Searches for new vacua II: A new Higgstory at the cosmological collider

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1904.00020, 1907.10624, 1908.00019
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Hierarchy problem

- EW hierarchy problem & CC problem
- Symmetry + Naturalness
- Landscape/Multiverse + Anthropic
Hierarchy problem

- EW hierarchy problem & CC problem
  - Symmetry + Naturalness
  - Landscape/Multiverse + Anthropic

(Credit: Giovanni Villadoro)
Multiverse

• “…knowing that it could be out there is itself very important information…” (Search for indirect evidence)

• Weinberg CC

• String Axiverse

• Split Supersymmetry

• How can we directly look for a minimum?

• Local bubbles

• High scale higgs minimum
Multiverse

- “...knowing that it could be out there is itself very important information”

- Weinberg CC
- String Axiverse
- Split Supersymmetry

- How can we directly look for a minimum?

  - Go far away: Local bubbles
  - Go back into the past: High scale Higgs minimum
Outline

- The higgstory
- The tale of SM fermions
- Result and remarks
- A lower risk lower reward signal

Anson Hook, JH, Davide Racco
arXiv:1908.00019
**Higgs instability (Implications)**

- Higgs instability

\[ \lambda_h < 0 \Rightarrow v_{\lambda=0} \sim 10^{11} \text{ GeV} \]

- The EW minimum \( v_{\text{EW}} \) is meta-stable

- During inflation \( (H \lesssim 6 \times 10^{13} \text{ GeV}) \), Higgs could leave EW minimum.

- What does Higgs instability + High scale inflation imply?

  - New physics at low energy scales?
  
  - New coupling of Higgs to Hubble/Inflaton?

\[ 1711.03988 \]

- *Can we be in a high scale Higgs minimum all along?*
A new Higgstory

- During inflation
  - Higgs fluctuates over $v_{\lambda=0}$ and rolls to the UV minimum
  - Stays there the whole time when $v_{UV} > H$
  - *Require:* Stringy/GUT contribution stabilize runaway direction

- After inflation:
  - Thermal contributions lift the UV minimum
  - The Higgs rolls back and decays through scattering with background SM radiation
  - *Require:* Reheat to temperatures $T_{\text{max}} > v_{UV}$
Summary: parameter space

In all of the white region, our history would apply.
Primordial perturbations (Brief)

- Primordial perturbation $\zeta(x)$
  
  ...their correlations $\langle \zeta(x_1)\zeta(x_2)\ldots\zeta(x_n) \rangle$
  
  encode information about inflation

- Correlation functions (Fourier)

  $\langle \zeta(x_1)\zeta(x_2)\ldots\zeta(x_n) \rangle \rightarrow \langle \zeta(k_1)\zeta(k_2)\ldots\zeta(k_n) \rangle$
Power spectrum (leading effect)

- Power spectrum (leading effect):
  \[ \langle \delta \phi(k_1) \delta \phi(k_2) \rangle \sim \frac{H^2}{k_1^3} \delta(\vec{k}_1 + \vec{k}_2) \]

- Density correlation function:
  \[ \langle \zeta(k_1) \zeta(k_2) \rangle = (2\pi)^3 \frac{2\pi^2 P_\zeta}{k_1^3} \delta(\vec{k}_1 + \vec{k}_2) \]
  \[ \langle \zeta(0) \zeta(x) \rangle \sim H^2 \log |x| \]
Cosmological collider (Brief)

- Non-Gaussianity:
  \[
  \langle \zeta(k_1)\zeta(k_2)\zeta(k_3) \rangle' = \frac{(2\pi)^4 p^2_\zeta}{k_1^2 k_2^2 k_3^2} S(k_1, k_2, k_3).
  \]

- Cosmological collider
  - Cosmological collider physics concerns the case where there are intermediate massive particles
  - Massive particle redshifts differently
  - and leads to oscillating shapes in the squeezed limit \( k_3 < k_2 \sim k_1 \)

  \[
  S \propto f_{\text{NL}}^{(\text{clock})} \left( \frac{k_3}{k_1} \right)^{2i\tilde{m}}
  \]
Universe as a Detector

