A MINIMAL COSMOLOGICAL SELECTION MODEL FOR THE HIERARCHY PROBLEM

BSM@50 conference

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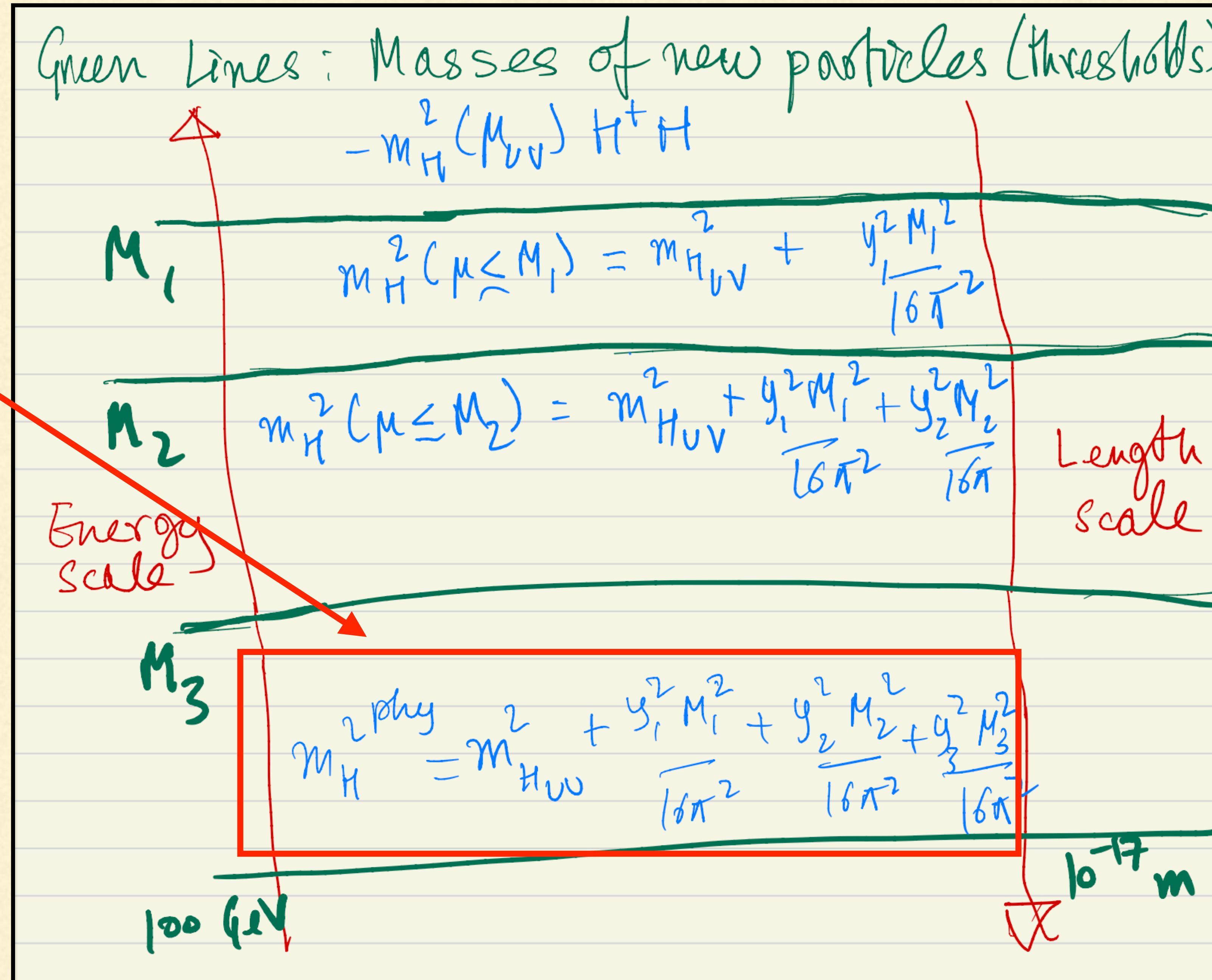
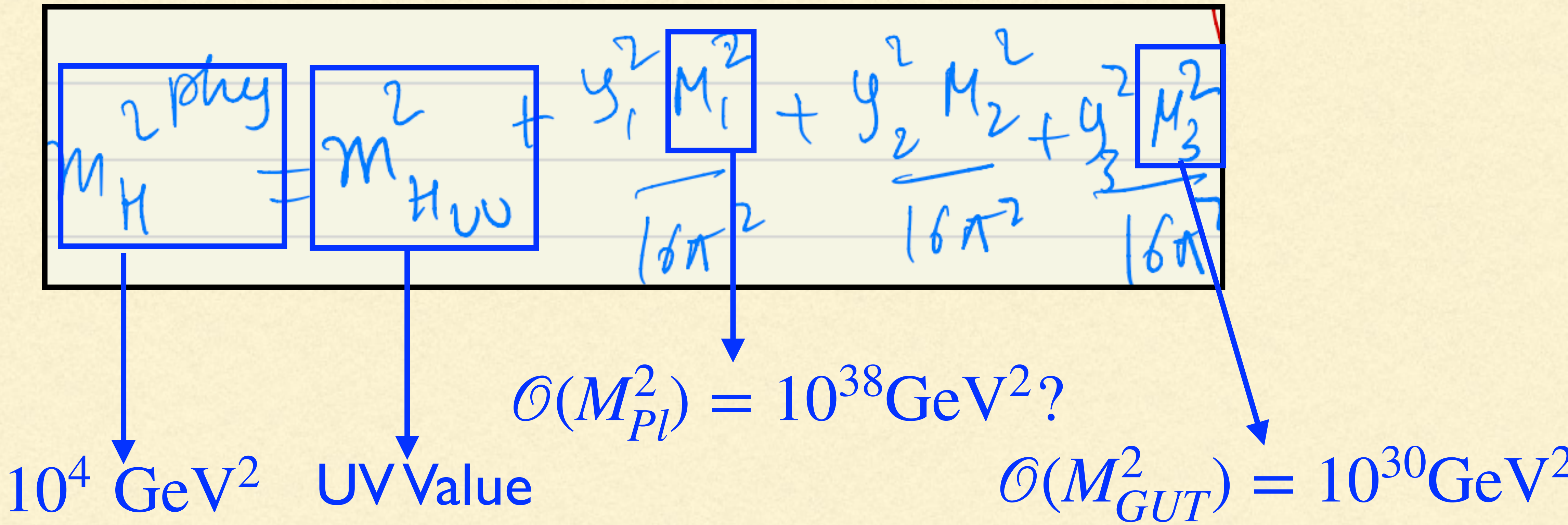
THE HIERARCHY PROBLEM

The hierarchy problem arises when we try to **predict the Higgs mass in terms of small length scale (high energy scale)** parameters.

Green lines: masses of new particles that couple to the Higgs (thresholds)



THE HIERARCHY PROBLEM



- The RHS contributions must be tuned against the loop corrections to one part in m_h^2/M^2, M being the new physics scale, for instance to the 26th decimal place for GUT scale new physics.

SYMMETRY BASED SOLUTIONS

- $m_h = 0$ $(\mu^2 = 0)$ a special point due to some symmetry. That is symmetry protects $m_h = 0$.

- However, there is no such symmetry in SM. SM needs to be extended to include this symmetry which is then broken.

- This gives Higgs mass:

$$m_h^2 \sim m_{soft}^2, y^2 f_{pi'}^2$$

- New particles (superpartners, composite states) close to symmetry breaking scale which is in tension with LHC null results.

LHC NULL RESULTS

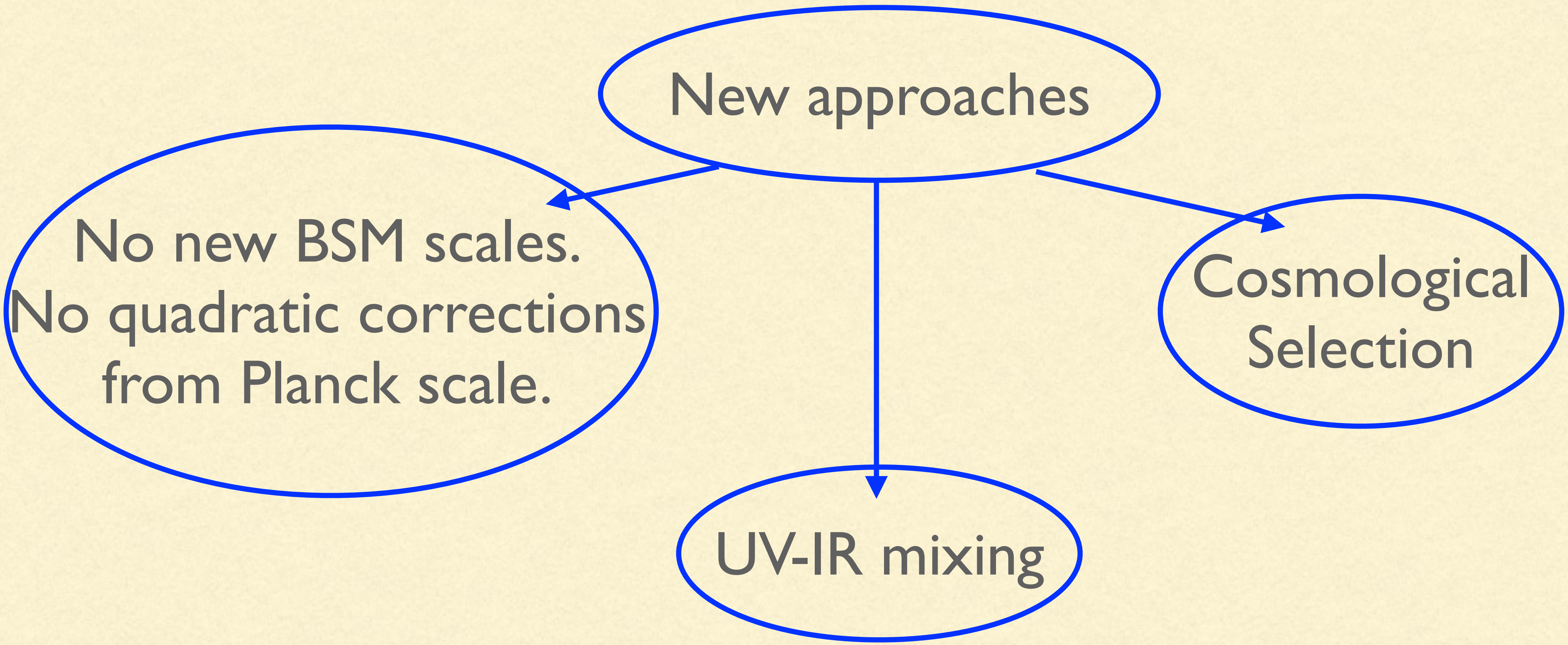
- The LHC, however has seen no such states even more than a decade after the Higgs discovery.
- If the LHC doesn’t see any new physics also in the future, was this argument wrong ?
- *It may have been wrong but if so it would be wrong in some interesting way.*

"The opposite of a fact is a falsehood, but the opposite of one profound truth may very well be another profound truth." – Niels Bohr

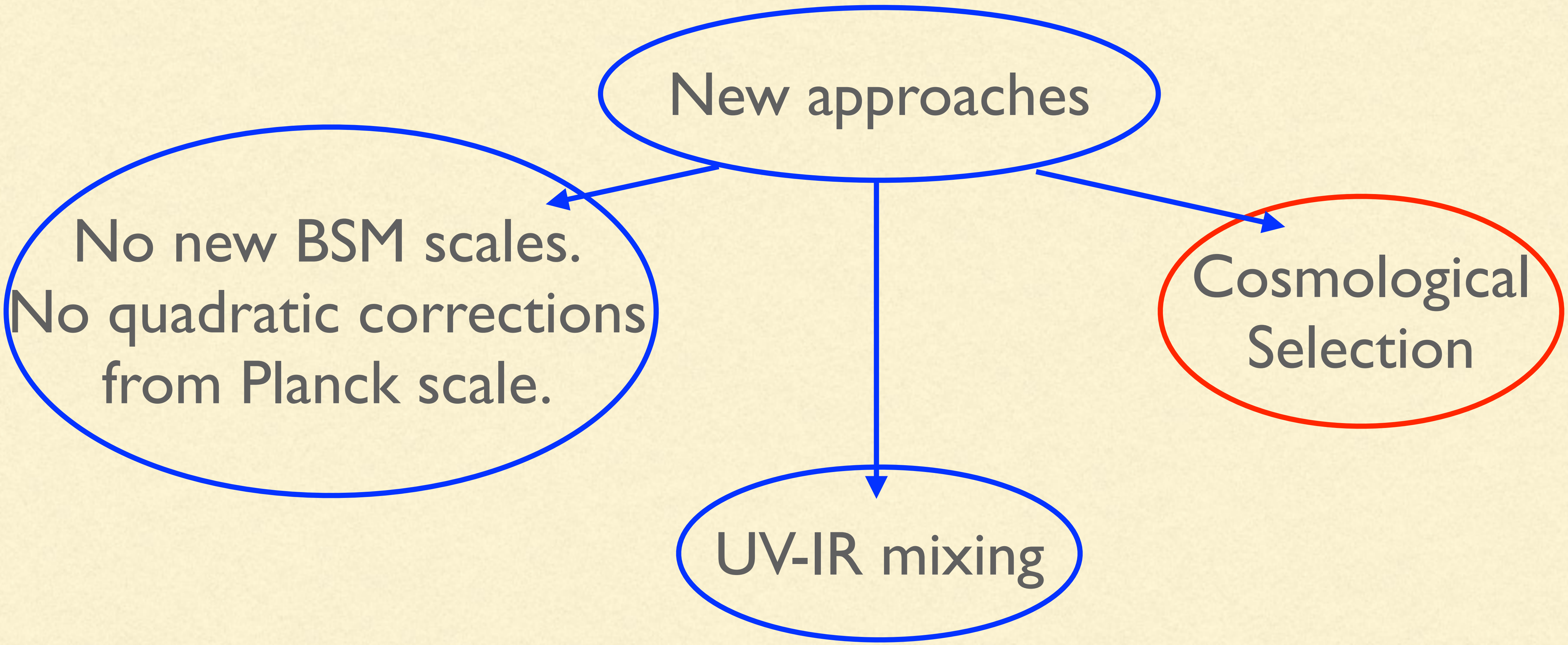
BYPASSING TEV SCALE PHYSICS

- Not easy to find a loophole in the standard argument for TeV scale physics
- Alternatives that allow $m_h \ll M, \; M \gg$ TeV theoretically constrained and thus interesting to pursue

