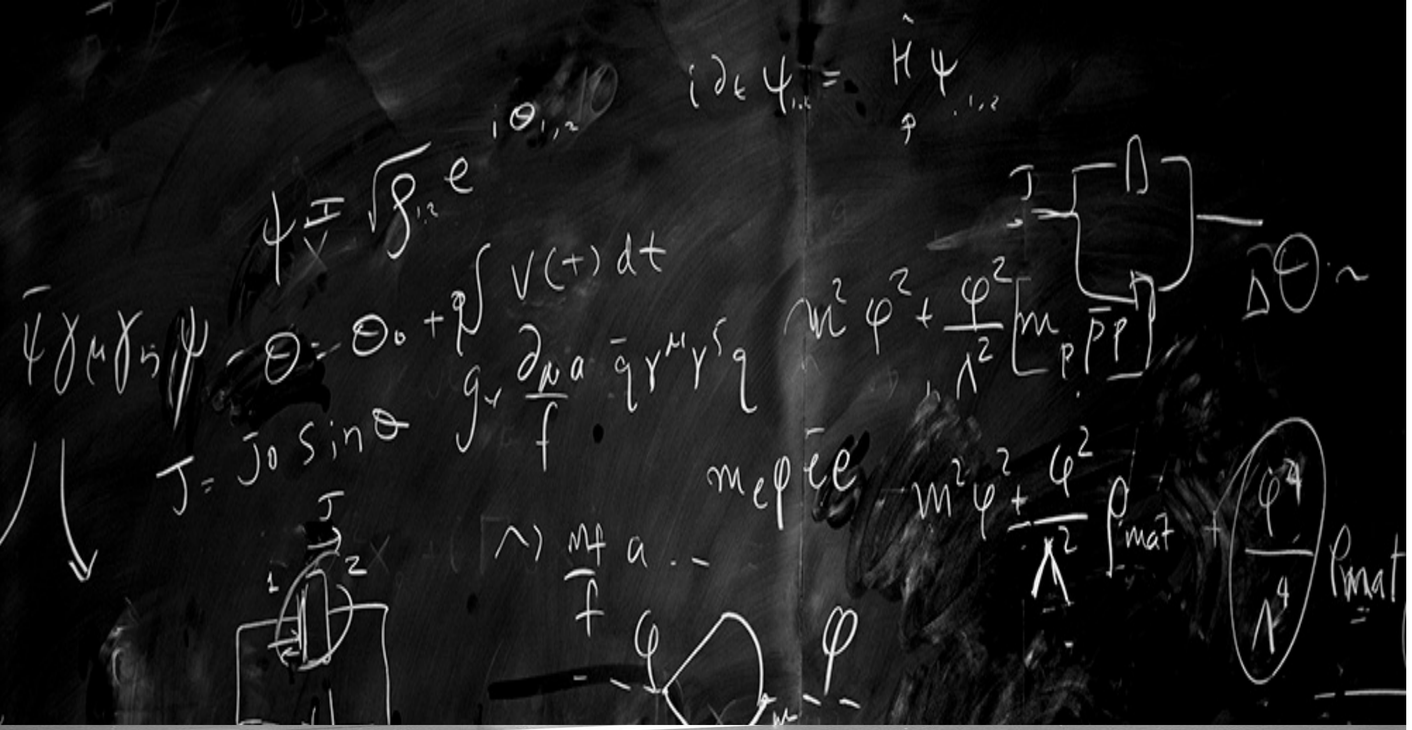


Mysterious
QG
Blob

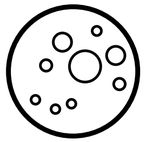
SM



The Theorist

who wants to be an

Experimentalist



Mysterious QG Blob

SUSY or confining sector or …

SM

Why $M_{\rm Pl}^4 \gg m_h^4, \Lambda_{\rm CC}^4$?

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Mysterious
QG
Blob

SM

Why $M_{\rm Pl}^4 \gg m_h^4, \Lambda_{\rm CC}^4$?

Mysterious QG Blob

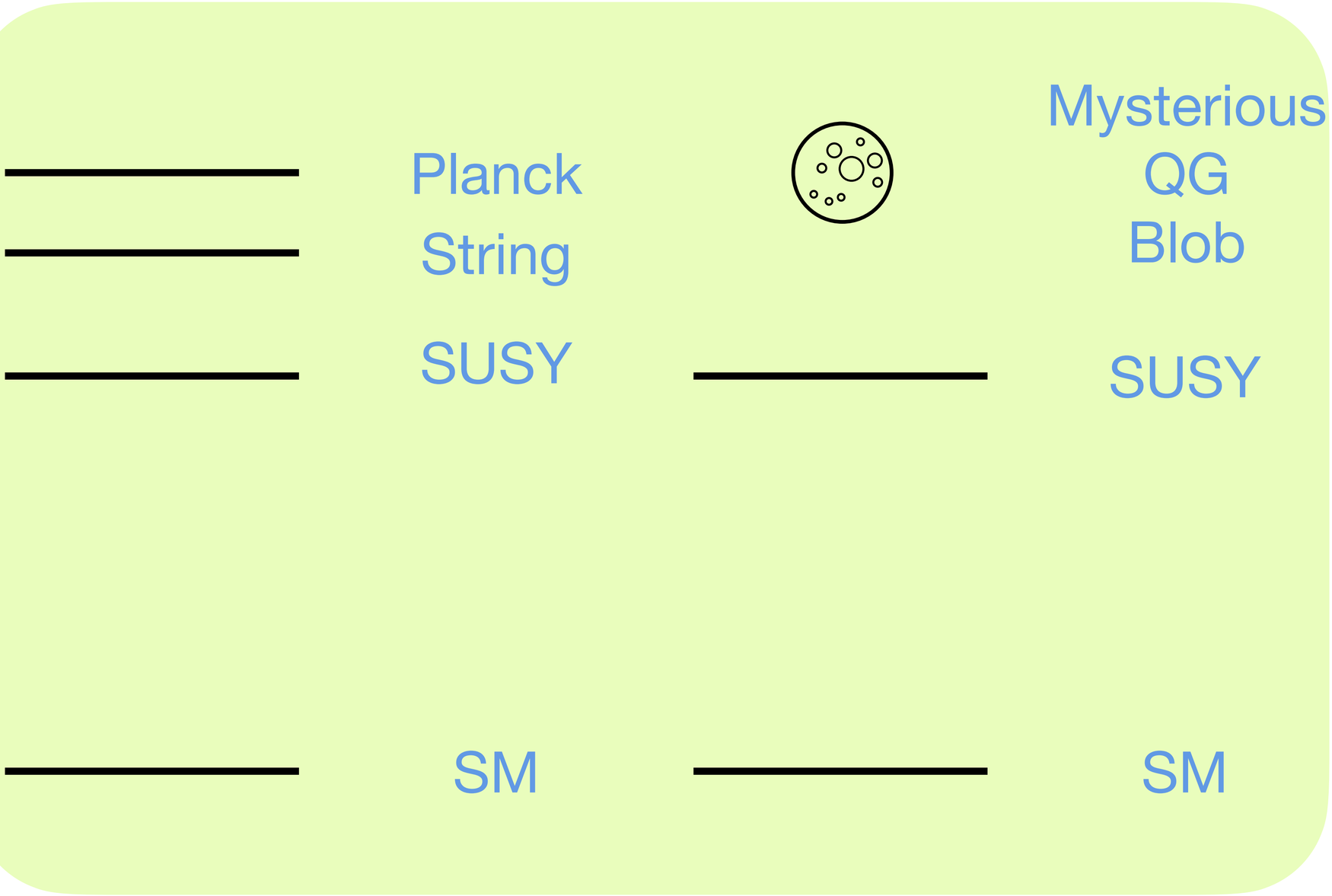
SM

1. Cosmological Constant and Higgs mass are inputs (can not be calculated, only measured)

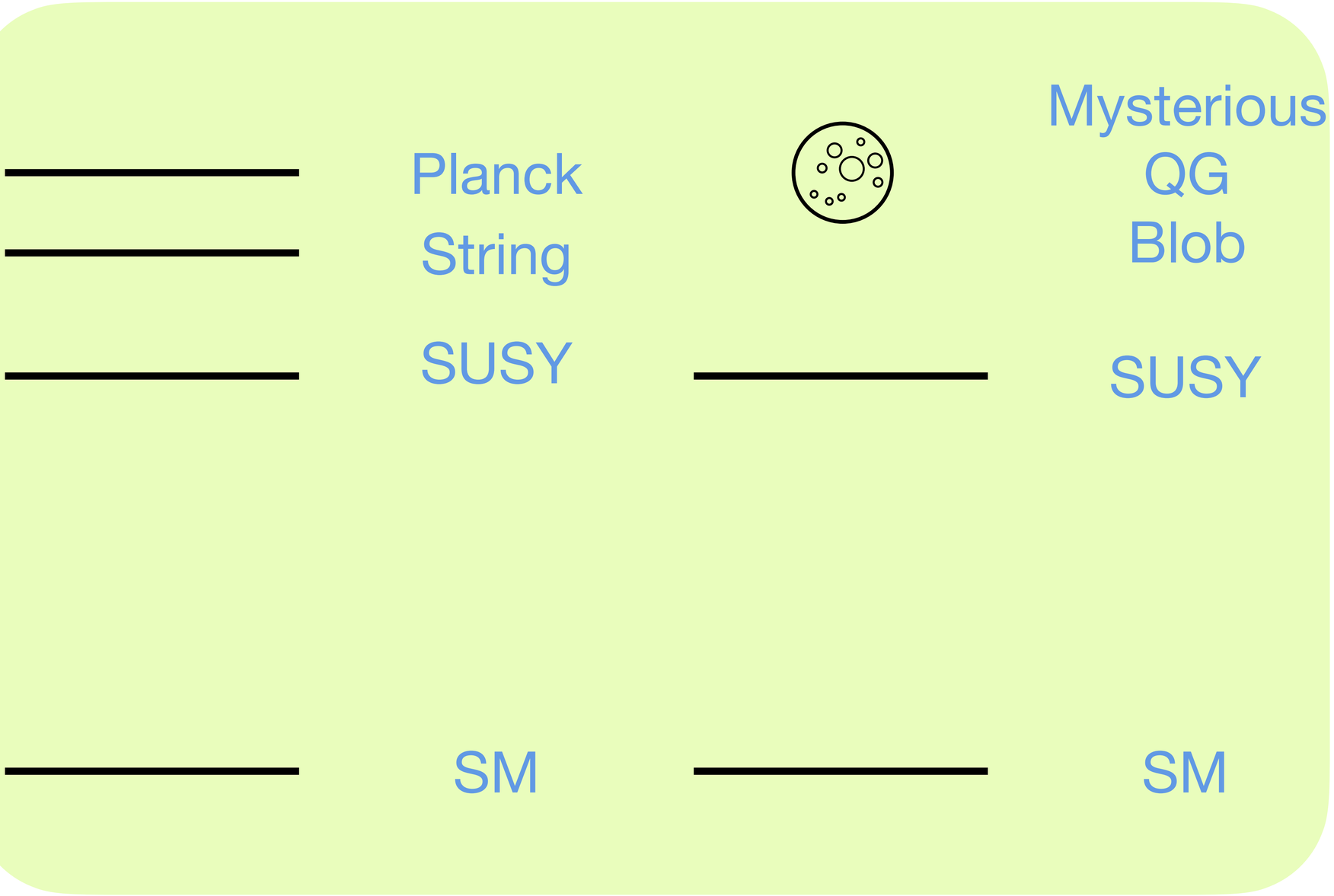
2. UV/IR Mixing

3. IR constraints from UV consistency (swampland, …)

Why $M_{\rm Pl}^4 \gg m_h^4, \Lambda_{\rm CC}^4$?