CMS detector

(Credit: Zhong-Zhi Xianyu)
Using SM Fermions

- Why fermions?
  - SM fermion masses scan many order of magnitude
  - Fermions have no hierarchy problem
    - Fermions enhance EW symmetry breaking
      Anson Hook, JH, Davide Racco, arXiv:1908.00019
- How to use SM fermions?
  - Couple them to inflaton (shift symmetric):
    \[
    - \frac{c f_i}{\Lambda_f} \partial_\mu \phi \overline{f_i} \gamma^\mu \gamma^5 f_i
    \]
    1805.02656
A fermion story

- Fermion dispersion relation (small Hubble)

- Rolling inflaton ($\dot{\phi}$) breaks Lorentz Symmetry

\[-\frac{c_f}{\Lambda_f} \partial_\mu \phi \overline{f}_i \gamma^\mu \gamma^5 f_i \quad \omega^2 = (|k| \mp \lambda)^2 + m^2 \quad \lambda = \frac{\dot{\phi}}{\Lambda_f}\]

- Fermion production ($H \ll m \ll \lambda$)
  - Fermion mode: ($\omega \sim m, k \sim \pm \lambda$)

- Production rate:
- Effective density:
- Fermion redshift
- Fermion annihilation
A fermion story

- Fermion dispersion relation
  \[ \omega^2 = (|k| \mp \lambda)^2 + m^2 \]

- Fermion production \((H \ll m \ll \lambda)\)
  - Fermion mode: \((\omega \sim m, k \sim \pm \lambda)\)
  - Production rate: 
    \[ \Gamma \propto e^{-\frac{\omega^2}{\lambda^2}} \sim e^{-\frac{m^2}{\lambda H}} \]
  - Effective density: 
    \[ n \sim k^2 \delta k \sim m \lambda^2 \]

- Fermion redshift
- Fermion annihilation
A fermion story

• Fermion dispersion relation: \( \omega^2 = (|k| \mp \lambda)^2 + m^2 \)

• Fermion production

• Fermion redshift: \( (k_3 \sim \omega(\tau_3) \sim m) \)
  • From \( (\omega \sim m, k \sim \lambda) \) to \( (\omega \sim \lambda, k \sim 0) \)
  • \( \omega \sim \lambda \) sets oscillation frequency \( \left( \frac{k_3}{k_1} \right) \)

• Fermion annihilation
  • Fermions \( (\omega \sim \lambda, k \sim 0) \) can only pair annihilate
    \[ (k_2 \sim k_1 \sim \omega(\tau_1) \sim \lambda) \]
    \[ \frac{k_3}{k_1} \sim \frac{m}{\lambda} \]
Signal strength

- **Signal from a fermion loop:** \( \mu = \sqrt{\lambda^2 + m^2} \sim \lambda \gg m \)

- **Shape:** \( S(k_1, k_2, k_3) \overset{k_3 \ll k_1 \sim k_2}{\approx} f_{\text{NL}}(\text{clock}) \left( \frac{k_3}{k_1} \right)^{2-2i\tilde{\mu}} + \cdots \)

- **Amplitude:** \( f_{\text{NL}}^{(\text{clock})} \approx \frac{N_c}{6\pi} P_\zeta^{-1/2} \left( \frac{m}{\Lambda_f} \right)^3 \lambda^2 \frac{e^{2\pi\lambda\mu\Gamma(-i\tilde{\mu})^2\Gamma(2i\tilde{\mu})^3}}{2\pi\Gamma(i(\lambda + \tilde{\mu}))^3\Gamma(i(\tilde{\mu} - \lambda) + 1)} \)
Signal strength

Take home:
1. SM fermions scan Hubble
2. Multiple SM fermions can be observed together
Distinguishing the signal

- How to distinguish the signal:
  - Amplitude ($f_{NL}$) and frequency $\rightarrow$ Mass ($m/H$) & Coupling ($\lambda/H$)
  - Two/multiple fermions:
    - Ratio of fermion masses: $\frac{\tilde{m}_i}{\tilde{m}_j} = \frac{y_i}{y_j}$
  - Implications:
    - A new minimum!
    - New probe of GUT, string theories…
    - No two Higgs doublet, no new coloured states…
Implications

- How to distinguish the signal:
  - Amplitude ($f_{NL}$) and frequency -> Mass ($m/H$) & Coupling ($\lambda$/$H$)
  - Two/multiple fermions:
    - Ratio of fermion masses: $\frac{\tilde{m}_i}{m_j} = \frac{y_i}{y_j}$
- Implications:
  - A new minimum!
  - UV: New probe of GUT, string theories…
  - IR: No two Higgs doublets, not many new coloured states…