NEW APPROACHES TO HIERARCHY PROBLEM

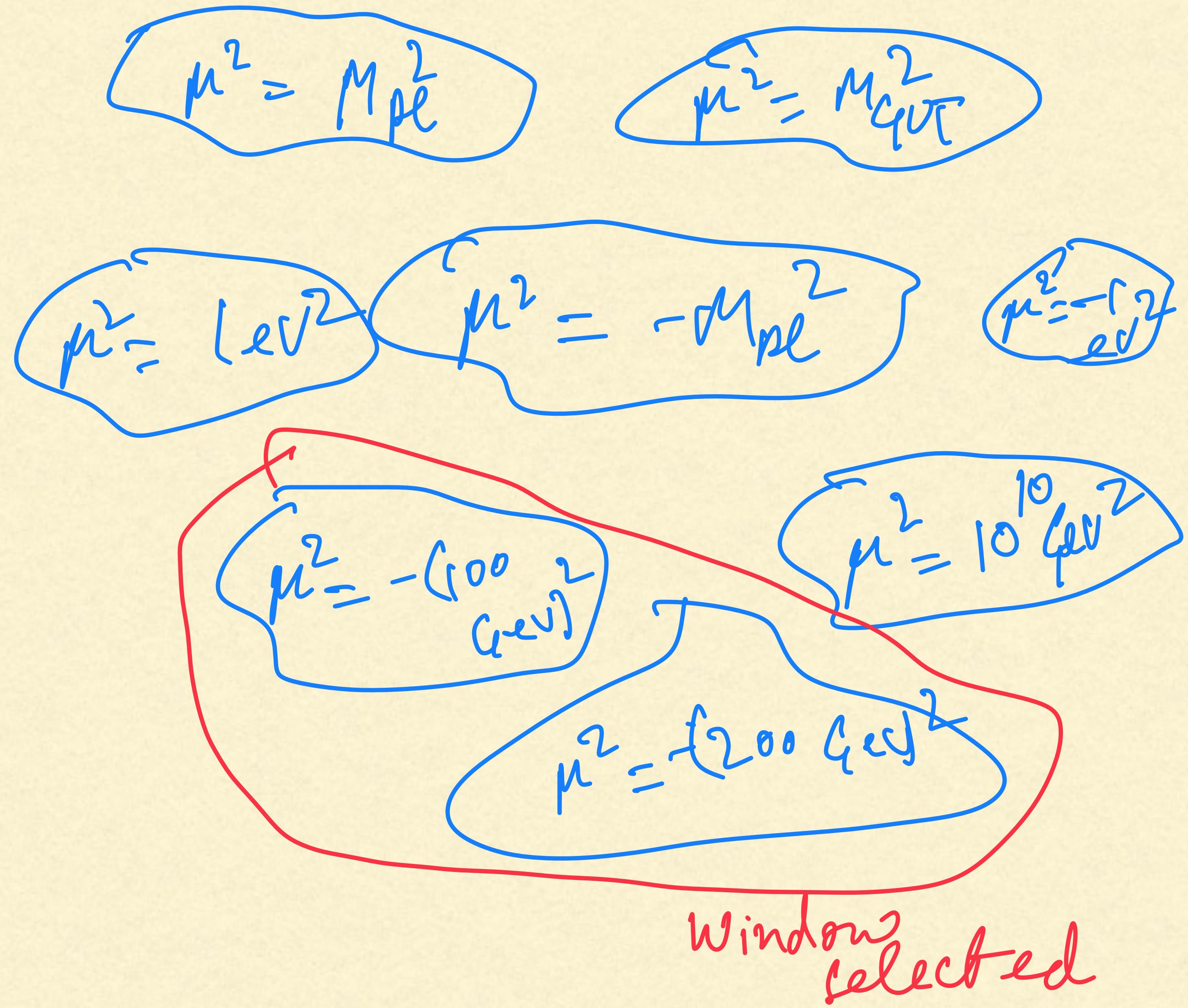


NEW APPROACHES TO HIERARCHY PROBLEM



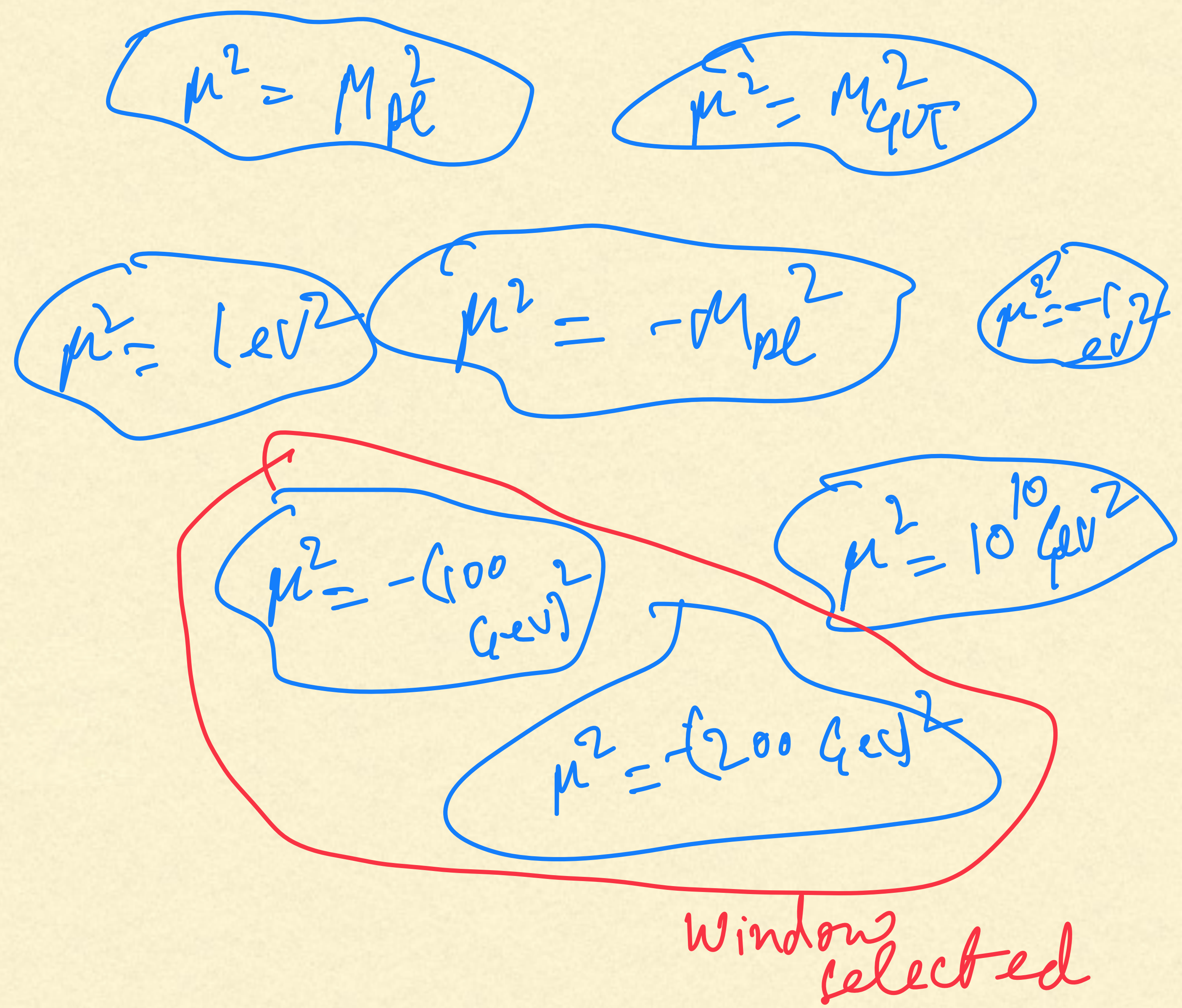
LANDSCAPE OF SOLUTIONS

- Imagine a landscape of Higgs mass values.
- These different μ^2 values might physically exist in a multiverse.
- OR the different μ^2values exist as possible theoretical solutions (vacua). Eg: relaxion models



LANDSCAPE OF SOLUTIONS

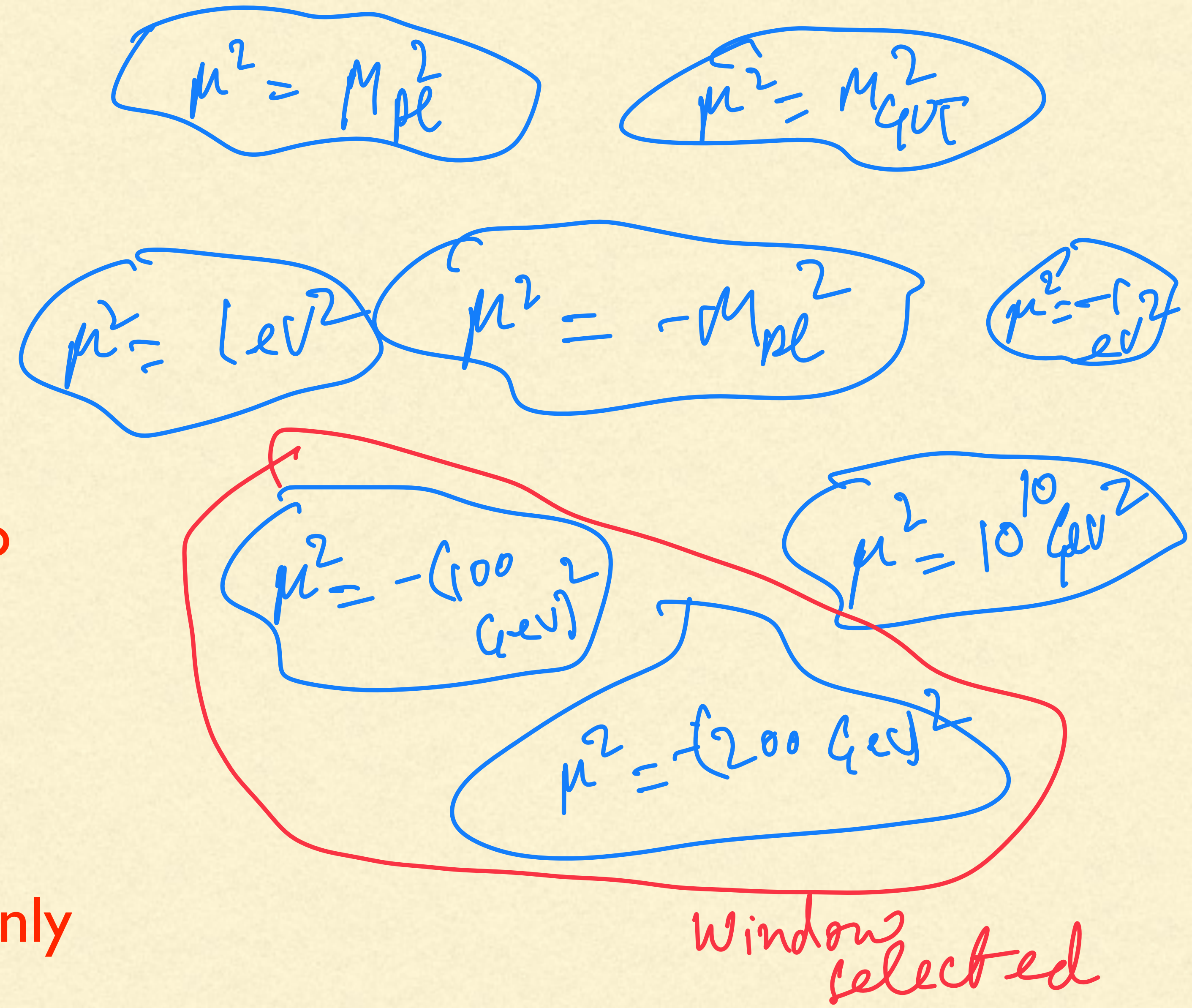
- Imagine a landscape of Higgs mass values.
- The other ingredient is a selection mechanism that selects only the solutions where μ^2 is in a certain window.
- Example: Anthropic selection: life can exist only for μ^2 is in a certain window.



Agrawal, Barr, Donoghue & Seckel (1998)

COSMOLOGICAL SELECTION

- Imagine a landscape of Higgs mass values.
- A new class of models have now appeared that propose non-anthropic cosmological selection mechanism
- These include scalars ϕ_i in addition to the Higgs whose dynamics selects particular window.
- Eg: Relaxion models are the most prominent example but are not the only example.