Why $M_{\rm Pl}^4 \gg m_h^4, \Lambda_{\rm CC}^4$?



Well-posed question in the low energy theory

Caveat: it could sill be answered in the UV (landscape+swampland, …)

EXAMPLE: HIGGS VEV IN THE MSSM

$$v^2 = \frac{2}{g^2 + g'^2}\left(\frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin(2\beta)^2}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2 + \frac{y_t^2}{16\pi^2} m_{\widetilde{t}}^2 f\left(\frac{m_{\widetilde{t}_1}^2}{m_{\widetilde{t}}^2}, \frac{m_{\widetilde{t}_2}^2}{m_{\widetilde{t}}^2}\right)\right) + \ldots$$

FINE-TUNING 101

A physical observable can be computed as the sum of multiple unrelated contributions

$$\mathcal{O} = O_1 + O_2 + ...$$

At least two of them are much larger than its observed value

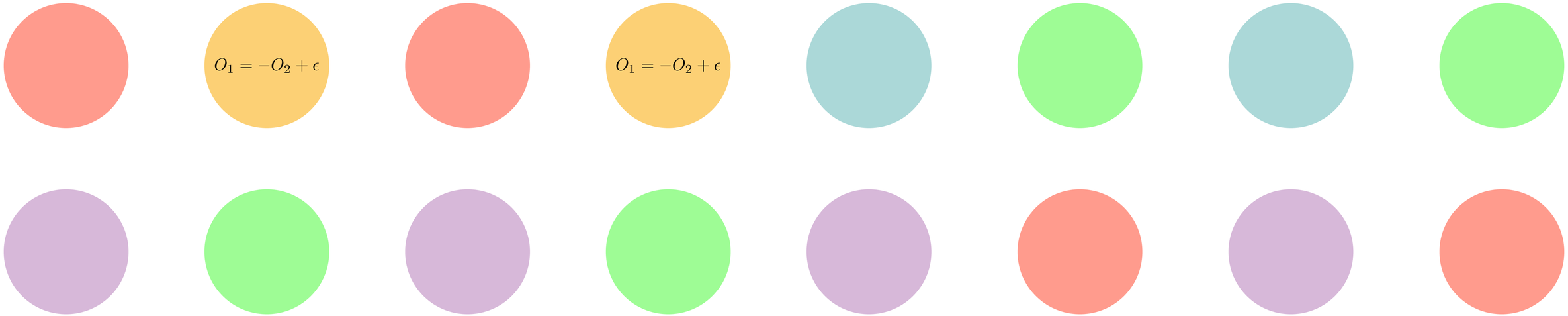
$$\mathcal{O}_{\rm obs} \ll |O_{1,2}|$$

FINE-TUNING 101

Is there a symmetry without a landscape?

$$O_1 = -O_2 + \epsilon$$

Is there a landscape?



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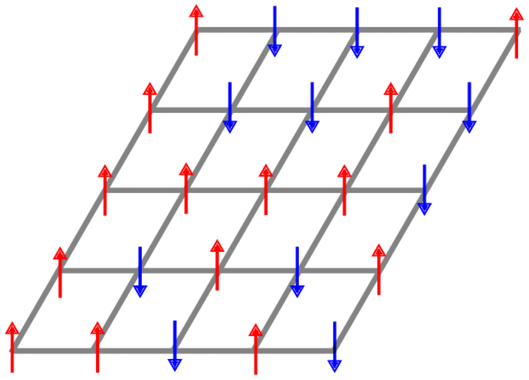
Example:

Prepare Ising Model



Scan Temperature

$$T - T_c \simeq 10^{-30}$$

The scalar is
much lighter
than the lattice spacing

STATUS OF THE FIELD

Is there a symmetry without a landscape?

$$O_1 = -O_2 + \epsilon$$

Cosmological Constant

$$\Lambda \simeq 10^{-12} m_h$$

Higgs Mass

Extremely different
scales (and physics)

Traditional Approach: Factorize the problems

$$\left(\Lambda^4\right) \times \left(m_h^2 |H|^2\right)$$

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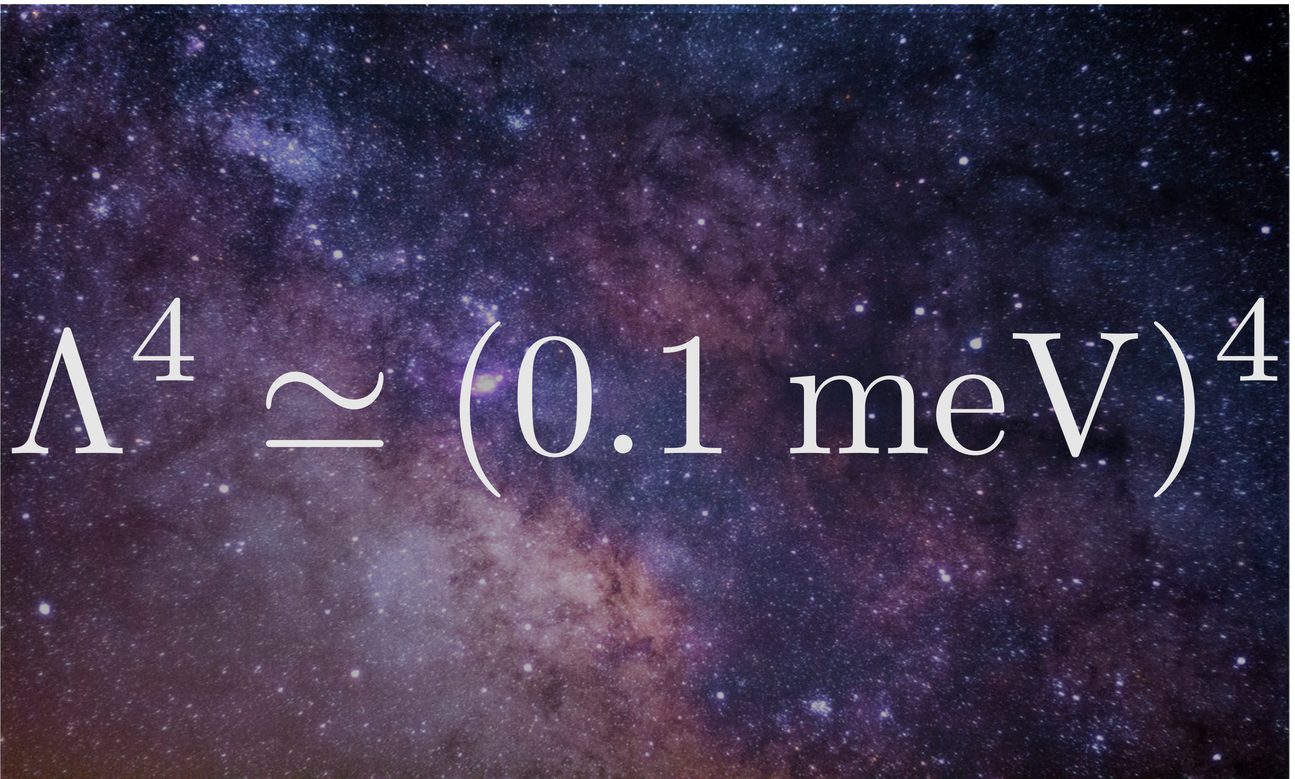

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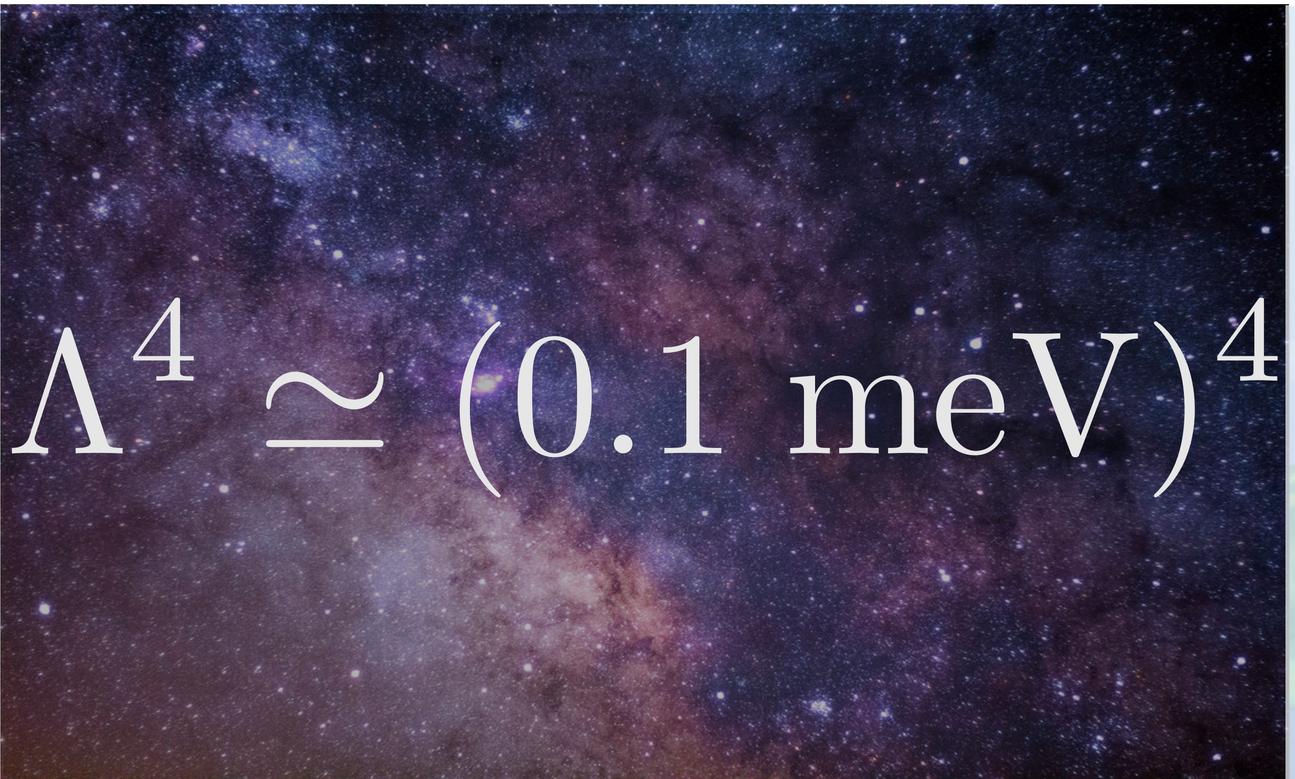
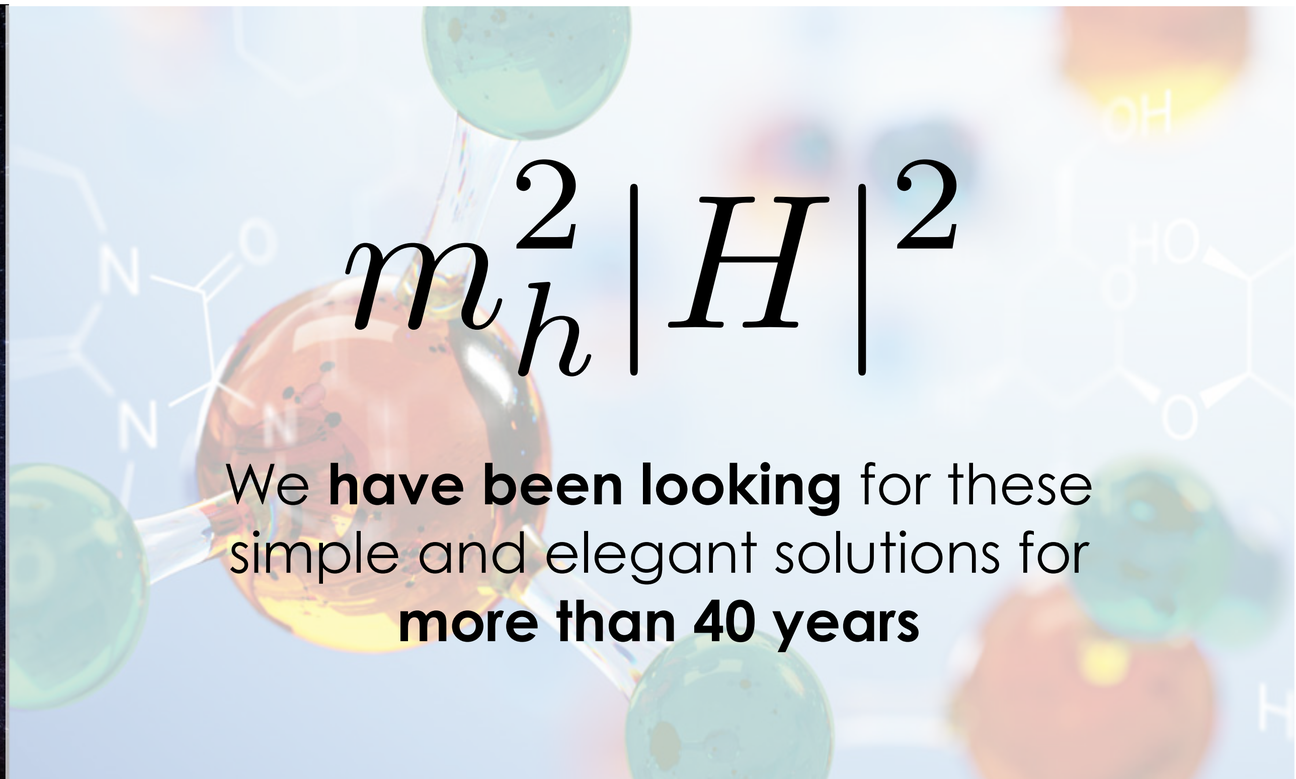