We can look for the landscape, directly!
Low(er) risk
&
low(er) reward

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arXiv:1908.00019
Parameter space II

- **Green**: Lighter SM fermions.
- **Above Blue line**: Top quark

How does the SM fermion density affect Higgs potential?
SM Matter effect

- Fermions produced (effective density):
  \[ n \sim k^2 \delta k \sim m \lambda^2 \bigg|_{m \ll H} \quad \Rightarrow \quad H \sim m_f n_f \sim y_f^2 \lambda_f^2 h^2 \gg H^2 h^2 \]

- Fermions impact the Higgs potential

- Correction to mass (small mass limit):

  Top quark density affects Higgs potential!
SM Matter effect

- Fermions produced (effective density):
  \[ n \sim k^2 \delta k \sim m \lambda^2 \bigg|_{m \ll H} \quad ? \quad H \sim m_f n_f \sim y_f^2 \lambda_f^2 h^2 \gg H^2 h^2 \]

- Fermions impact the Higgs potential

- Correction to mass (small mass limit):
  \[ \delta V_h = -\frac{y_f^2}{2\pi^2} \lambda_f^2 h^2 \]
  Especially the top quark
**Dynamical Higgs minimum**

- Dynamical equilibrium:
  1. Fermion production
  2. Higgs rolls to the minimum
  3. Fermions become heavy
  4. Particle production shuts off

\[
\Gamma \propto e^{-\frac{\omega^2}{\omega}} \sim e^{-\frac{m^2}{\lambda H}} \left| 1 \ll m^2/\lambda H \ll \lambda/H \right.
\]

- The resulting Higgs potential:

\[
V_h = -m_h^2|\mathcal{H}|^2 + \lambda_h|\mathcal{H}|^4 - \frac{N_c y_f^2}{\pi^2} \lambda_f^2|\mathcal{H}|^2 \exp \left[-\frac{\pi y_f^2|\mathcal{H}|^2}{\lambda_f H} \right]
\]
Dynamical Higgs minimum

- The resulting Higgs potential:

\[ V_h = -m_h^2 |\mathcal{H}|^2 + \lambda_h |\mathcal{H}|^4 - \frac{N_c y_f^2}{\pi^2} \lambda_f^2 |\mathcal{H}|^2 \exp \left[ -\frac{\pi y_f^2 |\mathcal{H}|^2}{\lambda_f H} \right] \]

- The dynamical Higgs minimum:

\[ v = \frac{1}{y_f} \sqrt{\frac{2}{\pi} \lambda_f H} \left( 1 - \frac{e \lambda_h / y_f^4}{\pi N_c \lambda_f / H} + O(\lambda_h^2) \right) \]

\[ \frac{m_t}{H} = \left( \frac{\lambda_t}{\pi H} \right)^{1/2} \]
One parameter signal

- The signal shape:

\[ S(k_1, k_2, k_3) \approx f_{\text{NL}}^\text{(clock)} \left( \frac{k_3}{k_1} \right)^{2-2i\lambda_f} \]

- The signal amplitude:

\[ f_{\text{NL}}^\text{(clock)} \approx \frac{4\sqrt{2} N_c P_c}{3\epsilon} \lambda_f^{13/2} \]

\[ \frac{\dot{\phi}}{\lambda_f^2} \]

\[ N_c = 3 \]

\[ f_{\text{NL}} \]

\[ \frac{\lambda_i}{H} \]
One parameter signal

- **Blue + Green**: Dynamical minimum with Top quark signal
- **Green**: Lighter SM fermions signal from a true minimum
Remarks

• We show, for the first time, two examples of how cosmological collider physics observations can be used to uncover some deep underlying dynamics during inflation.

• This makes “cosmological collider physics” a tool to look for physics beyond the standard model.

• Extending the Standard Model, with a single coupling between the Standard Model fermions and the inflaton, inevitably gives rise to one of the two observable signatures.
Does one new minimum hint multiverse? Would a few of them convince you?

不识庐山真面目
只缘身在此山中
——苏轼

Why can't I tell the true shape of Lu-shan? Because I myself am in the mountain.
——Shi Su