P. W. Graham, D. E. Kaplan, and S. Rajendran (2015)

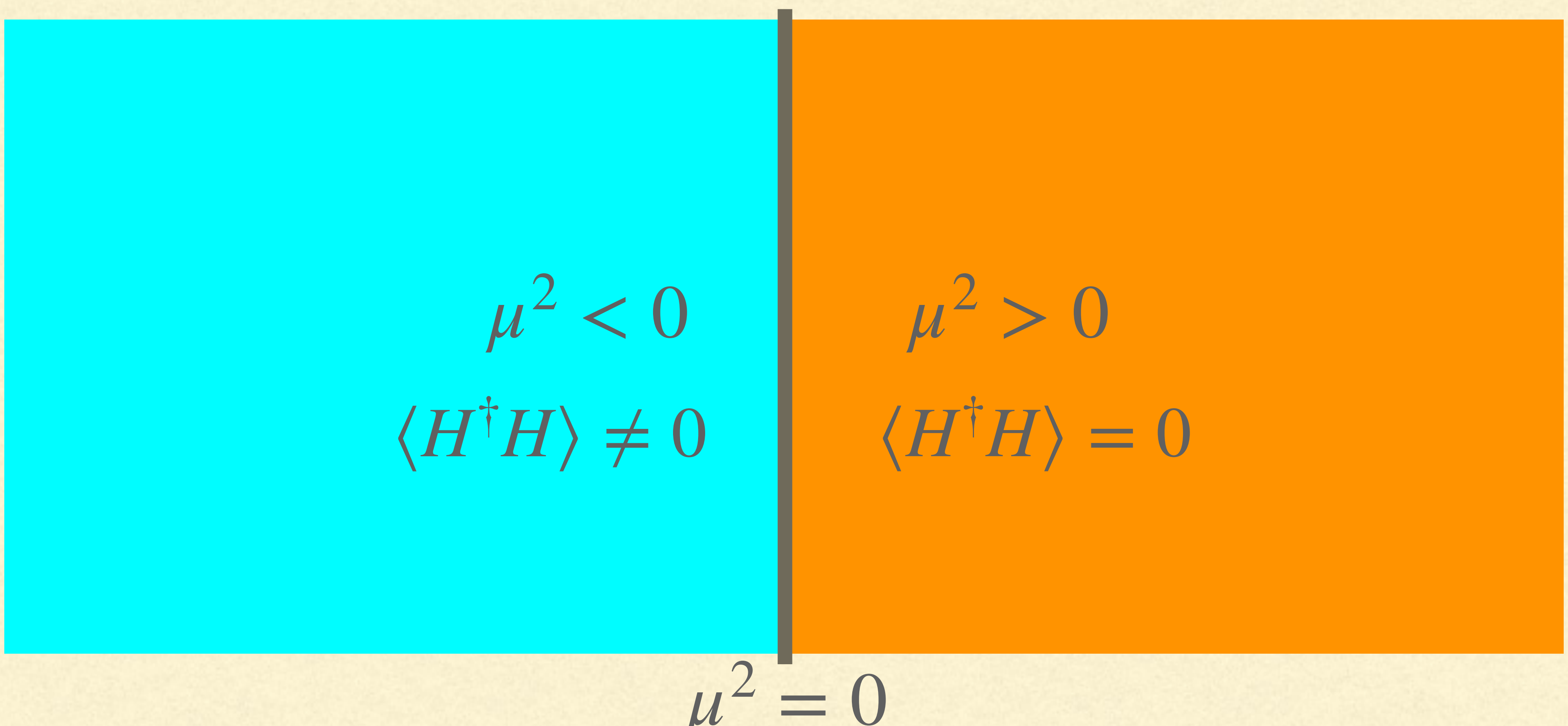
COSMOLOGICAL SELECTION OF WEAK SCALE: MANY NEW APPROACHES

1. G. Dvali and A. Vilenkin, “Cosmic attractors and gauge hierarchy,” (2004)
2. G. Dvali, “Large hierarchies from attractor vacua,” (2006)
3. P. W. Graham, D. E. Kaplan, and S. Rajendran, “Cosmological Relaxation of the Electroweak Scale,” (2015)
4. N. Arkani-Hamed, T. Cohen, R. T. D'Agnolo, A. Hook, H. D. Kim, and D. Pinner, “Solving the Hierarchy Problem at Reheating with a Large Number of Degrees of Freedom,” (2016)
5. C. Cheung and P. Saraswat, “Mass Hierarchy and Vacuum Energy,”(2018)
6. G. F. Giudice, A. Kehagias, and A. Riotto, “The Selfish Higgs,”(2019)
7. A. Strumia and D. Teresi, “Relaxing the Higgs mass and its vacuum energy by living at the top of the potential,” (2020)
8. C. Csaki, R. T. D'Agnolo, M. Geller, and A. Ismail, “Crunching Dilaton, Hidden Naturalness,” (2020)
9. M. Geller, Y. Hochberg, and E. Kuflik, “Inflating to the Weak Scale,” (2019)
10. N. Arkani-Hamed, R. T. D'Agnolo, and H. D. Kim, “The Weak Scale as a Trigger,” (2020)
11. G. F. Giudice, M. McCullough, and T. You, “Self-Organised Localisation,” (2021)
12. R. Tito D'Agnolo and D. Teresi, “Sliding Naturalness,” (2021)
13. R. Tito D'Agnolo and D. Teresi, “Sliding Naturalness: Cosmological selection of the weak scale” (2022)

Mostly from last decade

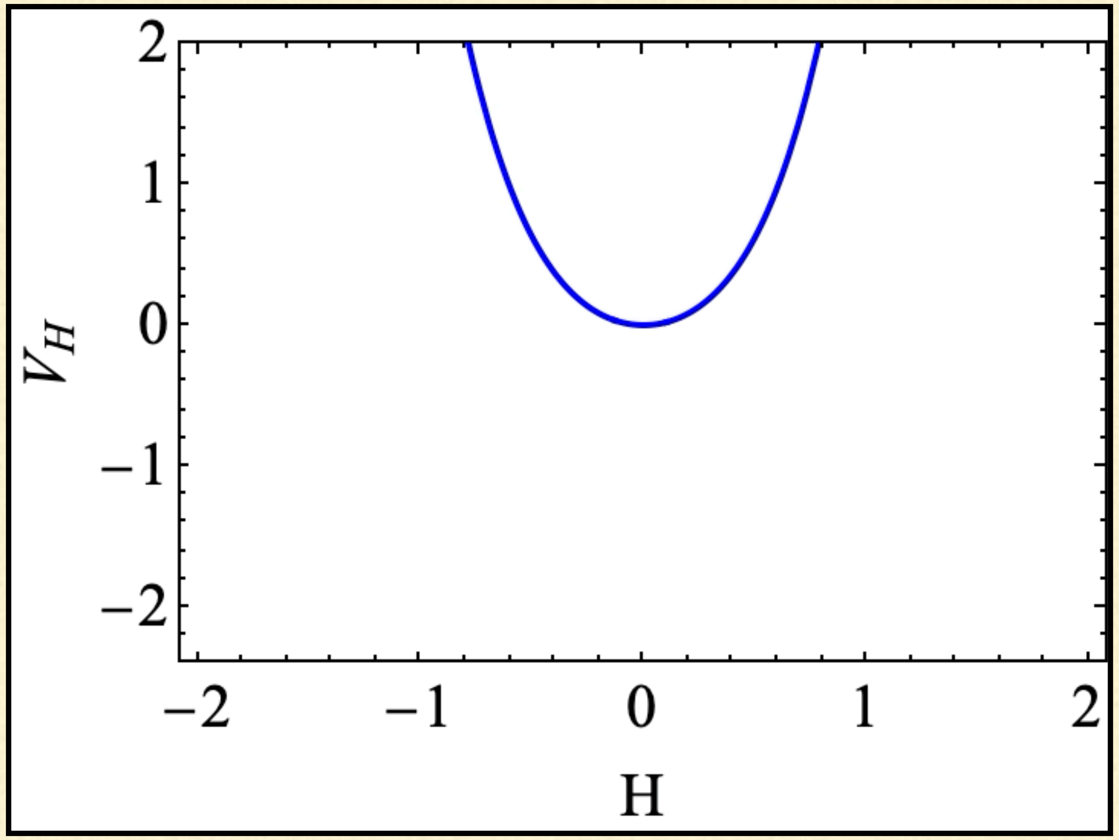
ANOTHER REASON WHY $\mu^2 \to 0$ IS SPECIAL

Cosmological selection utilises the following : Even if $\mu^2 \to 0$, does not lead to symmetry enhancement it is still special because, $\mu^2 = 0$, is still special. It separates two phases, one with EWSB, $\langle H^\dagger H \rangle \neq 0$, and one without.



WHAT CAN BE TRIGGERED BY THE HIGGS VEV ?

- One clear physical consequence of the Higgs VEV is that it lowers the ***vacuum energy***
- Suggests a selection mechanism: regions with higher vacuum energy expand the most during inflation and dominate the universe
- Thus large Higgs VEVs disfavoured over small VEVs



Higgs VEV dialled from small to large values

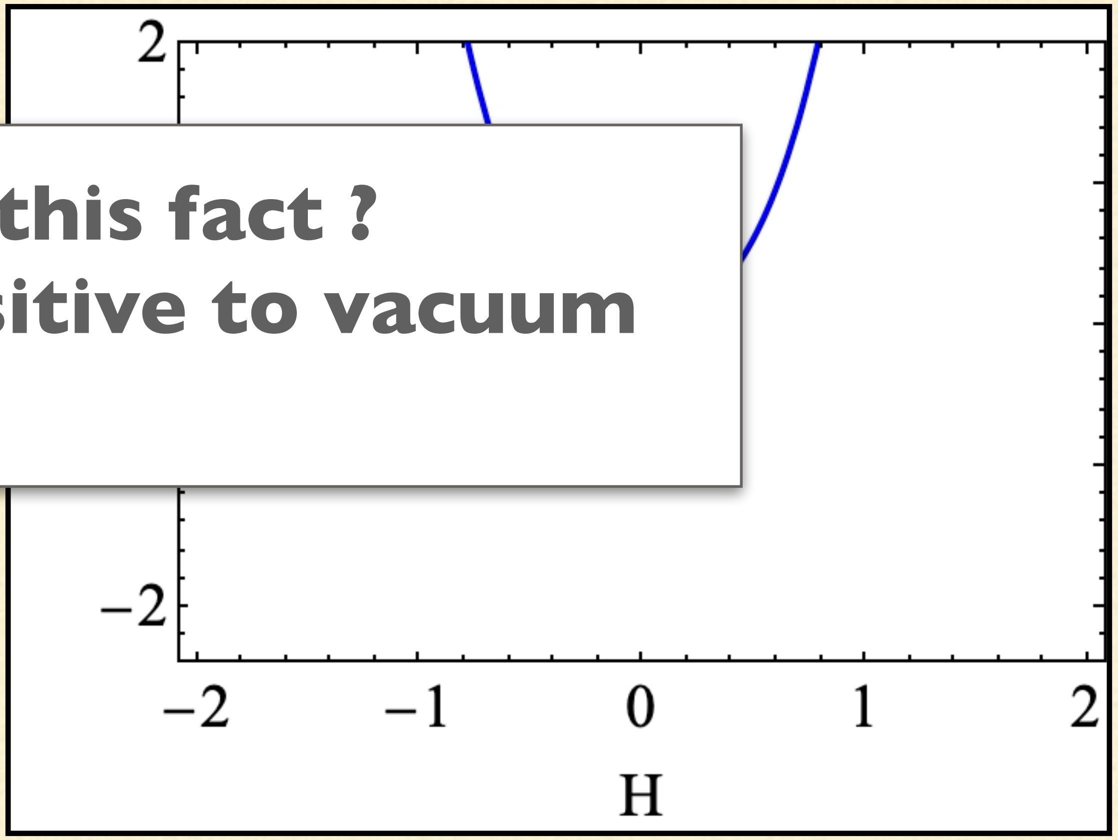
WHAT CAN BE TRIGGERED BY THE HIGGS VEV ?

- One clear physical consequence of the Higg
  vacuu

How can we use this fact ?
Recall that gravity sensitive to vacuum energy.

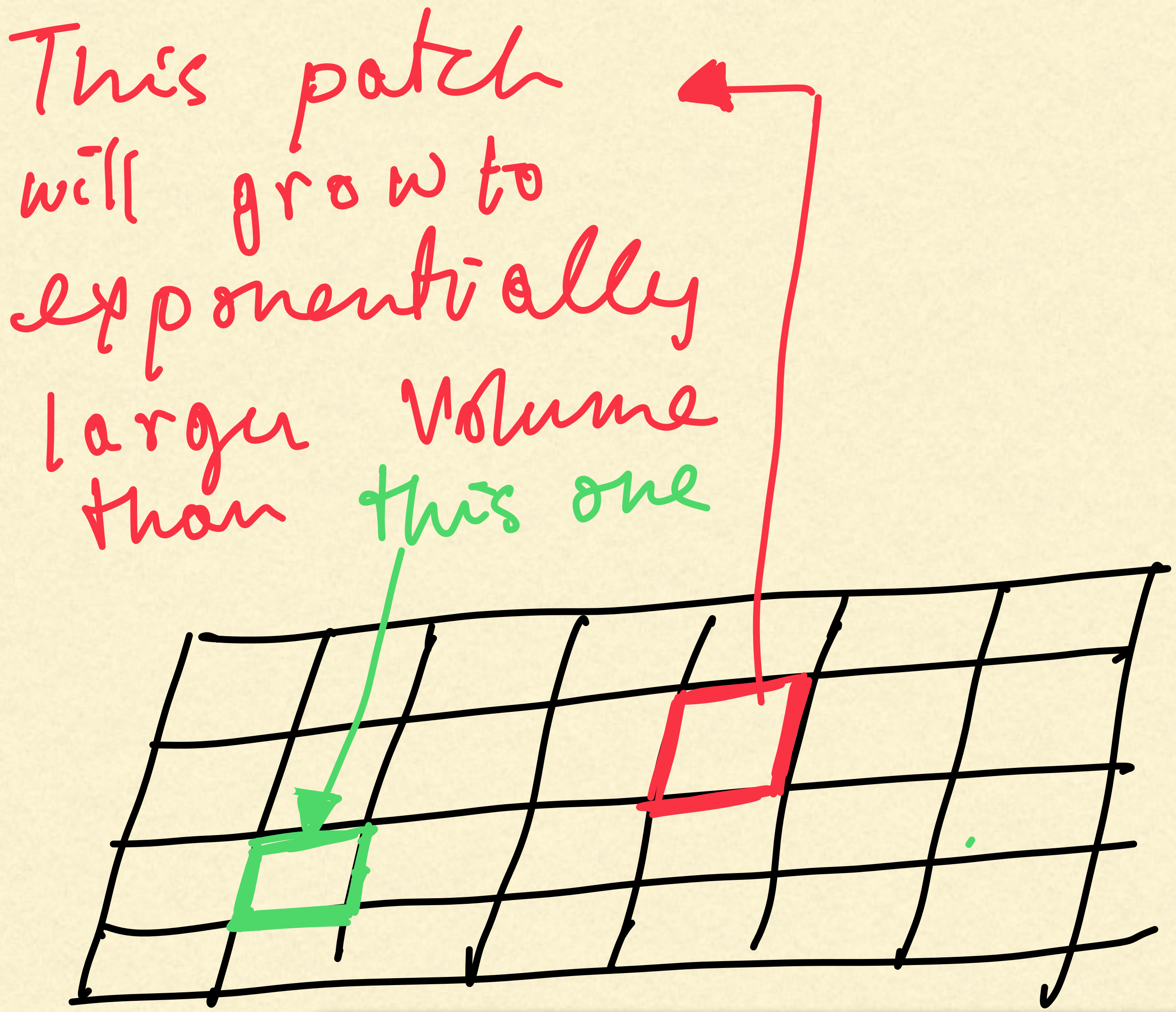
- Suggests a selection mechanism: regions with higher vacuum energy expand the most during inflation and dominate the universe