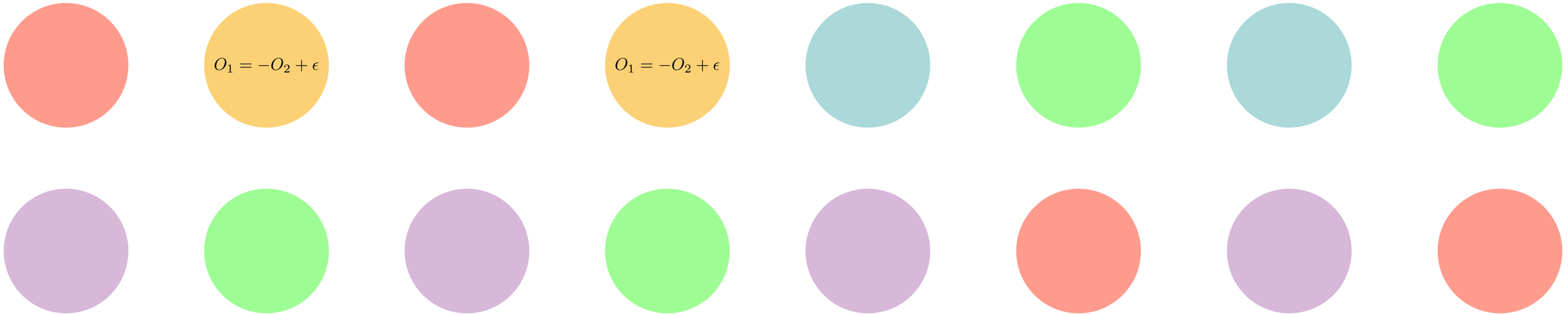


We **have been looking** for these simple and elegant solutions for **more than 40 years**

It is a good time to **consider seriously more creative alternatives**

A LANDSCAPE

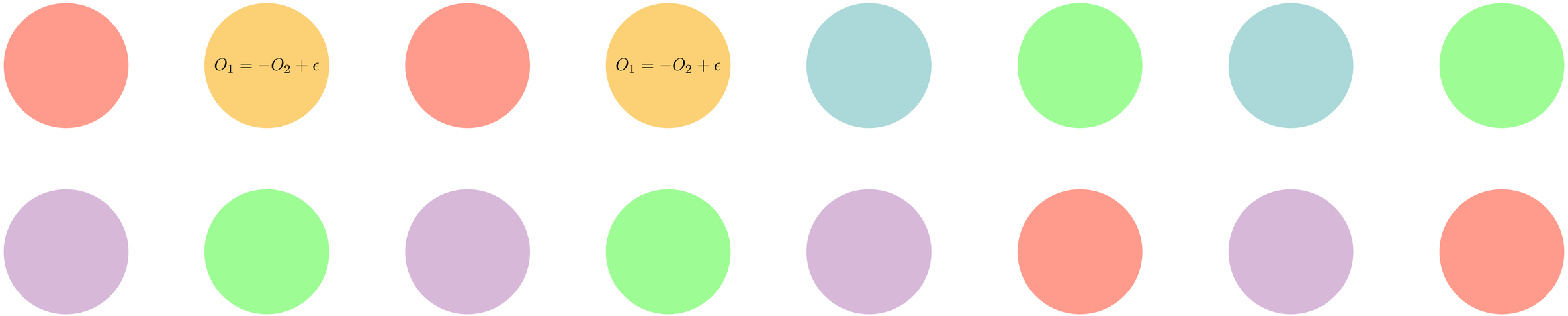
Is there a landscape?



A LANDSCAPE

1. One day it can be tested experimentally
2. Currently our most concrete explanation for the CC
3. It probably exists independently of the two problems

Is there a landscape?



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$$m_{H_u}^2 \gg m_h^2$$

Is there a problem? You first need to know the distribution of these parameters in the landscape

Change of perspective:

Can we find the origin of the weak scale early in the history of the Universe?

Historically:

Multiverse
+Anthropic selection

Recently:

New class of ideas that can be tested in the laboratory in the near future

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EXAMPLE: ANTHROPICS

Anthropic Arguments: **a symmetry and a landscape**

$$\Lambda_{\rm CC} \leftrightarrow \rho_{\rm MR} \left(\frac{\delta\rho}{\rho}\right)^3 \ll M_{\rm Pl}^4$$ [Weinberg '87]

$$v \leftrightarrow \Lambda_{\rm QCD} \ll M_{\rm Pl}$$ [Agrawal, Barr, Donoghue, Seckel '97]

EXAMPLE: ANTHROPICS

Anthropic Arguments: **a symmetry and a landscape**

$$\Lambda_{\rm CC} \leftrightarrow \rho_{\rm MR} \left(\frac{\delta\rho}{\rho}\right)^3 \ll M_{\rm Pl}^4$$

We do not know yet, but
easy to achieve

$$v \leftrightarrow \Lambda_{\rm QCD} \ll M_{\rm Pl}$$

Approximate scale invariance

Historically:

Multiverse
+Anthropic selection

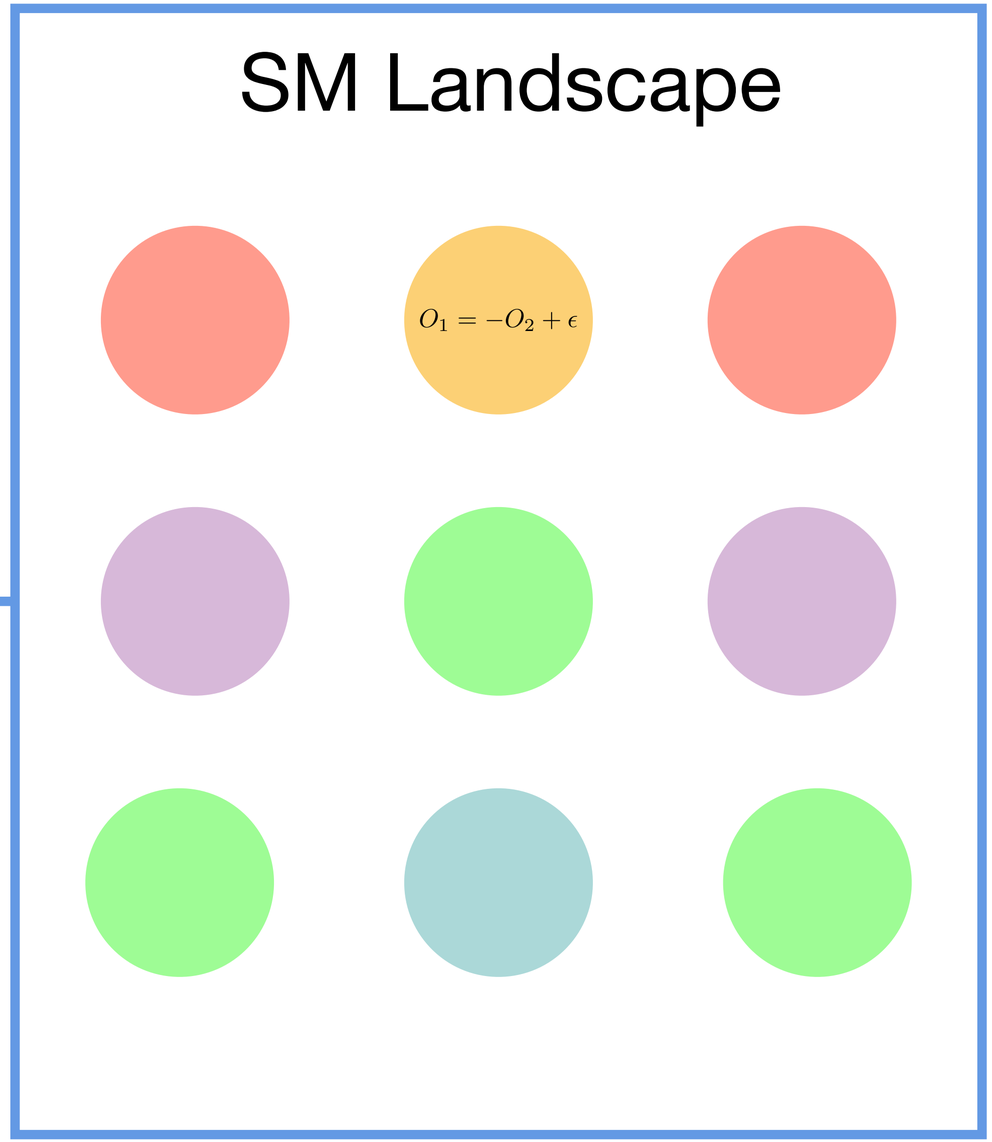
Recently:

New class of ideas that can be tested in the laboratory in the near future

Early History of the Universe

Symmetric Sector

$$\Lambda_S \ll M_{\rm Pl}$$

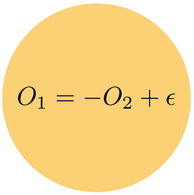


Late times

Symmetric Sector

$$\Lambda_S \ll M_{\rm Pl}$$

SM Landscape



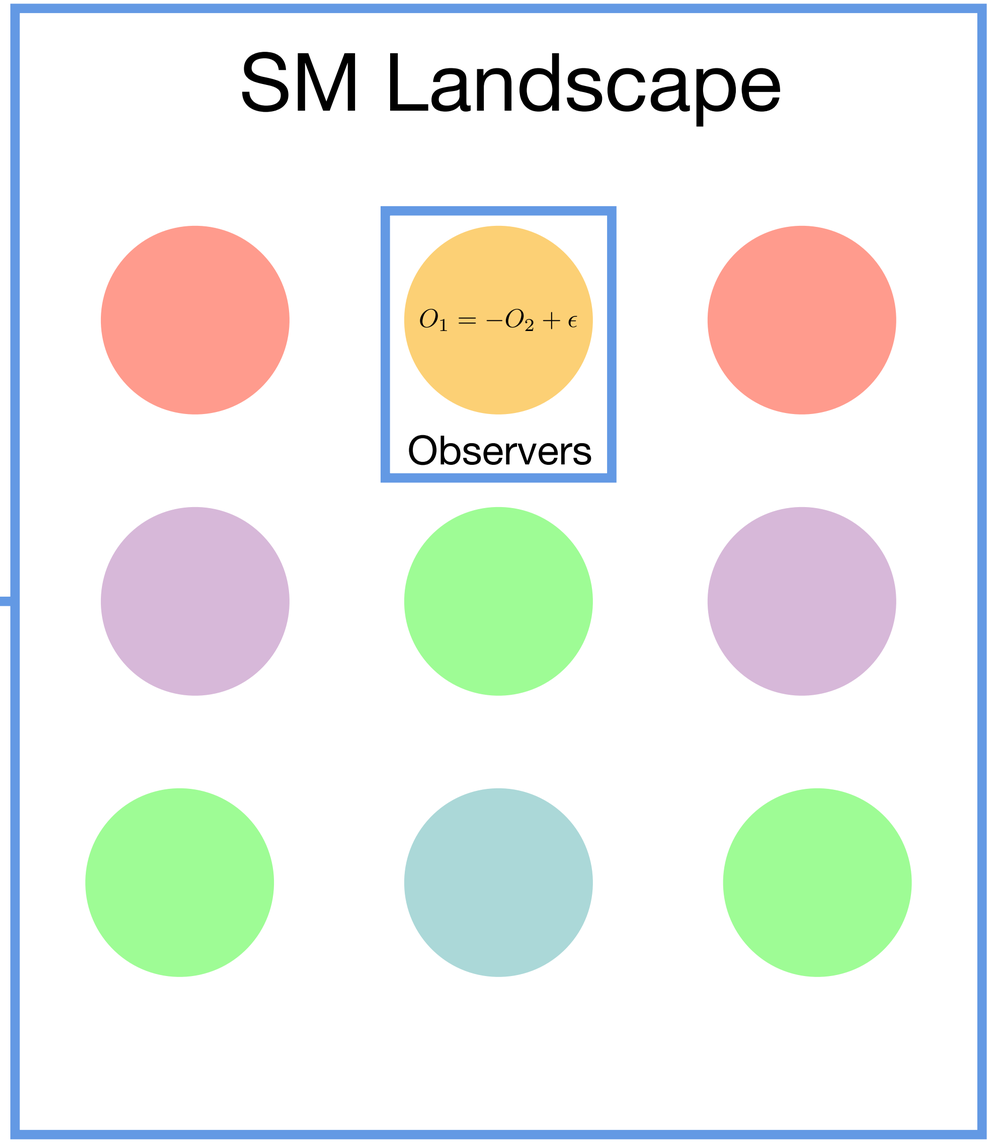
An event triggered by the symmetric sector selects the observed

$$m_h^2$$

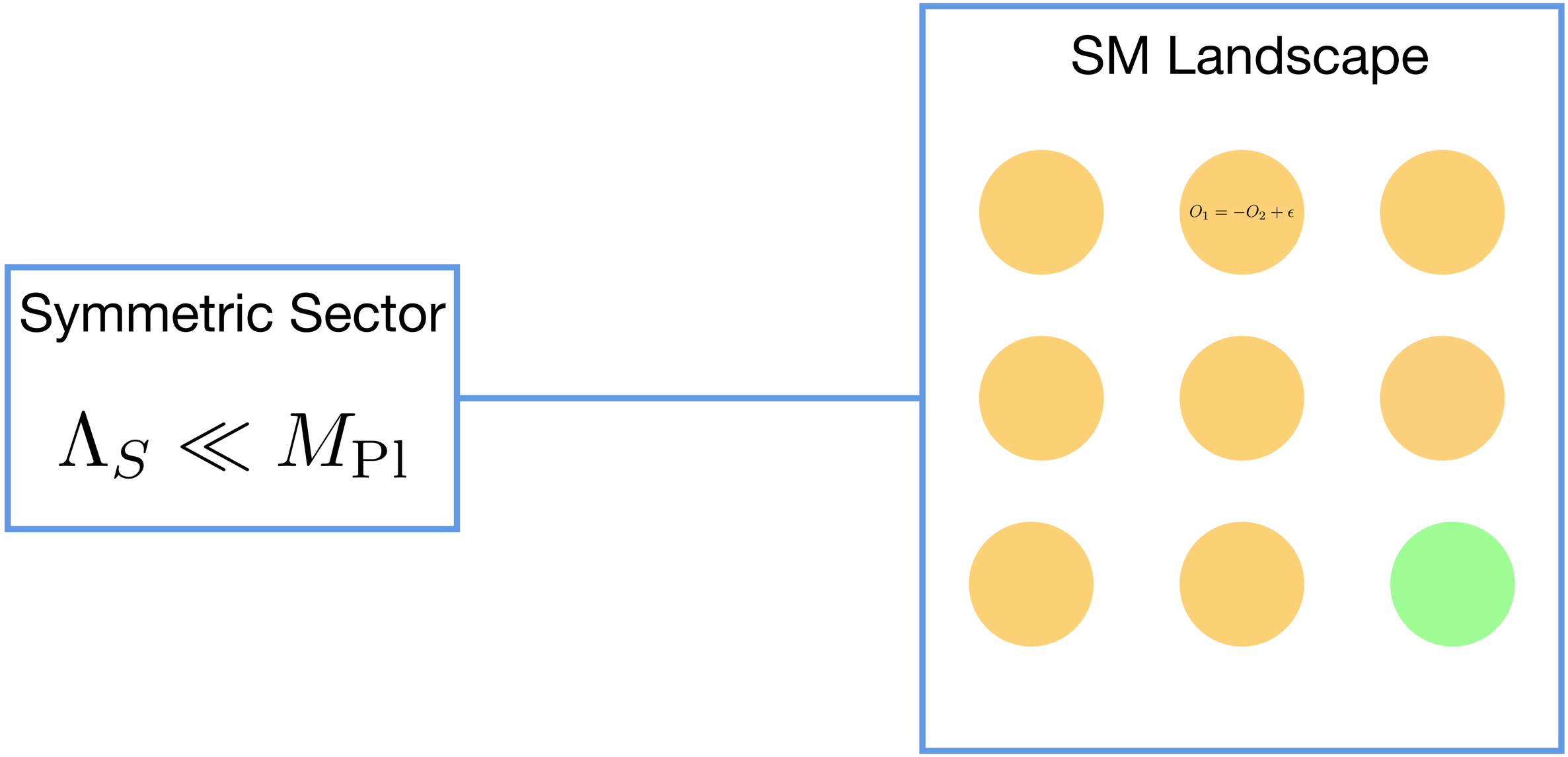
“Anthropic” Selection

Symmetric Sector

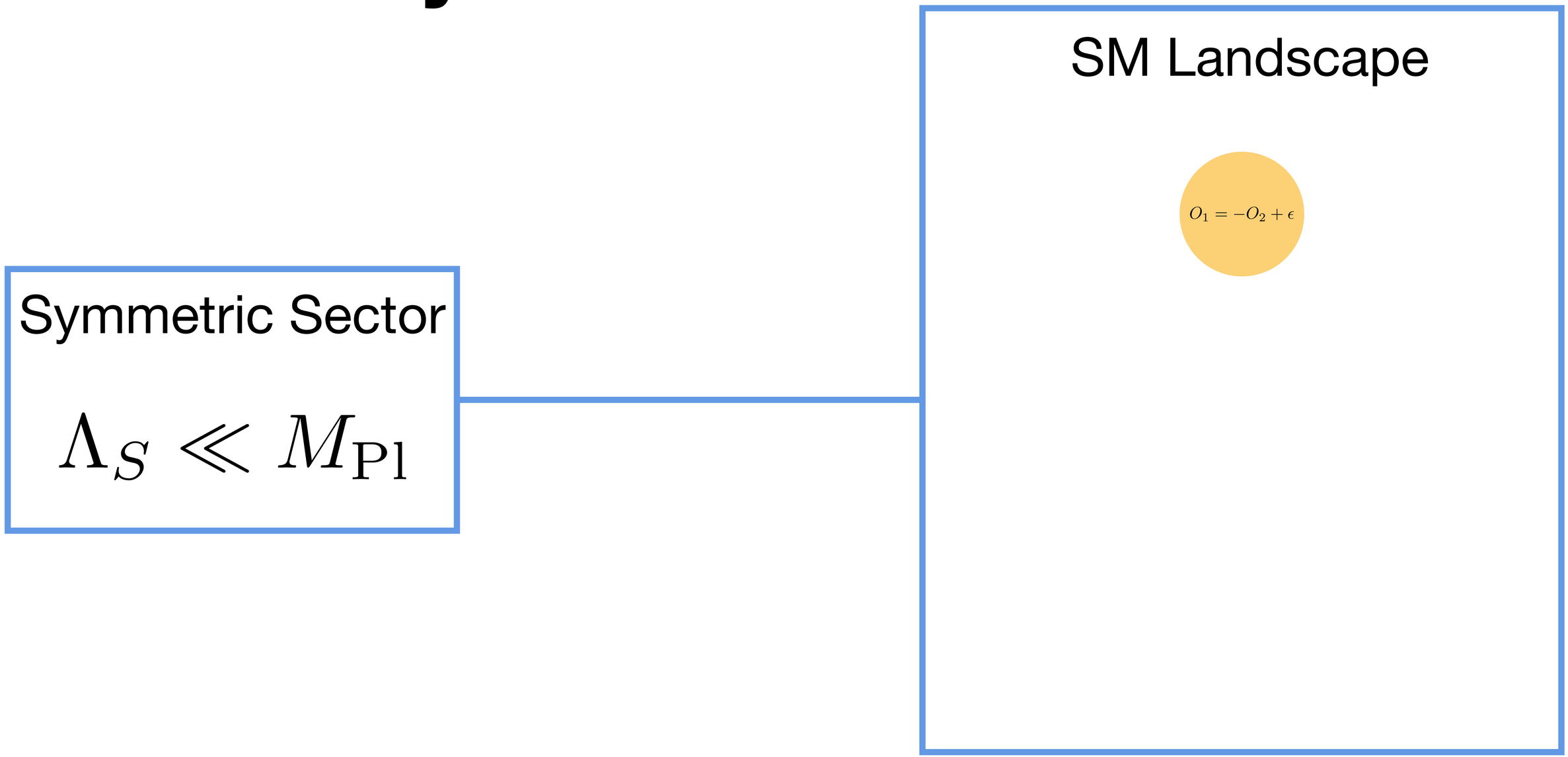
$$\Lambda_S \ll M_{\rm Pl}$$



“Statistical” Selection



“Dynamical” Selection



From now on: **focus on the Higgs vev**

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Anthropic Selection

[Agrawal, Barr, Donoghue, Seckel ’97], [Arvanitaki, Dimopoulos, Gorbenko, Huang, Van Tilburg ’16],