- Thus large Higgs VEVs disfavoured over small VEVs



Higgs VEV dialled from small to large values

SELECTION BASED ON VACUUM ENERGY



Red patch has larger vacuum energy than green one

- During inflation regions of the multiverse that have higher vacuum energy grow exponentially more than other regions
- Regions with small Higgs VEV expand exponentially more than regions with large VEVs

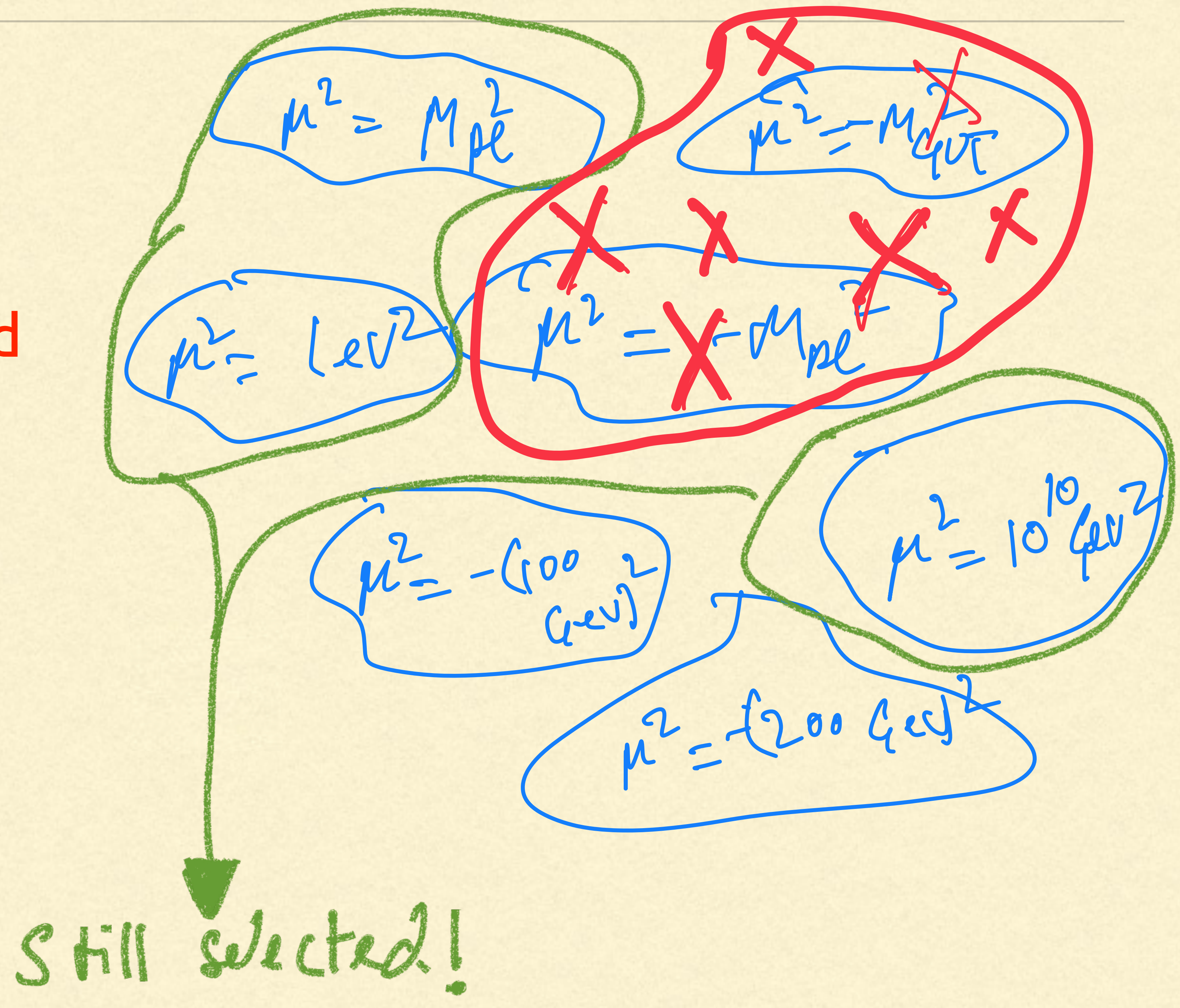
M. Geller, Y. Hochberg, and E. Kuflik (2019)
C. Cheung and P. Saraswat, (2018)
G. F. Giudice, M. McCullough, and T. You, (2021)

WHAT CAN BE TRIGGERED BY THE HIGGS VEV ?

- Thus large Higgs VEVs disfavoured over small VEVs, so small negative Higgs mass squared would be preferred over large negative Higgs mass squared .
- But if Higgs mass squared is positive VEV=0 vacuum energy contribution is always 0.
- This does not give a selection mechanism to exclude large positive Higgs mass squared values.

SELECTION MECHANISM ONLY FOR -VE μ^2

- Large Higgs VEVs disfavoured over small VEVs, so small negative Higgs mass squared would be preferred over large negative Higgs mass squared
- Positive μ^2 still selected



M. Geller, Y. Hochberg, and E. Kuflik (2019)

MINIMAL COSMOLOGICAL SELECTION MODEL

- Our model maximises vacuum energy only in a certain window where Higgs has a non-zero but small VEV.

$$V = V(H) + \Delta V_T(\phi, H)$$

Large VEV implies low-vacuum energy and is thus excluded

TRIGGER TERM: Zero VEV excluded as it leads to bigger vacuum energy in ϕ sector

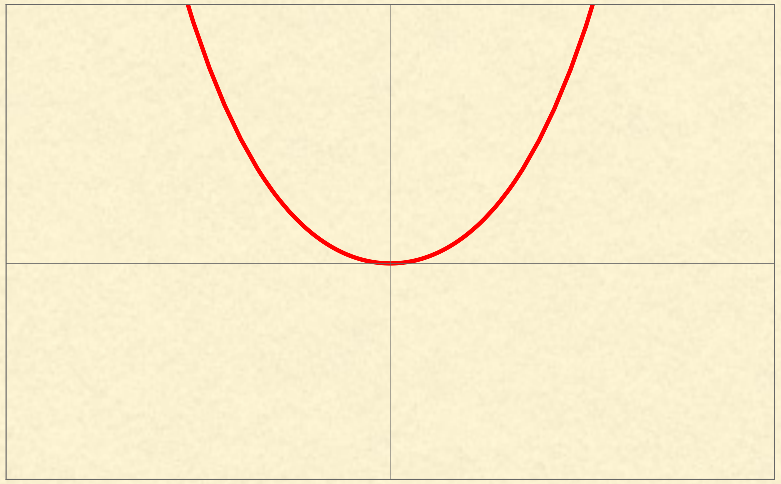
Chattopadhyay, Chattopadhyay, & RSG (in progress)

HIGGS VEV AS A TRIGGER

A VEV for the Higgs lifts the scalar phi raising the total vacuum energy:

$$V_{Trigger} = (\underbrace{-m^2 + \kappa |H|^2}_{m_{eff}^2})\phi^2 + \lambda_\phi \phi^4$$

$\langle H \rangle = 0 \rightarrow m_{eff}^2 < 0$



$\langle H \rangle = v \rightarrow m_{eff}^2 > 0$

HIGGS VEV AS A TRIGGER

A VEV for the Higgs lifts the scalar phi raising the total vacuum energy:

$$V_{Trigger} = (\underbrace{-m^2 + \kappa |H|^2}_{m^2_{eff}})\phi^2 + \lambda_\phi \phi^4$$

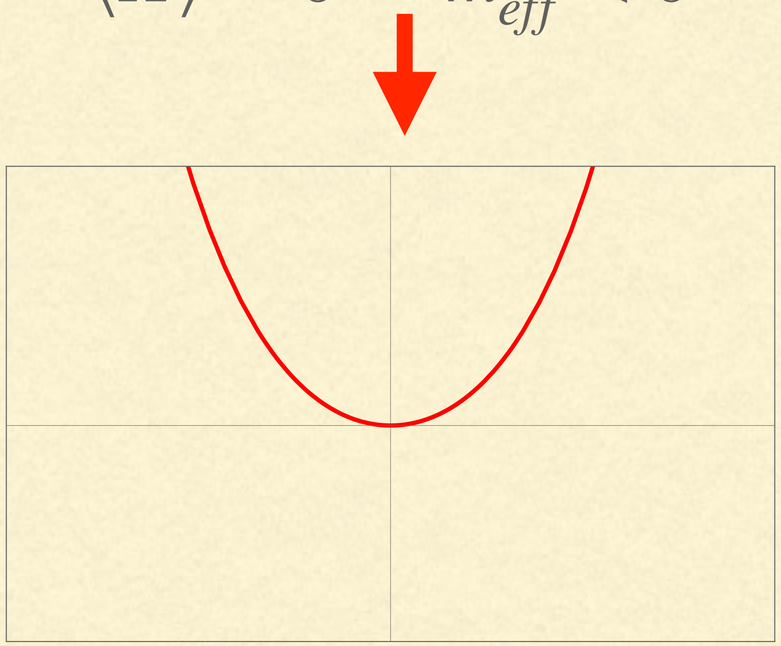
By closing loops, however, we can generate a contribution to the mass term:

$$\kappa\ \phi^2 |H|^2 \rightarrow \kappa\ \phi^2 \frac{\Lambda^2}{16\pi^2}$$

For trigger to be effective we must have:

$$\Lambda \lesssim 4\pi v$$

$\langle H \rangle = 0 \rightarrow m^2_{eff} < 0$



$\langle H \rangle = v \rightarrow m^2_{eff} > 0$

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- This is a general issue for all cosmological selection models with $|H|^2$ triggers. Whatever VEV can trigger can be already triggered by closing Higgs loop!

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant (2015)

- For Higgs VEV to be the real trigger:

1. we must close the loop at low scales $\Lambda \lesssim 4\pi v$. Eg.: Dark QCD model used for relaxions

Graham, Kaplan, and Rajendran (2015)

2. have a specific 2HDM where quartics are such that you cannot close loops. Again this implies new physics: charged Higgs and pseudo scalar.

Arkani-Hamed, D'Agnolo, and Kim (2020)

A MINIMAL COSMOLOGICAL SELECTION MODEL

- Our model maximises vacuum energy only in a certain window where Higgs has a non-zero but small VEV.

$$V = \boxed{V(H_1, H_2)} + \boxed{\Delta V_T(\phi, H_1, H_2)}$$

Large EW VEV implies low-vacuum energy and is thus excluded

TRIGGER TERM: Zero EW VEV excluded as it leads to bigger vacuum energy in ϕ sector

(Recall that in 2HDMs we can always go to a basis where only a single doublet, H has all the VEV.)

Chattopadhyay, Chattopadhyay, & RSG (in progress)

A MINIMAL COSMOLOGICAL SELECTION MODEL

- We consider a 2HDM and an additional scalar ϕ.
- Respects a $Z4$ symmetry $H_1 \to H_1;\ H_2 \to -H_2;\ \phi \to i\phi$ broken only by m. Potential natural even with trigger term.

$$V = V(H_1, H_2) + \kappa\phi^2 H_1 H_2 + V(\phi)$$

$$V(\phi) = m^2 f^2 \left(\frac{\phi^2}{f^2} + \alpha \frac{\phi^4}{f^4} + \cdots \right)$$

$$(\kappa \lesssim 4\pi m/f)$$

$$V_{H_1 H_2} = \frac{m_1^2}{2}|H_1|^2 + \frac{m_2^2}{2}|H_2|^2 + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1 H_2|^2 + \left(\frac{\lambda_5}{2}(H_1 H_2)^2 + \text{h.c.}\right) .$$

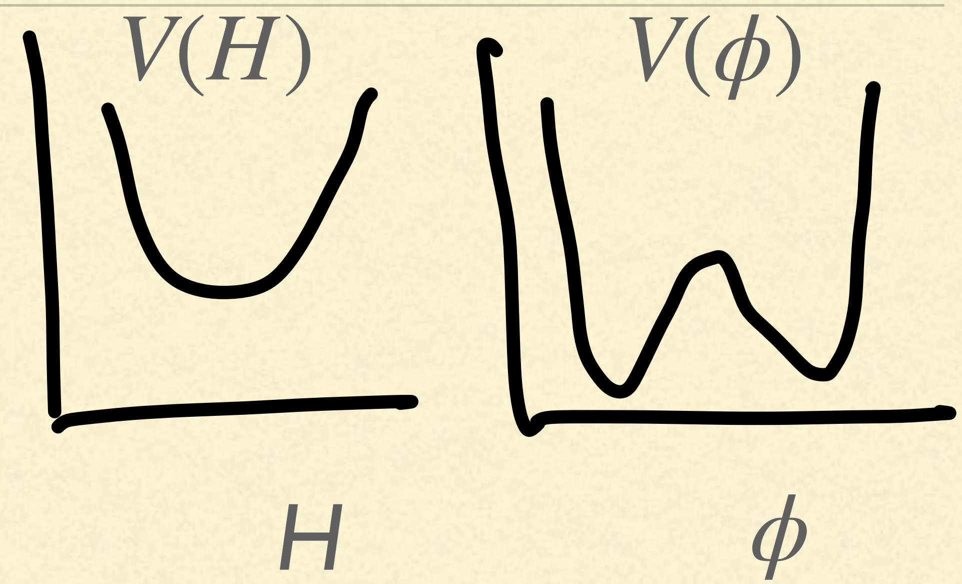
Chattopadhyay, Chattopadhyay, & RSG (in progress)

A MINIMAL COSMOLOGICAL SELECTION MODEL

$$H = \frac{v_1}{v} H_1^0 + \frac{v_2}{v} H_2^0$$

Higgs direction that gets all the VEV
(Orthogonal direction: no VEV)

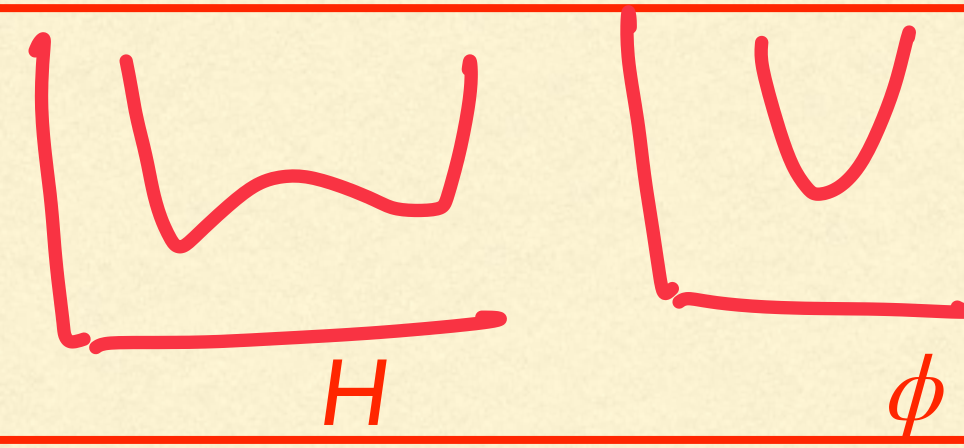
$\langle H \rangle = 0$



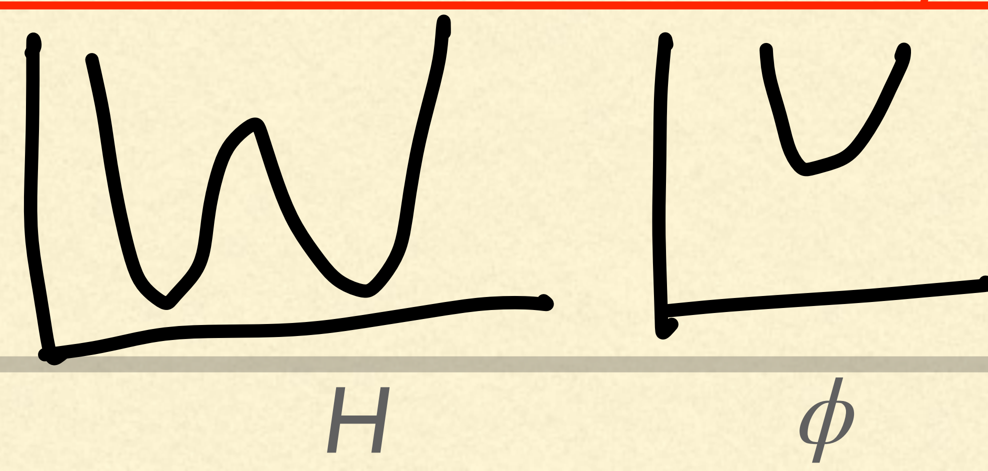
Highest vacuum energy. Regions with $\langle H \rangle \sim 100$ GeV selected
As they expand more during inflation
Provided

$$\kappa s_\beta c_\beta > 4\tilde{\lambda}\lambda_\phi$$

$\langle H \rangle \sim 100$ GeV



$\langle H \rangle \gg 100$ GeV



A MINIMAL COSMOLOGICAL SELECTION MODEL

Cut-off can be as high as Planck scale for small enough *m:*

$$\frac{\kappa}{2} s_\beta c_\beta v^2 \sim m^2 \qquad (\kappa \lesssim 4\pi m/f)$$

$$\Lambda \sim 4\pi f \sim 16\pi^2 \frac{v^2}{m} \qquad (\tan\beta = v_2/v_1 \sim 1)$$

2HDM PHENOMENOLOGY

vacuum energy

$$\mathcal{E} = -\frac{m^2}{4\lambda_\phi}\Theta(2m^2 - \kappa v_1 v_2) - \left(\frac{\lambda_1}{8}c_\beta^4 + \frac{\lambda_2}{8}s_\beta^4 + \lambda_{345}c_\beta^2 s_\beta^2\right)v^4$$

$(v^2 = v_1^2 + v_2^2)$

- Maximizing first term gives $\kappa v_1 v_2 > 2m^2$
- Keeping $v_1 v_2$ fixed if $v_2 \gg v_1$ or vice-versa the second term gives us a big negative contribution
- **This selects universes with** $\tan\beta \sim 1$
- We will take a Type II 2HDM where up and down type fermions couple to different doublets.

2HDM CONSTRAINTS

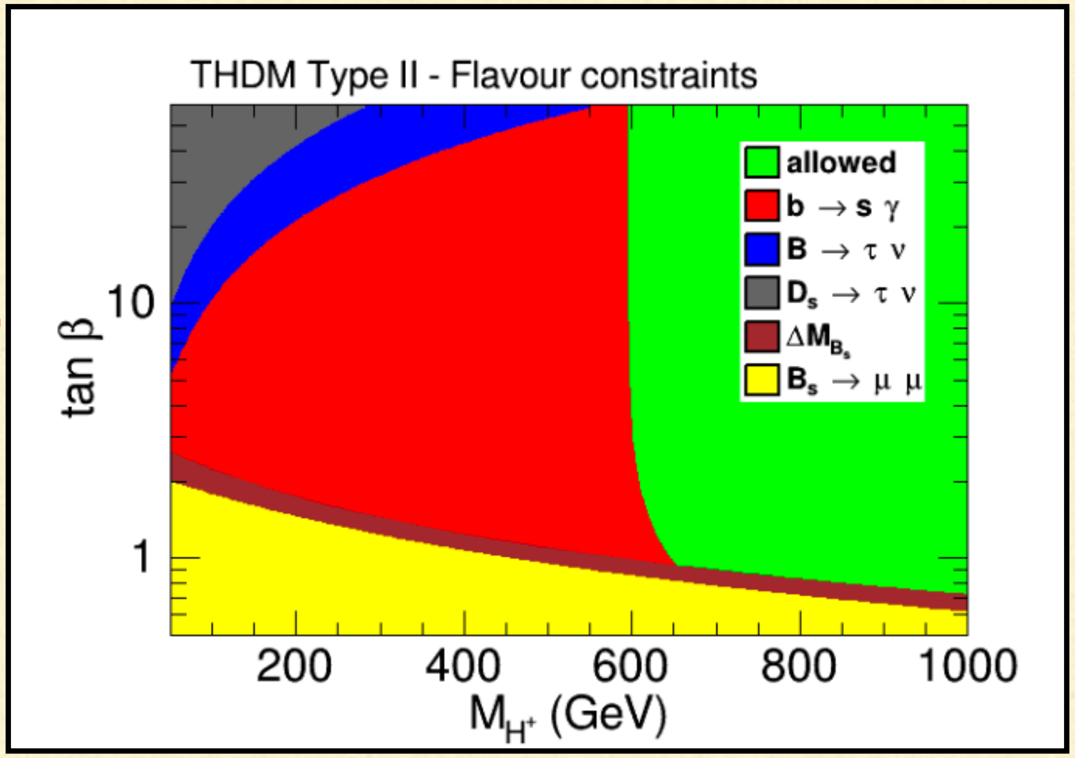
$m_{H^+} > 650\ \text{GeV}$

Can be attained by appropriately choosing

$\lambda_4 + \lambda_5$

One of the states becomes SM-like provided

$$\left| \frac{\lambda_{345}}{\lambda_1 - \lambda_2} \right| \gg 1$$



$$V_{H_1H_2} = \frac{m_1^2}{2}|H_1|^2 + \frac{m_2^2}{2}|H_2|^2 + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1H_2|^2 + \left(\frac{\lambda_5}{2}(H_1H_2)^2 + \text{h.c.}\right) .$$

COSMOLOGICAL REQUIREMENTS

- Classical dynamics assumed (that is the fact we assumed that is at the minimum) can be justified for small enough Hubble during inflation,

$$H_I^4 \ll m^2 f^2 \,.$$

(from the volume weighted Fokker Planck Equation)

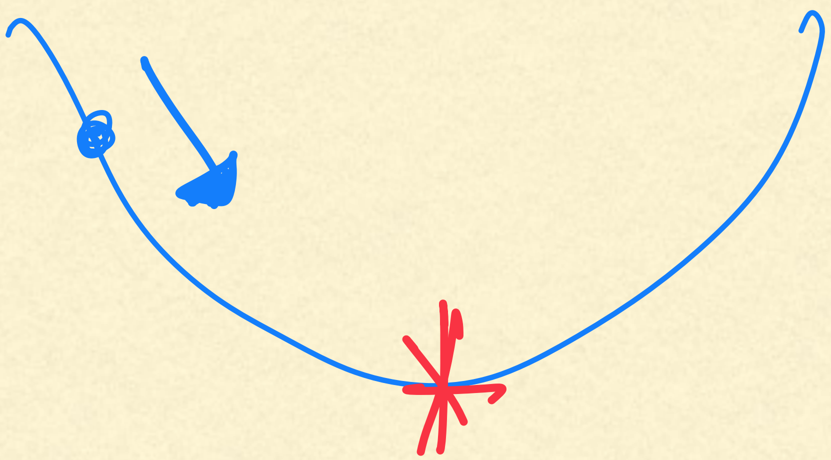
- Vacuum energy in $H - \phi$ system must be subdominant to sector driving inflation:

$$m^2 f^2 \ll V_{inf} \sim H_I^2 M_{pl}^2 \,.$$

PHENOMENOLOGY OF ϕ

- $\phi \to -\phi$ symmetry not broken either explicitly or spontaneously. Will be quadratically coupled to SM particles, eg.

- It is possible to get misalignment dark matter in some cases (if μ^2 not scanned too finely) and then the above couplings can also be probed.



COMPARISON WITH PREVIOUS WORK

- Our work is built on these models that used a similar mechanism:

M. Geller, Y. Hochberg, and E. Kuflik (2019)
C. Cheung and P. Saraswat, (2018)
G. F. Giudice, M. McCullough, and T. You, (2021)

- These models were more ambitious and included a mechanism to scan the Higgs mass (like in relaxion models). Eg:

$$(\Lambda^2 - g\Lambda\phi)H^\dagger H$$

- Not including other trigger mechanism like models where Higgs VEV triggers a big crunch

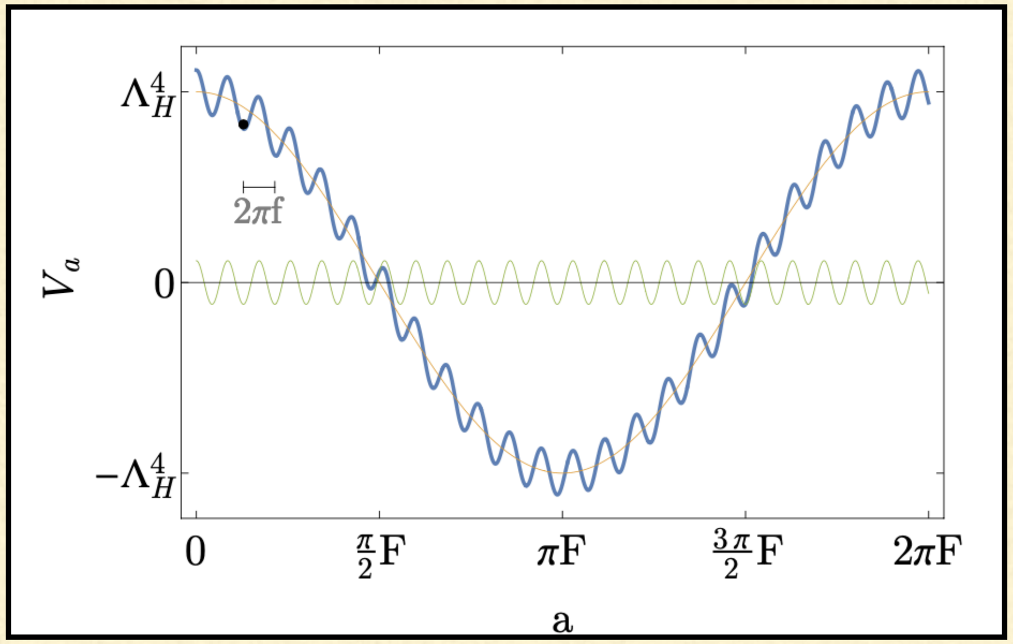
Csaki, D'Agnolo, Geller, and Ismail, (2020)
D'Agnolo and Teresi, (2021)
D'Agnolo and Teresi, (2022)

COMPARISON WITH PREVIOUS WORK

M. Geller, Y. Hochberg, and E. Kuflik (2019)

- First work to propose selection mechanism based on high vacuum energy patches inflating more
- More involved potential and mechanism

$$V = \left(M^2 + yM\phi + \ldots\right) h^2 + \lambda h^4 + yM^3\phi + \ldots + \frac{a}{f} G\tilde{G} + \Lambda_H^4 \cos\frac{a}{F}\,.$$



- Cut-off: $\Lambda \lesssim 10^7$ GeV
- Needs a doubly periodic potential that can be obtained from clockwork mechanism

COMPARISON WITH PREVIOUS WORK

C. Cheung and P. Saraswat, (2018)

- Linked critical points in Higgs potential to maxima in ϕ
- However could raise cut-off at most to 2 loop factors above the weak scale:

$$\Lambda \lesssim 16\pi^2 v$$

- Also needs clockwork to trap ϕ at maxima

COMPARISON WITH PREVIOUS WORK

G. F. Giudice, M. McCullough, and T. You, (2021)

- Much wider in scope. Proposed explanation of near criticality of Higgs mass, self coupling and also a solution to CC problem.