[Arkani-Hamed, RTD, Kim, ‘20],

[Giudice, Kehagias, Riotto, ’20],

…

Statistical Selection

[Dvali, Vilenkin ’03], [Dvali ’04], [Geller, Hochberg, Kuflik,’18], [Giudice, McCullough, You, ’21],

…

Dynamical Selection

[Graham, Rajendran, Kaplan, ’15], [Arkani-Hamed, Cohen, RTD, Kim, Pinner, ’16], [Csaki, RTD, Geller, Ismail, ’20], [Strumia, Teresi, ’20], [RTD, Teresi, ’21],

…

EXAMPLE: ANTHROPIC

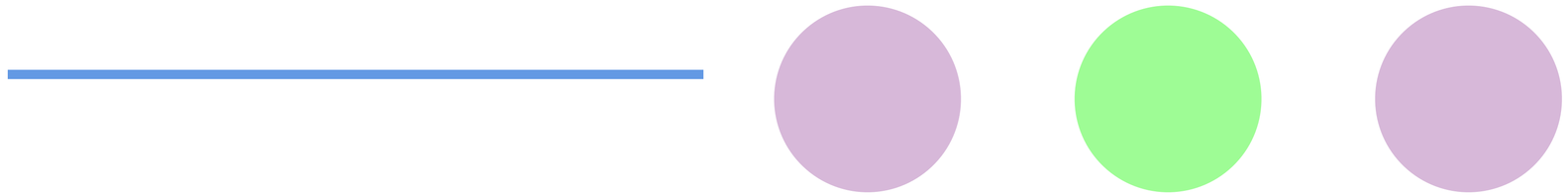
[Agrawal, Barr, Donoghue, Seckel ’97]

For complex chemistry we need a Higgs vev not too far from the QCD scale

Symmetric Sector

$$\Lambda_{\rm QCD} \ll M_{\rm Pl}$$

SM Landscape



QCD

$$Y_q Q H q^c$$

“Friendly”
String Landscape?

[Arakni-Hamed, Dimopoulos, Kachru, ‘05]

EXAMPLE: STATISTICAL

[Dvali, Vilenkin ’03], [Dvali ’04]

$$F_4 = dA_3$$

EXAMPLE: STATISTICAL

[Dvali, Vilenkin ’03], [Dvali ’04]

$$F_4 = dA_3$$

$$S \supset \int d^4x\sqrt{-g}\left(\frac{F_4^2}{48} + M_{\rm Pl}^2(-1 + \frac{F_4^2}{M_{\rm Pl}^2} + ...)|\phi|^2 + ...\right) + q(\phi)\int d^3\xi A_{\mu\nu\rho}\frac{\partial x^\mu}{\partial \xi^a}\frac{\partial x^\nu}{\partial \xi^b}\frac{\partial x^\rho}{\partial \xi^c}\epsilon^{abc}$$

EXAMPLE: STATISTICAL

[Dvali, Vilenkin ’03], [Dvali ’04]

$$q(\phi) = \frac{\phi^N}{M_{\rm Pl}^{N-2}}$$

$$\Delta\langle\phi\rangle^2/\langle\phi\rangle^2 \sim \langle\phi\rangle^{N-2}$$

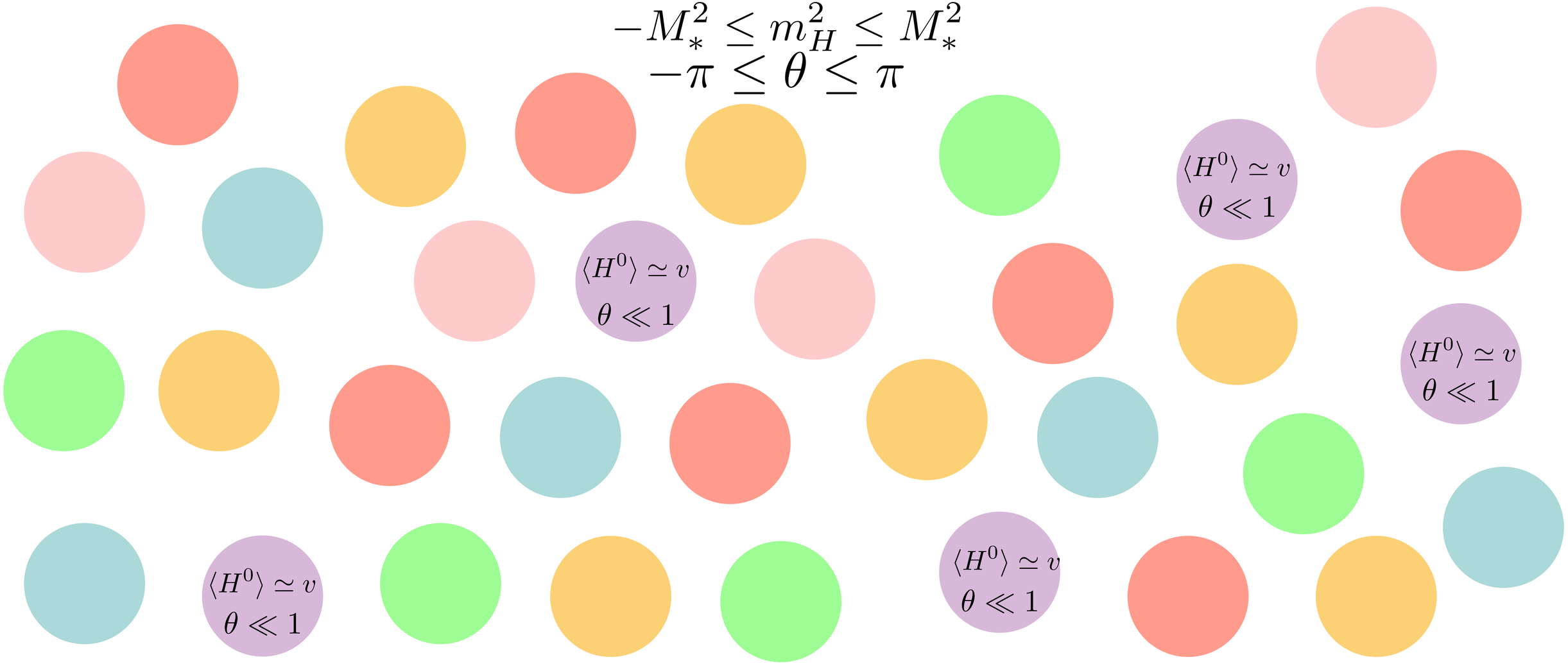
At every step the brane charge is smaller -> most vacua are at small vev

EXAMPLE: DYNAMICAL

[Bloch, Csaki, Geller ,Volansky ’19], [Csaki, Geller, RTD, Ismail, ‘20], [RTD, Teresi ’21]

Landscape of Higgs Masses and theta-angles populated by inflation

$$-M_*^2 \leq m_H^2 \leq M_*^2$$
$$-\pi \leq \theta \leq \pi$$



EXAMPLE: DYNAMICAL

[Bloch, Csaki, Geller ,Volansky ’19], [Csaki, Geller, RTD, Ismail, ‘20], [RTD, Teresi ’21]

After reheating and a time

$$t_c \sim 1/H(\Lambda_{\rm QCD}) \sim 10^{-5}\ s$$

All patches where the Higgs vev

$$\langle H^0 \rangle \equiv h$$

Is outside of a certain range

$$h_{\rm min} \lesssim h \leq h_{\rm crit}$$

And theta is large

$$\theta \leq \theta_{\rm max}$$

crunch

$\langle H^0 \rangle \simeq v$
$\theta \ll 1$

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Only universes with the observed value of the weak scale can live longer than EW time. **Today the multiverse looks like**:

$\langle H^0 \rangle \simeq v$
$\theta \ll 1$

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EXAMPLE: DYNAMICAL

[RTD, Teresi ’21]

$$V = \mp m_{\pm}^2 \phi_{\pm}^2 - \lambda_{\pm} \phi_{\pm}^4 + \frac{\alpha_s}{8\pi} \left(\theta + \frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} \right) G\tilde{G}$$

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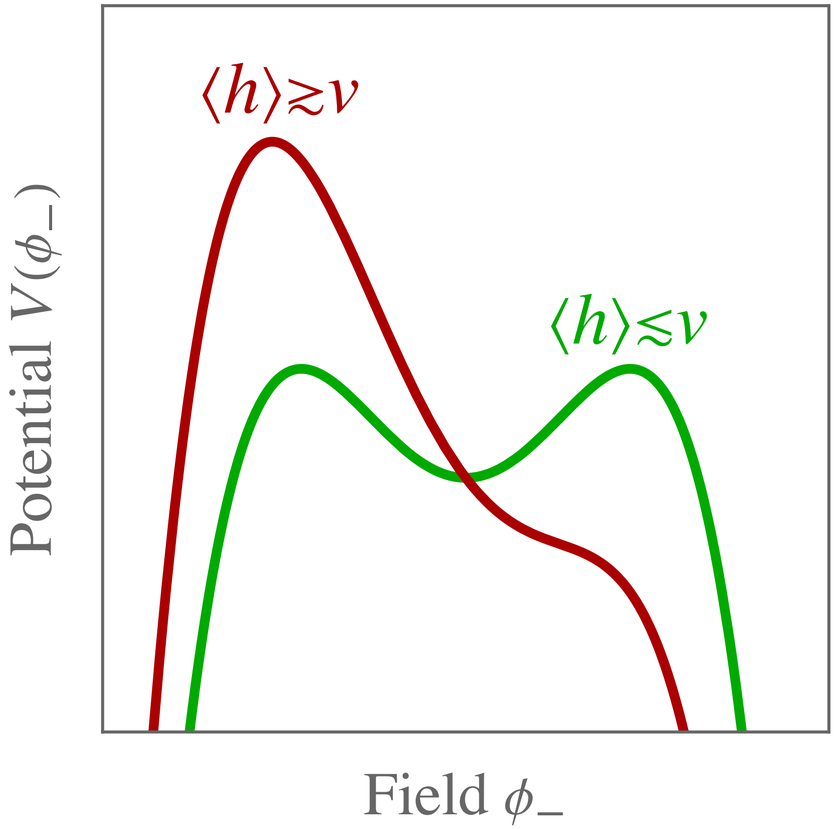

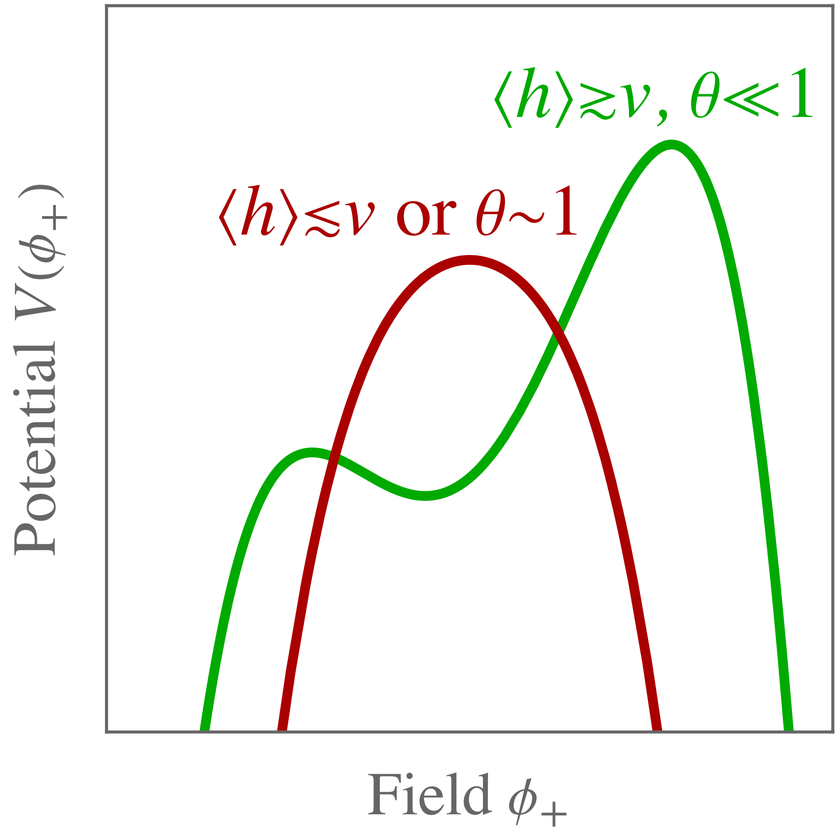

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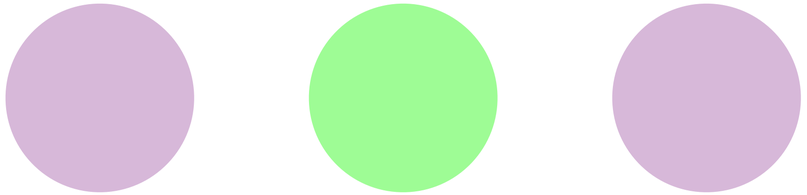
Symmetric Sector

$$m_{\pm} \ll M_{\rm Pl}$$

SM Landscape



$\phi_{\pm}$

$\phi_{\pm} G\tilde{G}$

“Friendly”
String Landscape?