- Solution to hierarchy problem explained why,

$$v = e^{-\frac{3}{4}}\,\Lambda_I$$

scale where Higgs quartic vanishes due to running $\sim 10^{11}$ GeV *in SM*

- Introduced vector-like fermions to lower Λ_I to TeV scale.

- Also needs clockwork to either trap ϕ at its maxima or explain super-planckian f.

SELECTION SANS SCANNING

- We were less ambitious and propose a minimal model that implements only selection and not scanning.
- We just assume existence of a landscape of vacua.
- This leads to some desirable features.

A MINIMAL COSMOLOGICAL SELECTION MODEL

- Cut-off can be as high as Planck scale
- Upto the presence of a PNGB, potential is completely generic with $\mathcal{O}(1)$ parameters. No clockwork needed.
- Field value always lower than cut-off and f is sub-planckian.

CONCLUSIONS

- We propose a cosmological selection model that assumes there is already a landscape of vacua with different Higgs μ^2
- Regions of this landscape with highest vacuum energy expand exponentially more
- Large Higgs VEVs automatically exceeded
- We construct a model where the vacuum energy peaks at small but finite Higgs VEV

Thank you for your attention!

MEASURE PROBLEM

- If one measures volumes in the multiverse by just taking proper time slices the youngness paradox arises

- Younger universes arise from a volume that gets more time in exponential expansion phase making them exponentially more likely

- This is rectified in the stationary measure by comparing volumes of two regions after the same amount of time *since stationarity is reached*

- Even in the stationary measure after a sufficient time regions with maximum $H - \phi$ vacuum energy will dominate

BACK UP

MINIMAL COSMOLOGICAL SELECTION MODEL

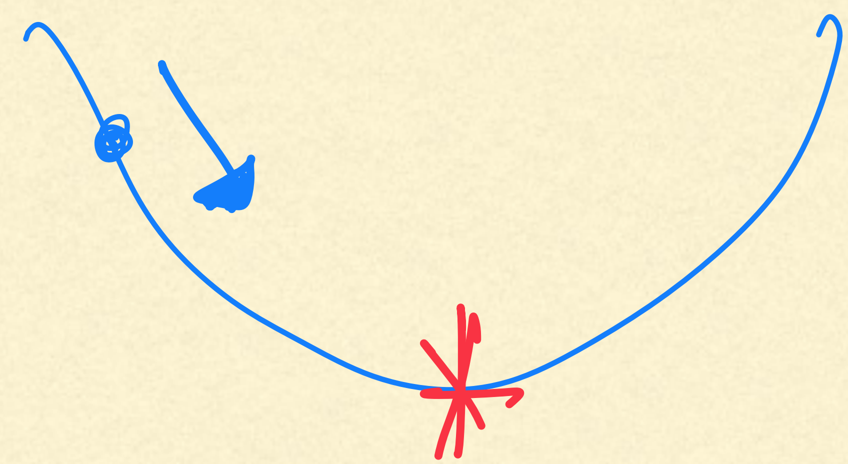
- Cut-off can be high as Planck scale
- Modulo the presence of a PNGB, potential completely generic with $\mathcal{O}(1)$ parameters. No clockwork needed.
- Field value always lower than cut-off

Chattopadhyay, Chattopadhyay, RSG & Karmakar (in progress)

WAVELIKE DARK MATTER

- ϕ is displaced from its minima and performs damped oscillations giving rise to wave-like dark matter.

$$\rho_\phi = \frac{m_\phi^2 \phi^2}{2} \sim \frac{1}{a^3}$$



- Has already been studied/addressed for relaxions, sliding naturalness and CS model.

Banerjee, Kim & Perez (2019)

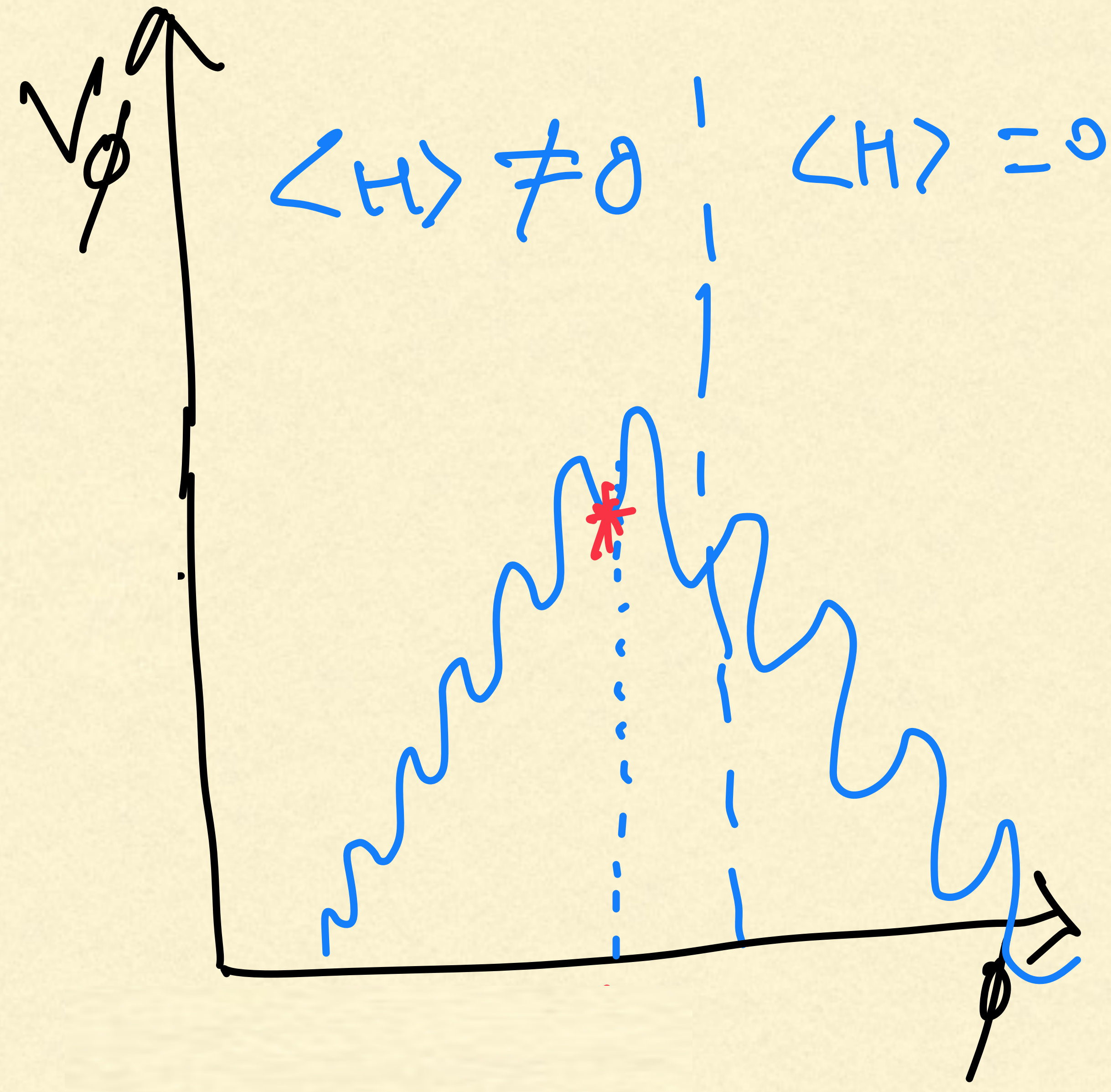
SHORTCOMINGS OF COSMOLOGICAL SELECTION MODELS

- Apart from the specific issue that the cut-off is not much higher than the weak scale Cheung-Saraswat (CS) model faces some universal issues faced by cosmological selection:

1. Potential very hard to realise: Periodic+Non-periodic. Requires elaborate clockwork mechanism.

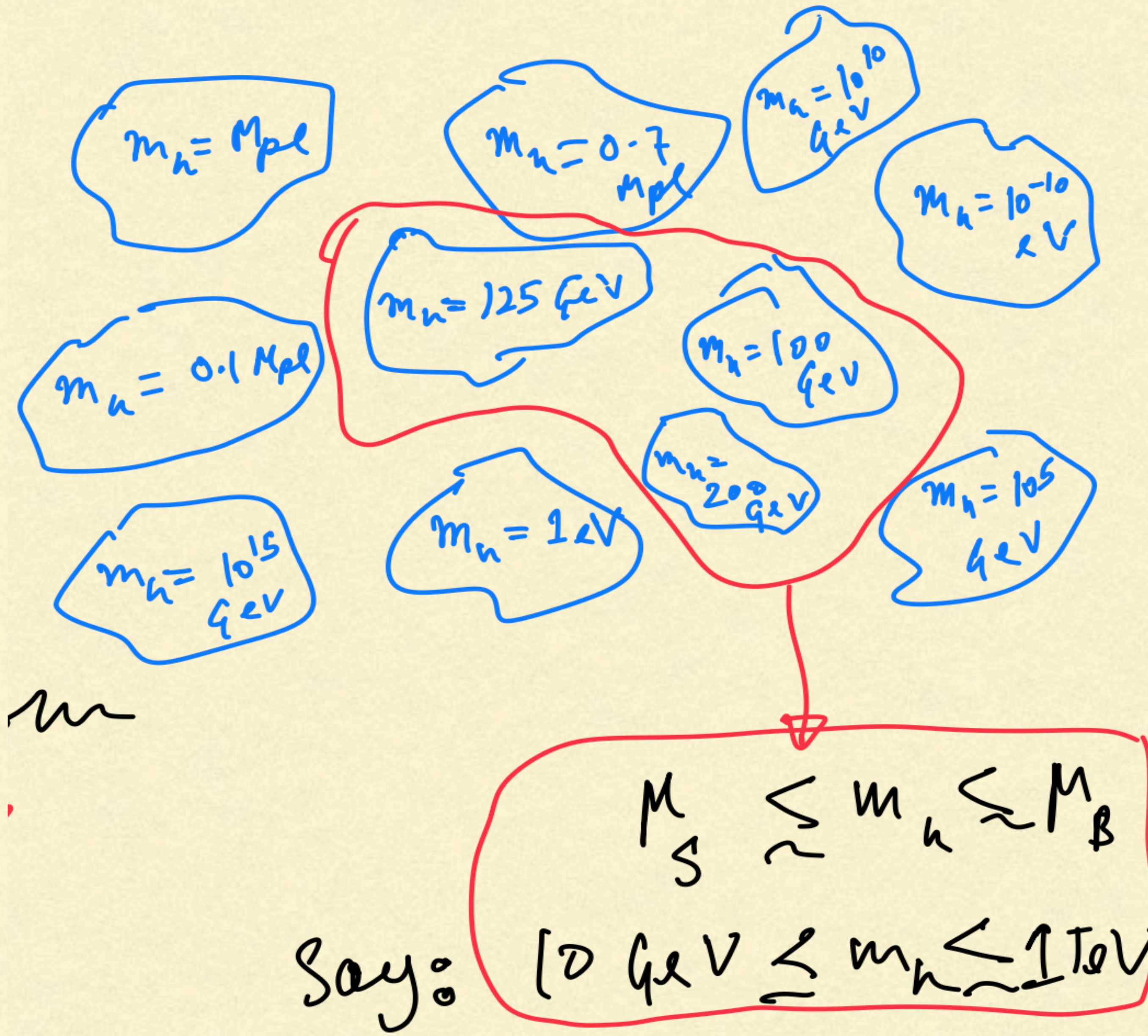
2. Extremely small/large numbers. Exponentially large number of e-folds.

3. In some other models (not CS) field excursions larger than cut-off, M_{pl}.



SELECTION SANS SCANNING

- Many of these problems arise in an attempt to scan the Higgs mass from - Λ^2 to Λ^2.
- We will be less ambitious and propose a minimal model that implements only selection and not scanning.
- We will assume as a given a multiverse with varying Higgs μ^2.



Chattopadhyay, Chattopadhyay, RSG & Karmakar (in progress)

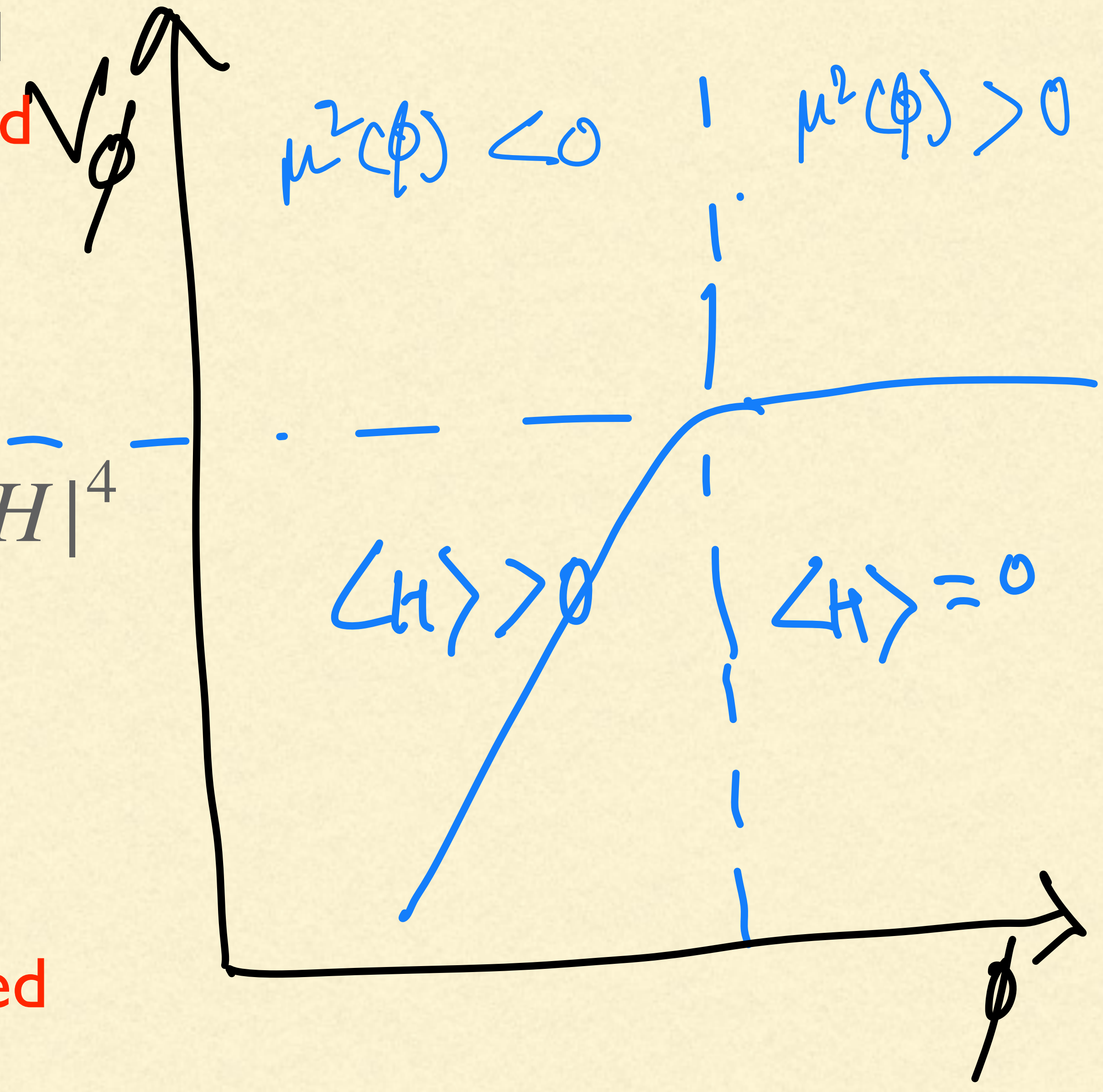
CHEUNG-SARASWAT MODEL

- Cheung and Saraswat proposed a model where the Higgs mass squared is scanned by a new scalar

- $V(H, \phi) = (\Lambda^2 - g\Lambda\phi)|H|^2 + \lambda|H|^4$

- Potential vanishes for positive μ^2 and falls for negative μ^2

- At this stage, positive μ^2 not disfavoured



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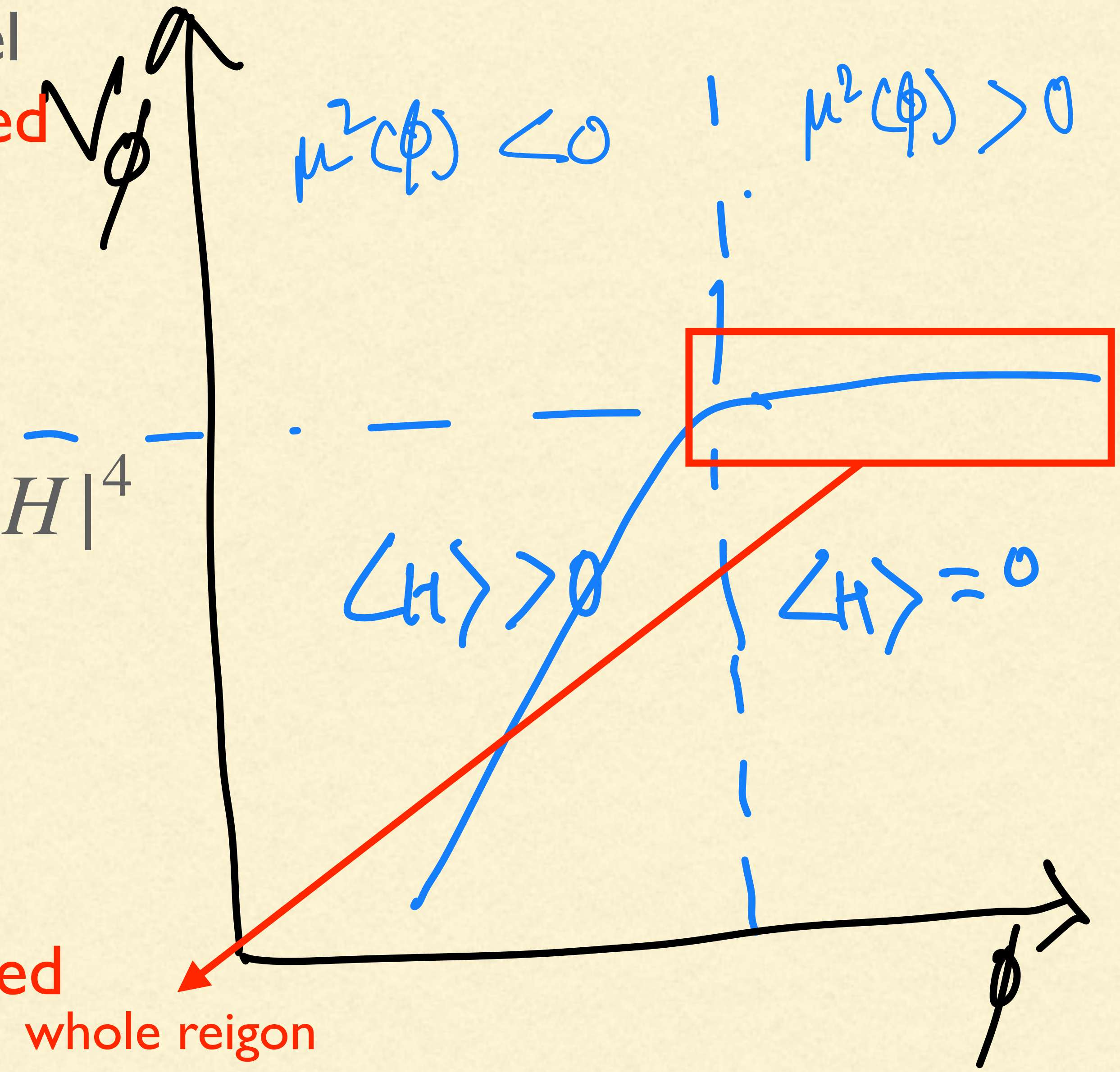


whole reigon selected including $\mu^2(\phi) \sim \Lambda^2$

Cheung & Saraswat (2019)

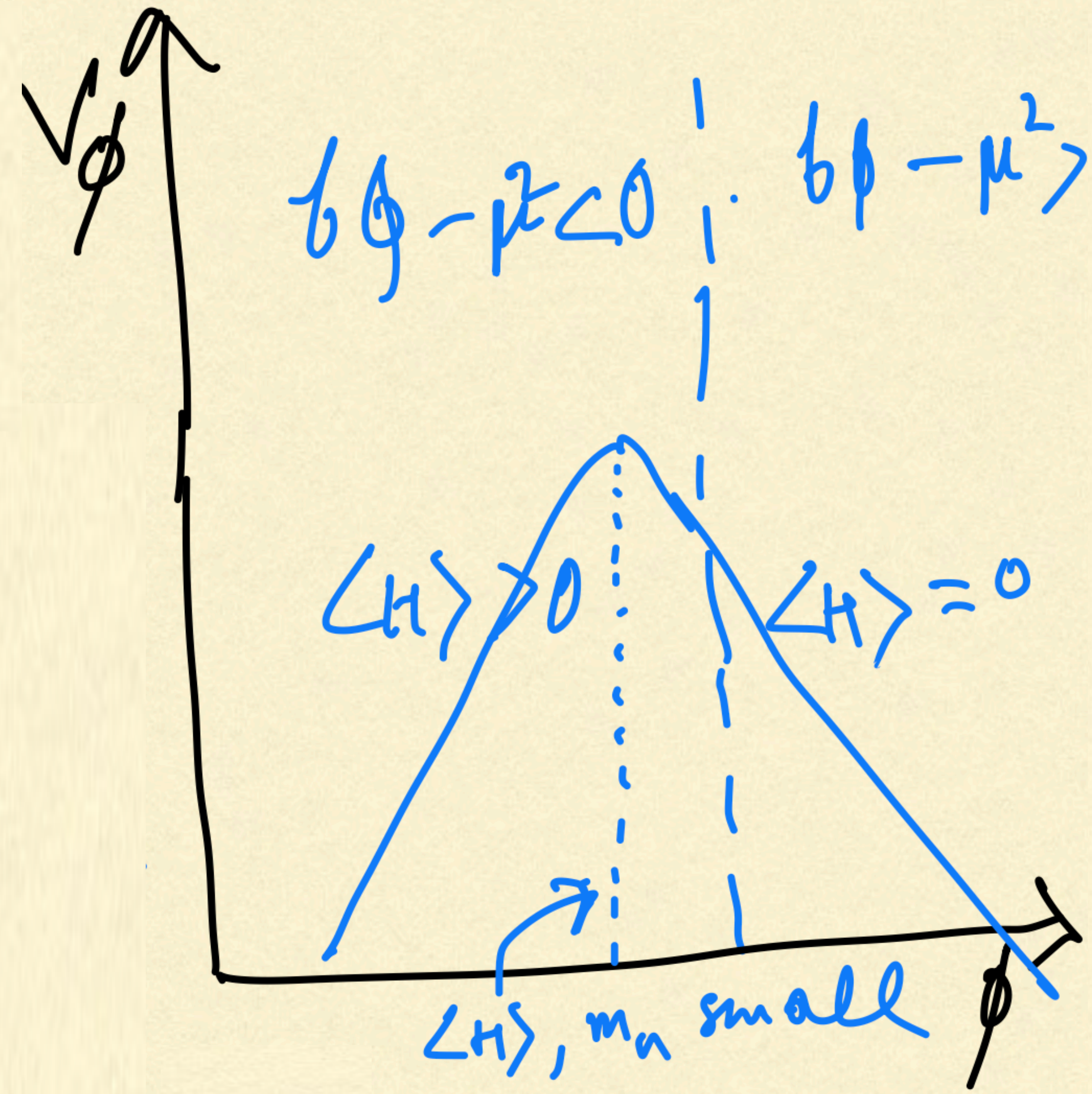
CHEUNG-SARASWAT MODEL

- At loop level,

$$\Delta V = -\, g\Lambda\phi \frac{\Lambda^2}{16\pi^2}$$

- Gives a vacuum energy peak at small values of provided, $v \sim \Lambda/4\pi$.

- Solves the Hierarchy problem only up to a scale $\Lambda \sim 4\pi v$.



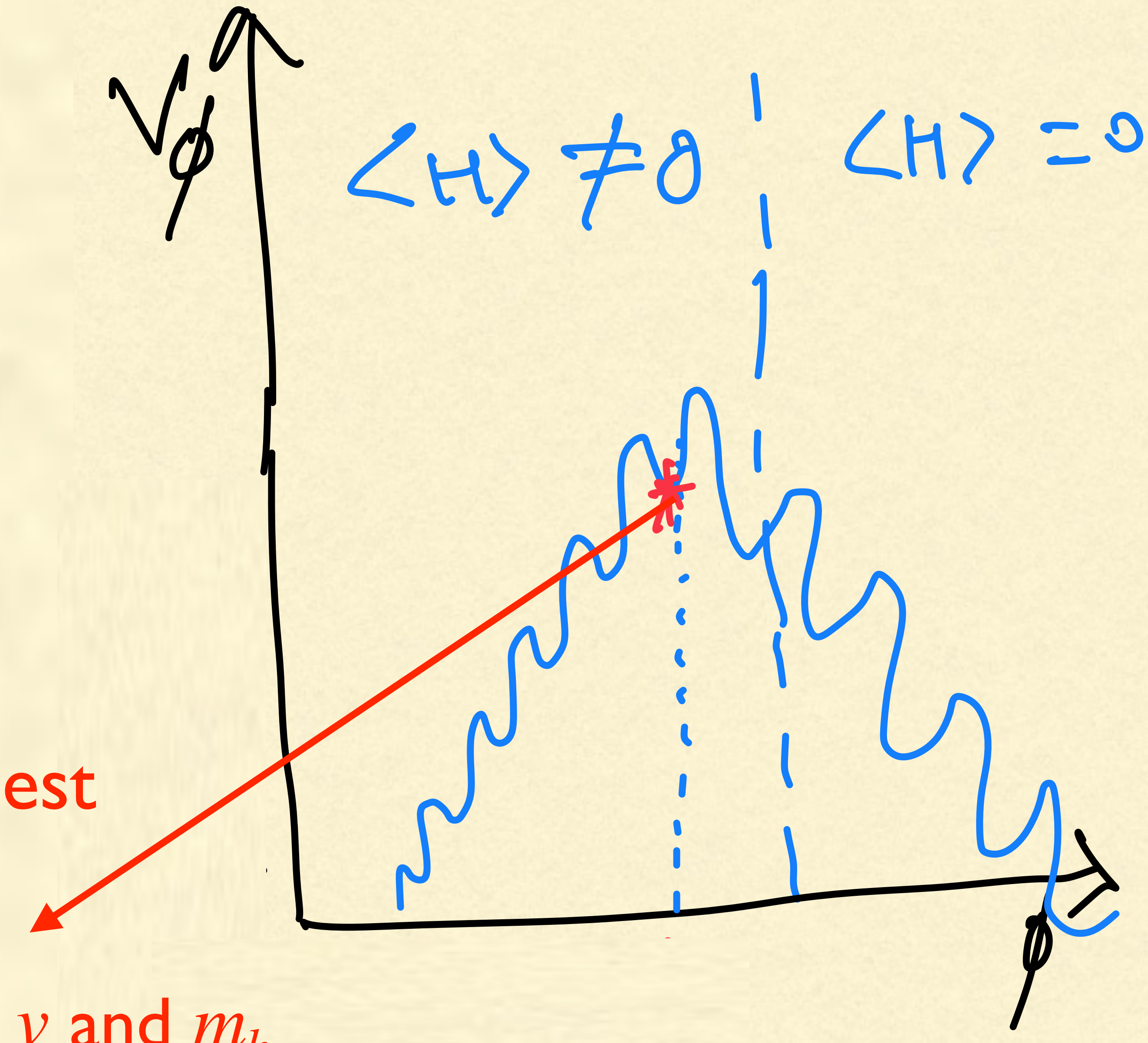
Cheung & Saraswat (2019)