[Arakni-Hamed, Dimopoulos, Kachru, ‘05]

Anthropic Selection

Does not require new physics with couplings to the SM stronger than gravitational

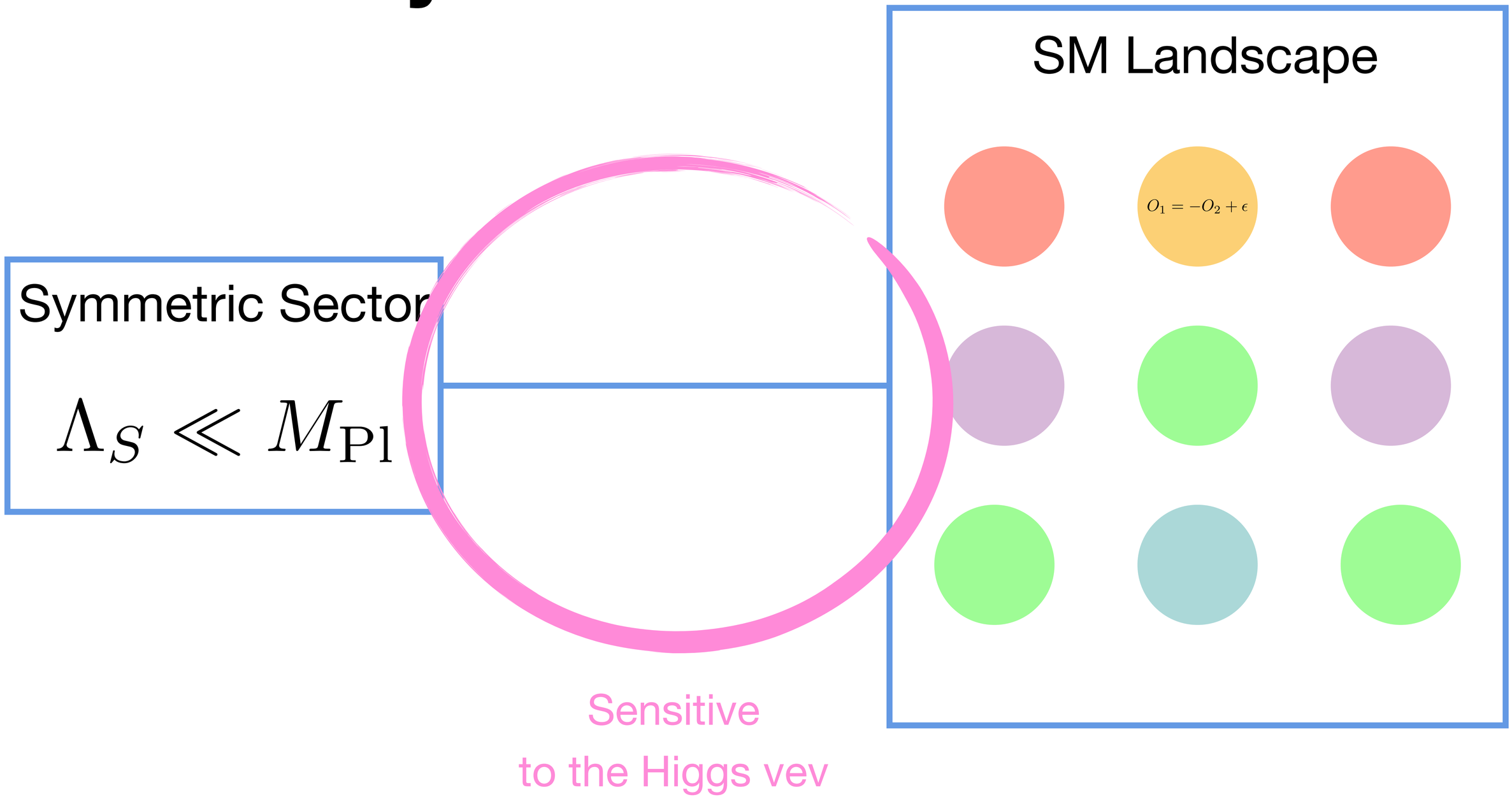
Statistical Selection

Does not require new physics with couplings to the SM stronger than gravitational

Dynamical Selection

Typically visible!

“Dynamical” Selection



HIERARCHY 102

[Arkani-Hamed, RTD, Kim '20]

Does anything change in the SM as we vary $\langle h \rangle$?

1. Obviously the spectrum

2. If we look at local operators we discover the hierarchy problem:

$$\langle h^\dagger h \rangle \sim \Lambda_H^2$$

HIERARCHY 102

Does anything change in the SM as we vary $\langle h \rangle$?

$$\frac{\alpha_s}{8\pi}(\xi\phi + \theta)\mathrm{Tr}\left[G\tilde{G}\right]$$

$$m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2}\sin^2\left(\xi\phi + \theta\right)}$$

$$(y_u + y_d) v f_\pi^3 \left(\theta\xi\phi + \xi^2\phi^2 + ...\right)$$

HIERARCHY 102

Does anything change in the SM as we vary $\langle h \rangle$?

$$\xi \phi \mathrm{Tr}\left[G\widetilde{G}\right]$$

Important Pheno Message:

Axion-Like phenomenology can be related to the hierarchy problem

TRIGGER PHENOMENOLOGY

$G\tilde{G}$

ALPs

TRIGGER PHENOMENOLOGY

$G\widetilde{G}$

ALPs

$F\widetilde{F} + yLHE^c$

Vector-like Leptons

TRIGGER PHENOMENOLOGY

$G\tilde{G}$ — ALPs

$F\tilde{F} + yLHE^c$ — Vector-like Leptons

$H_1 H_2$ — Type-0 2HDM

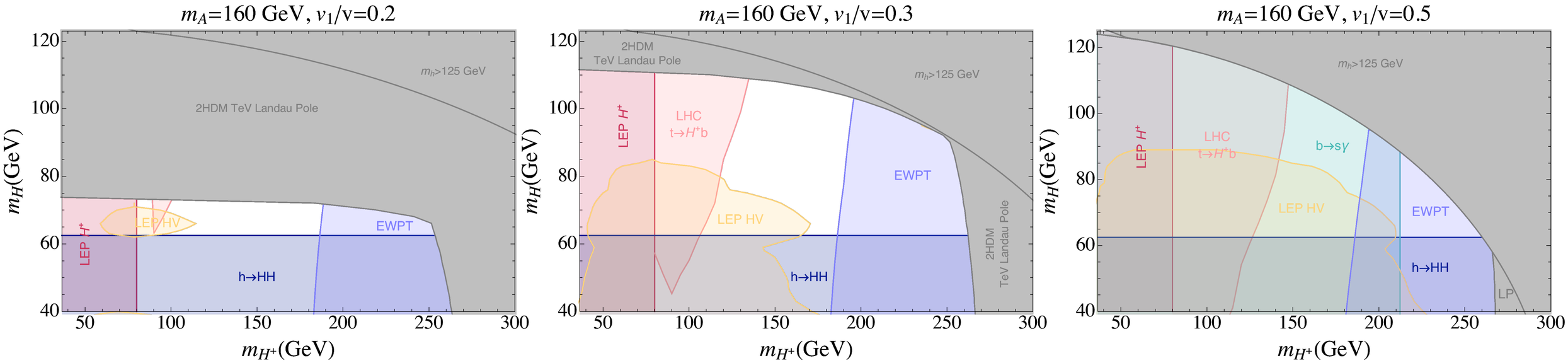
See [Arkani-Hamed, RTD, Kim, ‘20]

[Arkani-Hamed, RTD, Kim, ‘20], [Dvali, Vilenkin ’03], [Geller, Hochberg, Kuflik,’18], [Graham, Rajendran, Kaplan, ’15], [Strumia, Teresi, ’20], [Espinosa, Grojean, Panico, Pomarol, Pujolas, ’15], …

EXAMPLE: TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim '20]

N.B. It is extremely hard to find a viable BSM trigger



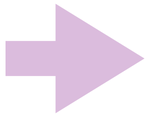
Sharp target which **can't be decoupled**!

$$m_{\rm NP} \lesssim m_h$$

Change of perspective:

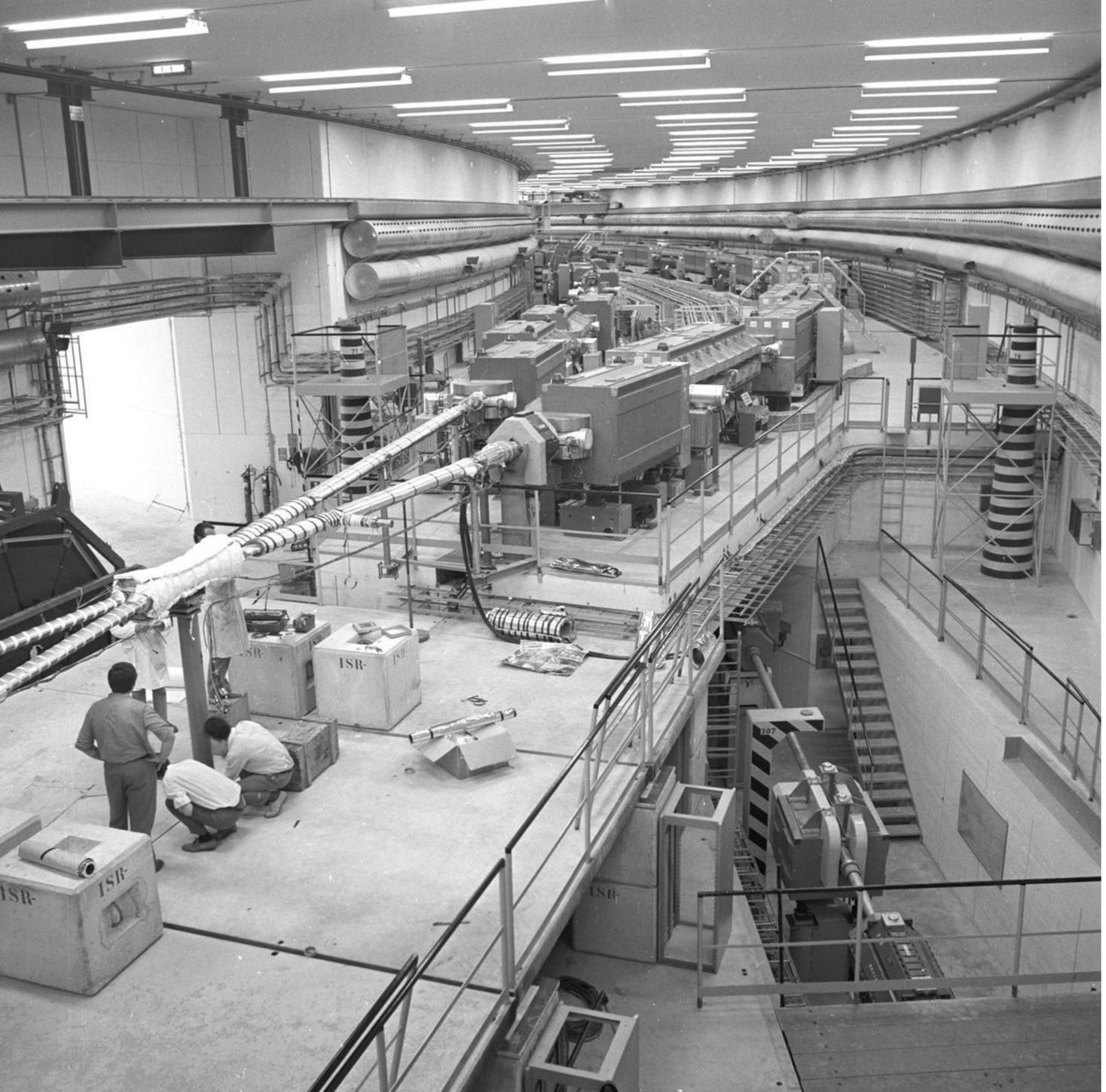
Can we find the origin of the weak scale early in the history of the Universe?

Completely new
perspectives
on key “classic” questions



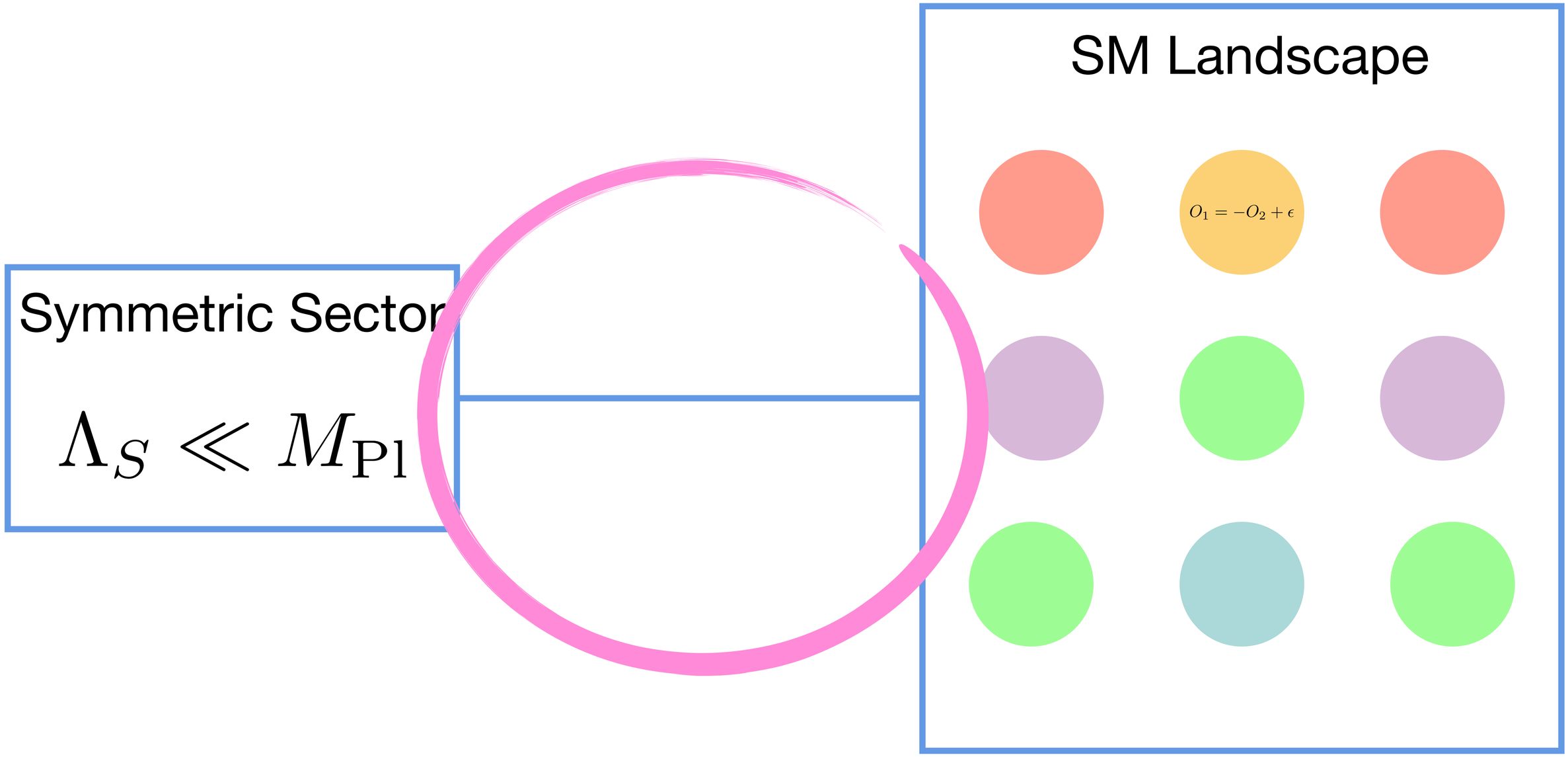
New Experimental Targets

BACKUP



CERN
1971

A change in theoretical perspective
can win (or lose) you
two Nobel Prizes


SM Landscape
Symmetric Sector
$\Lambda_S \ll M_{\rm Pl}$
$O_1 = -O_2 + \epsilon$

EXAMPLE: STATISTICAL

[Dvali, Vilenkin ’03], [Dvali ’04]

$$F_4 = dA_3$$

$$S \supset \int d^4x\sqrt{-g}\left(\frac{F_4^2}{48} + M_{\rm Pl}^2(-1+\frac{F_4^2}{M_{\rm Pl}^2}+...)|\phi|^2+...\right) + q(\phi)\int d^3\xi A_{\mu\nu\rho}\frac{\partial x^\mu}{\partial\xi^a}\frac{\partial x^\nu}{\partial\xi^b}\frac{\partial x^\rho}{\partial\xi^c}\epsilon^{abc}$$

Large initial “Electric Field” (Brown-Teitelboim)

$$F_4^2 \sim M_{\rm Pl}^4$$

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Very slow process: requires eternal inflation!

Branes can be spontaneously nucleated (tunnelling)

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The scalar mass is scanned

$$\Delta F_4 = q(\phi)$$

Cosmological Constant

Higgs Mass Squared

1. The two quantities are not calculable

2. Scale of gravity?

Theory ~ 10^{120} Experiment

Theory~10^{34} Experiment

Cosmological Constant

Higgs Mass Squared

1. The two quantities are not calculable

2. Scale of gravity?

3. Planck Scale = QFT Mass Scale?

Theory ~ 10^{120} Experiment

Theory~10^{34} Experiment

HIERARCHY 102

[Arkani-Hamed, RTD, Kim ’20]

Does anything change in the SM as we vary $\langle h \rangle$?

HIERARCHY 102

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1. Obviously the spectrum

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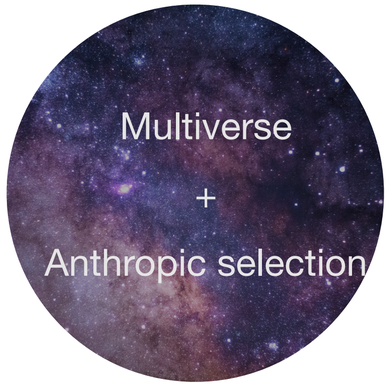


HIERARCHY 102

Does anything change in the SM as we vary $\langle h \rangle$?

$$\xi \phi \mathrm{Tr}\left[G\widetilde{G}\right]$$

Dvali, Vilenkin ‘01
Graham, Kaplan, Rajendran ‘15
Geller, Hochberg, Kuflik ’18
…

EXAMPLE: STATISTICAL

[Giudice, McCullough, You ’21]

Scalar dominated by quantum dynamics during inflation

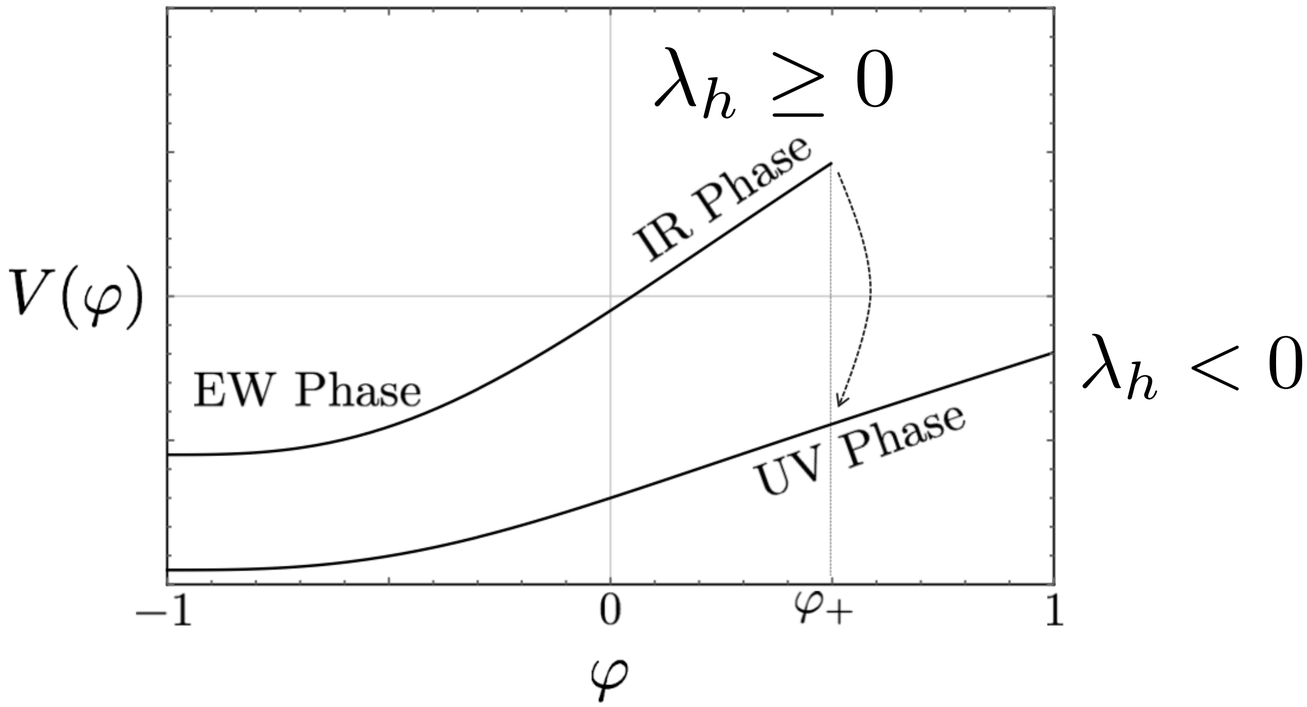
Solve Fokker-Planck Equation

In most gauges you will find that the volume is dominated by quantum dynamics for critical points of some potentials

(measure problem)

EXAMPLE: STATISTICAL

[Giudice, McCullough, You ’21]



Can select Higgs vev corresponding to zero quartic

EXAMPLE: DYNAMICAL

[Graham, Kaplan, Rajendran ’15],

$$V(\phi) = g\phi + ... + (M^2 + g\phi + ...)|H|^2 + \frac{\phi}{f} G\tilde{G}$$

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[Graham, Kaplan, Rajendran '15],

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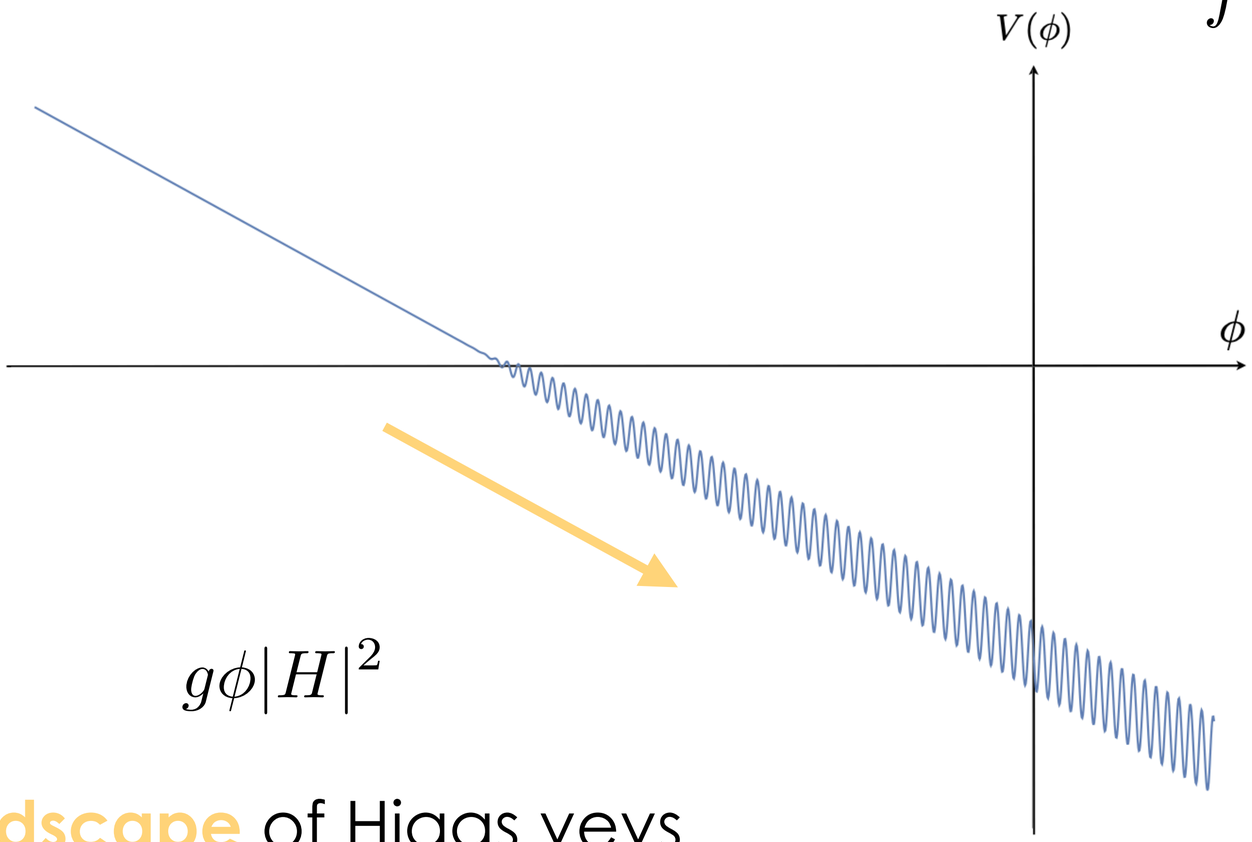

$g\phi|H|^2$

Landscape of Higgs vevs

EXAMPLE: DYNAMICAL

[Graham, Kaplan, Rajendran ’15],

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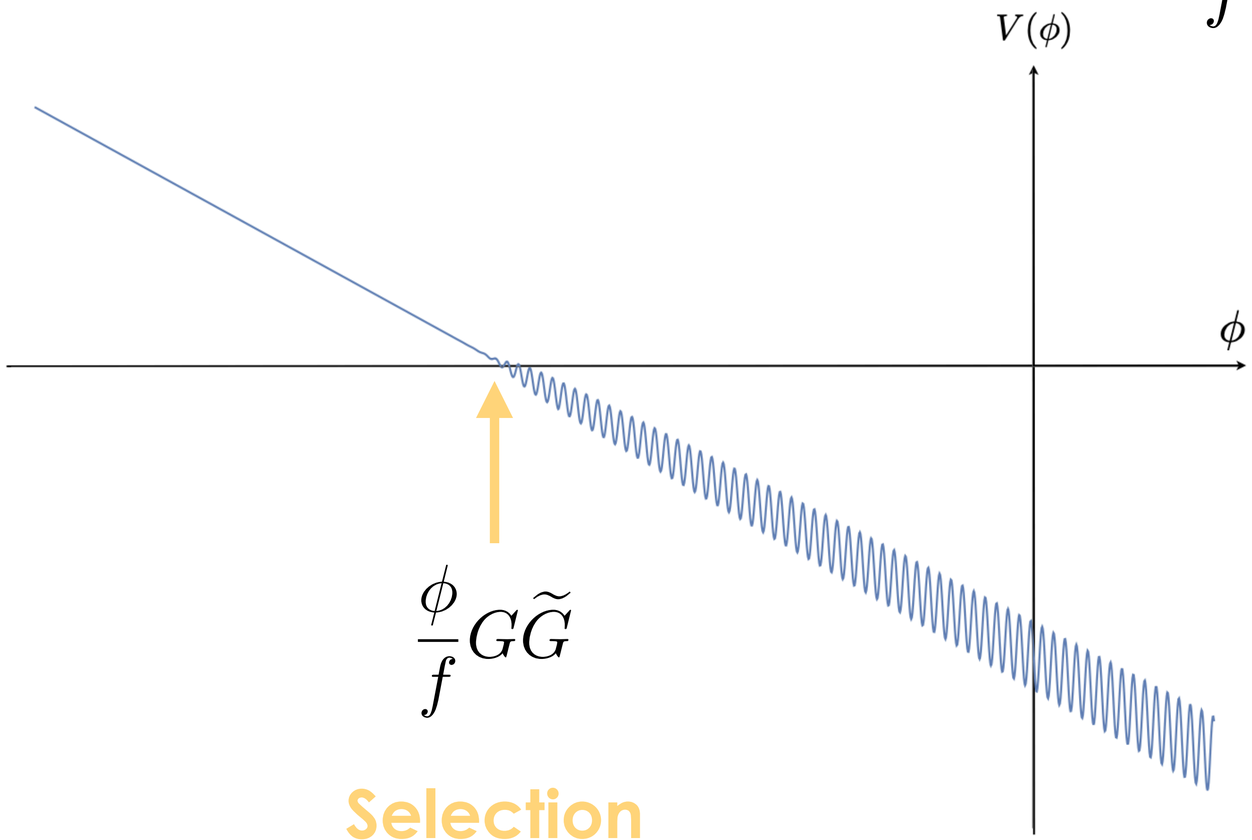


Selection

EXAMPLE: DYNAMICAL

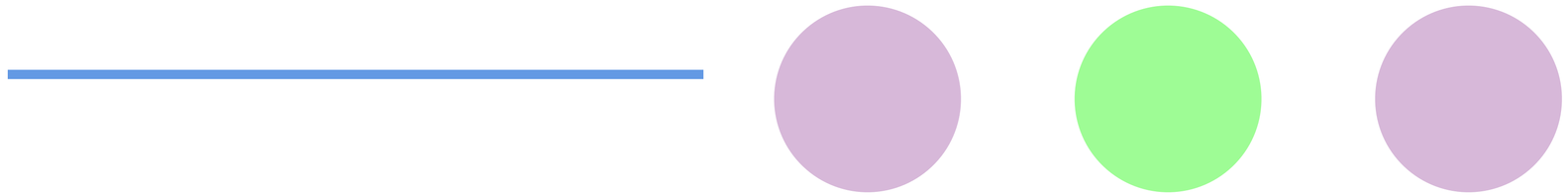
[Graham, Kaplan, Rajendran '15],

$$V(\phi) = g\phi + ... + (M^2 + g\phi + ...)|H|^2 + \frac{\phi}{f} G\tilde{G}$$

Symmetric Sector

$$g \ll M_{\rm Pl}^3$$

SM Landscape



ϕ $\phi G\tilde{G}$ $g\phi|H|^2$

EXAMPLE: STATISTICAL

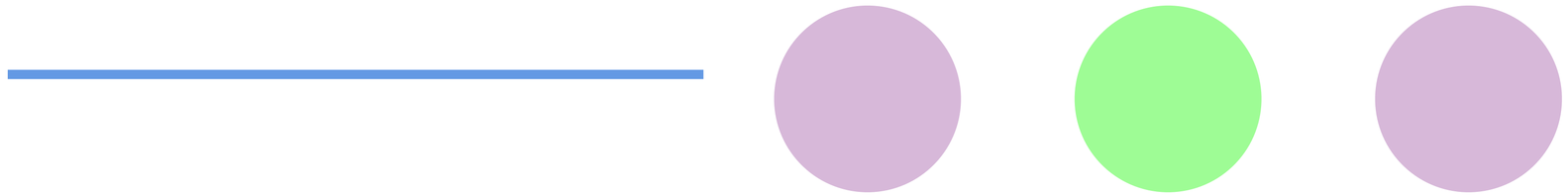
[Dvali, Vilenkin ’03], [Dvali ’04]

$$F_4 = dA_3$$

Symmetric Sector

$$q(\phi) \lesssim M_{\rm Pl}^2$$

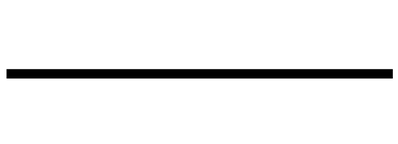
SM Landscape

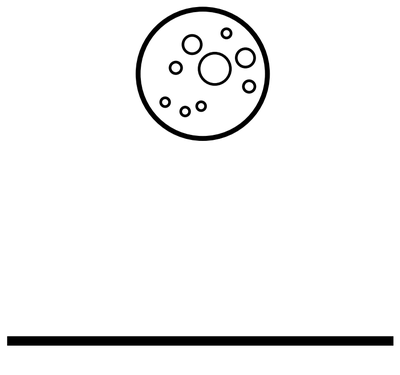


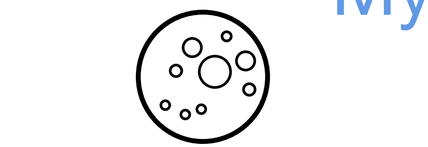
A_3

$$\frac{\phi^N}{M_{\rm Pl}^{N-2}} \int_{2+1} A_3$$

$$\frac{F_4^2}{M_{\rm Pl}^2} |\phi|^2$$


Planck
String
SUSY
SM


Mysterious
QG
Blob
SUSY
SM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