CHEUNG-SARASWAT MODEL

- Now add an oscillator term:

$$M^4 \cos\left(\frac{\phi}{f}\right)$$

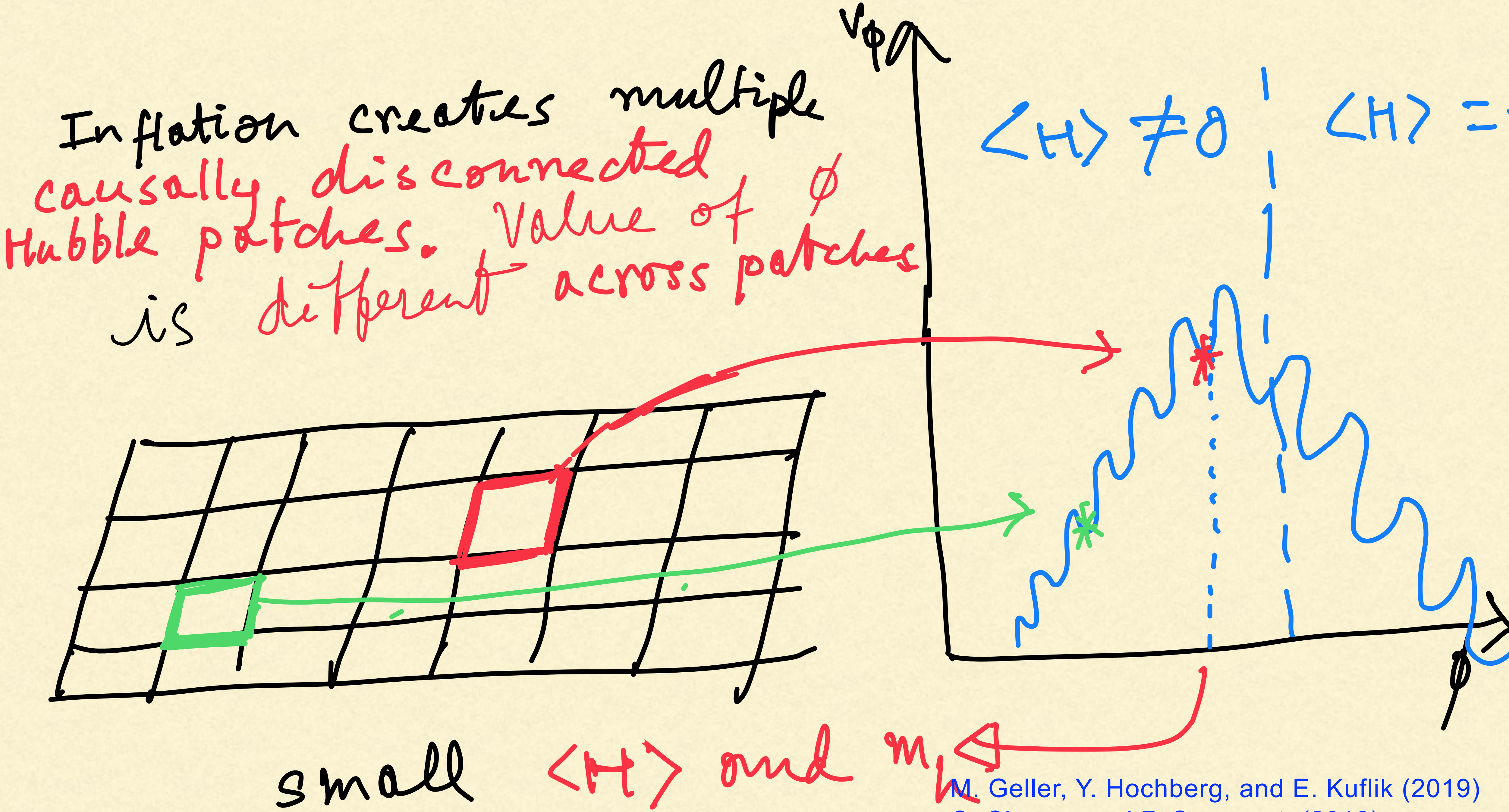
- The minima at the top have highest vacuum energy.



Small v and m_h

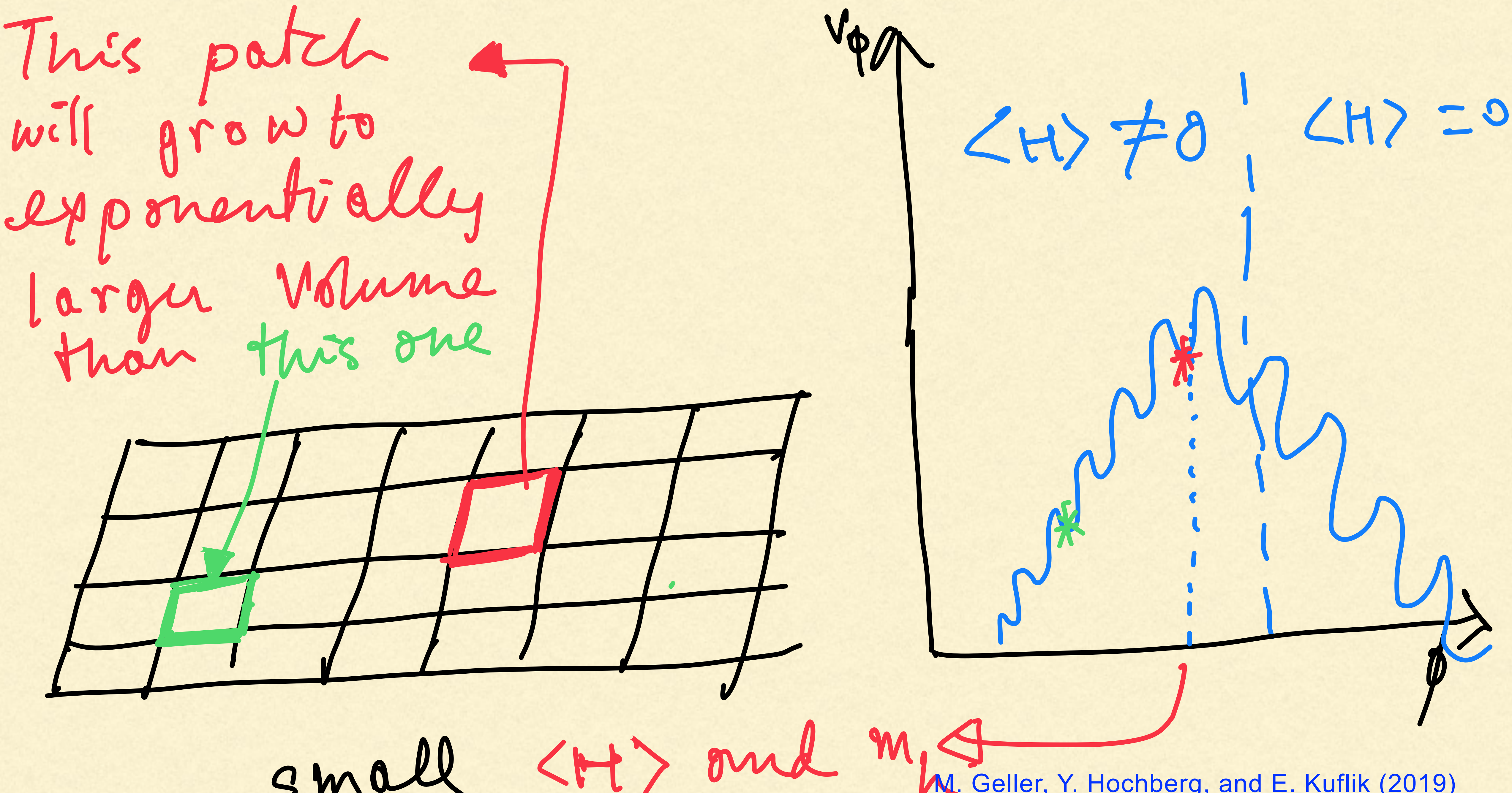
Cheung & Saraswat (2019)

CHEUNG-SARASWAT MODEL



M. Geller, Y. Hochberg, and E. Kuflik (2019)
C. Cheung and P. Saraswat, (2018)
G. F. Giudice, M. McCullough, and T. You, (2021)

CHEUNG-SARASWAT MODEL



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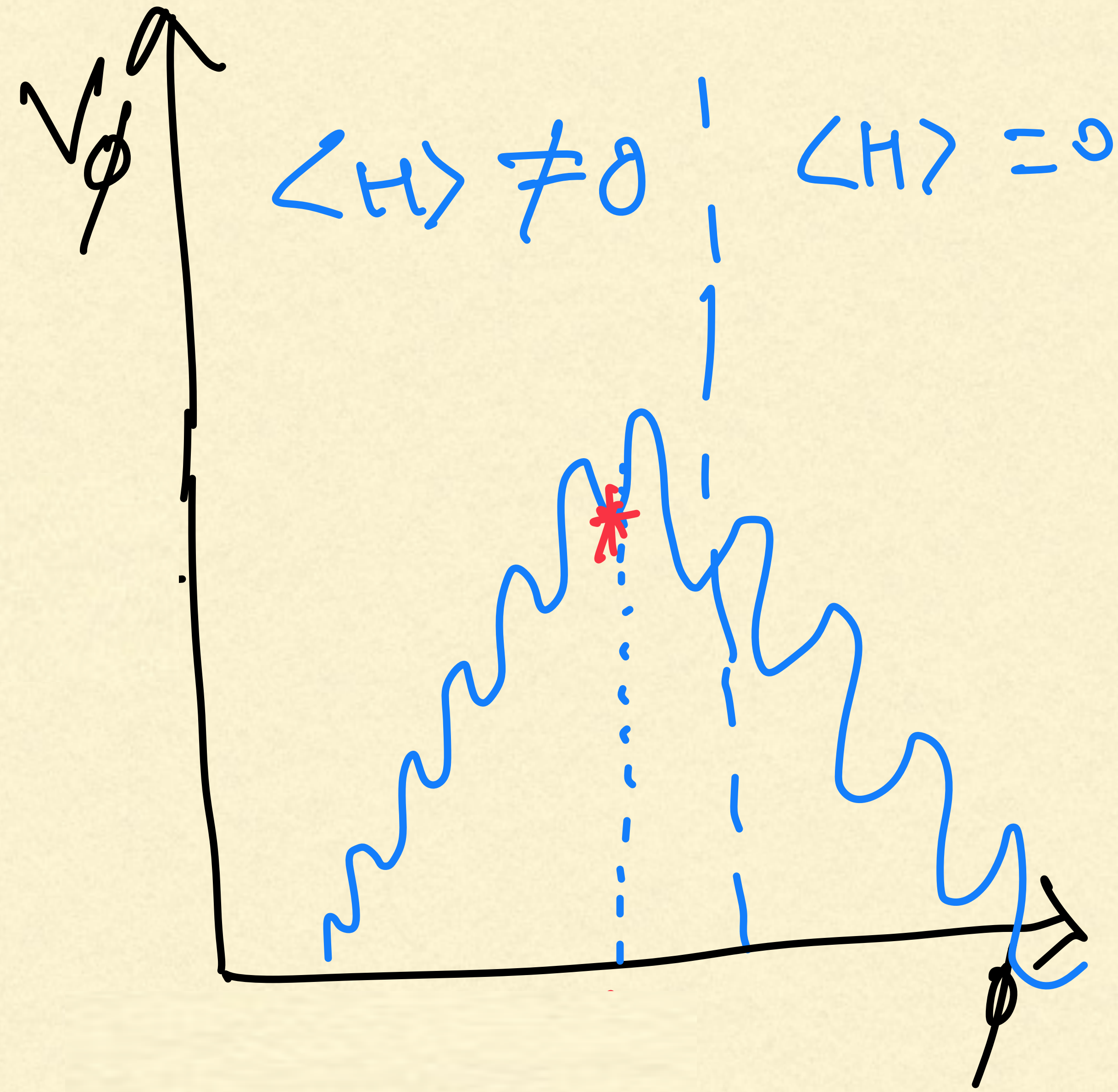
SHORTCOMINGS OF COSMOLOGICAL SELECTION MODELS

- Apart from the specific issue that the cut-off is not much higher than the weak scale Cheung-Saraswat (CS) model faces some universal issues faced by cosmological selection:

1. Potential very hard to realise: Periodic+Non-periodic. Requires elaborate clockwork mechanism.

2. Extremely small/large numbers. Exponentially large number of e-folds.

3. In some other models (not CS) field excursions larger than cut-off, M_{pl}.



THE HIERARCHY PROBLEM

$$m_H^{2\,phy} = m_{H_{UV}}^2 + \frac{y_1^2 M_1^2}{16\pi^2} + \frac{y_2^2 M_2^2}{16\pi^2} + \frac{y_3^2 M_3^2}{16\pi^2}$$

- If we accept the tuning, we need to know the parameters in the UV theory in the RHS to one part in $10^{-34}(10^{-26})$ for Planck (GUT) scale new physics and theoretical predictions to many loop orders to be able to actually predict the Higgs mass.

Panico & Wulzer, 2015