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

Junwu Huang
Perimeter Institute
Oct, 2019 @ GGI

1904.00020, 1907.10624, 1908.00019
Anson Hook, **Junwu Huang,** Davide Racco

Hierarchy problem

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

(Credit: Giovanni Villadoro)

Multiverse

- "…knowing that it could be out there is itself very important information…" (Nima or Savas)
  - Weinberg CC
  - String Axiverse
    0905.4720
  - Split Supersymmetry
    hep-ph/0406088, hep-ph/0409232, 1210.0555
- How can we directly look for a minimum?
  - Local bubbles
  - High scale higgs minimum

One step further:
see a new minimum!

Multiverse

- "…knowing that it could be out there is itself very important information" (Nima or Savas)
    - Weinberg CC
    - String Axiverse
    - Split Supersymmetry
- How can we directly look for a minimum?
    - Go far away: Local bubbles
      *Anson Hook, **JH**, arXiv:1904.00020*
    - Go back into the past: High scale Higgs minimum

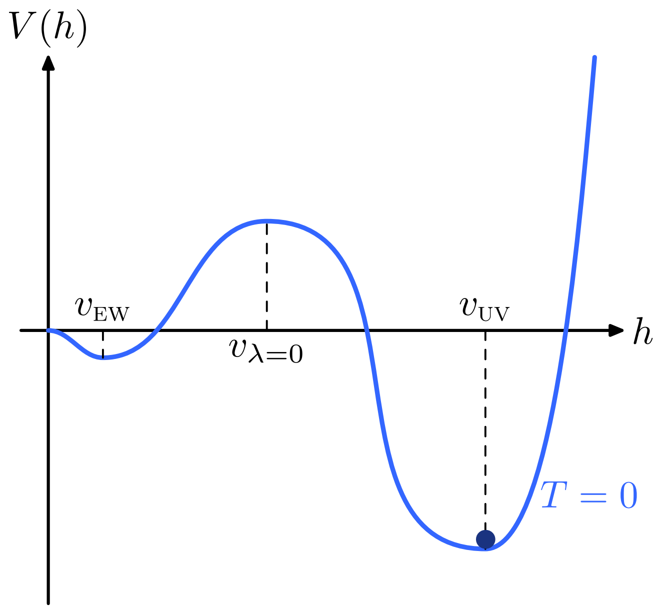
Outline

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

*Anson Hook, **JH**, Davide Racco*
arXiv:1908.00019

A new Higgstory

Higgs instability (Brief)

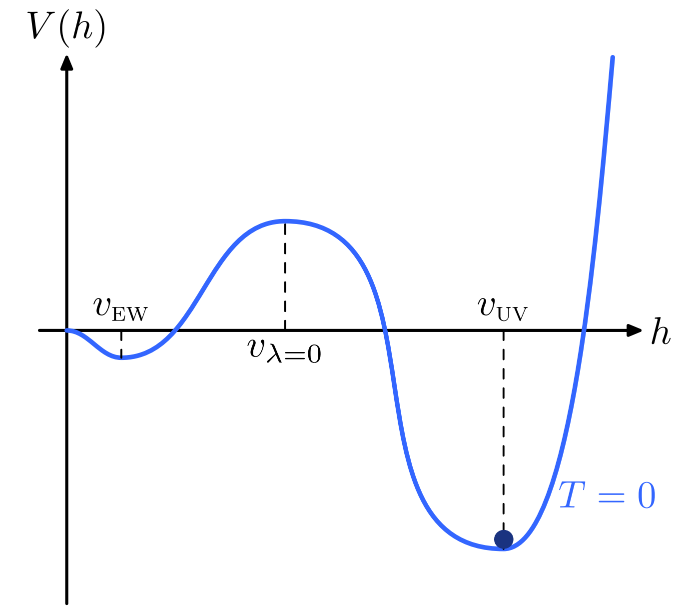


- Higgs instability

  1505.04825

  - Higgs quartic $\lambda_h < 0 \,@\, v_{\lambda=0} \sim 10^{11}\,\text{GeV}$
  - The EW minimum v_{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?
  - *Can we be in a high scale Higgs minimum all along?*

Higgs instability (Implications)



- Higgs instability

  1505.04825

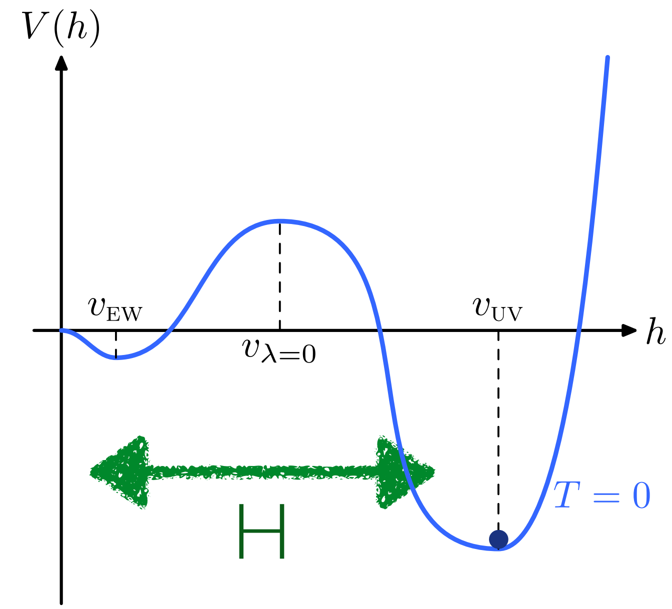
  - Higgs quartic $\lambda_h < 0\,@\,v_{\lambda=0} \sim 10^{11}\,\mathrm{GeV}$
  - The EW minimum v_{EW} is meta-stable
  - During inflation ($H \lesssim 6 \times 10^{13}\,\mathrm{GeV}$), Higgs could leave EW minimum.
- What does Higgs instability + High scale inflation imply?
  - New physics at low energy scales?
  - New coupling of Higgs to Hubble/Inflaton?

    1711.03988

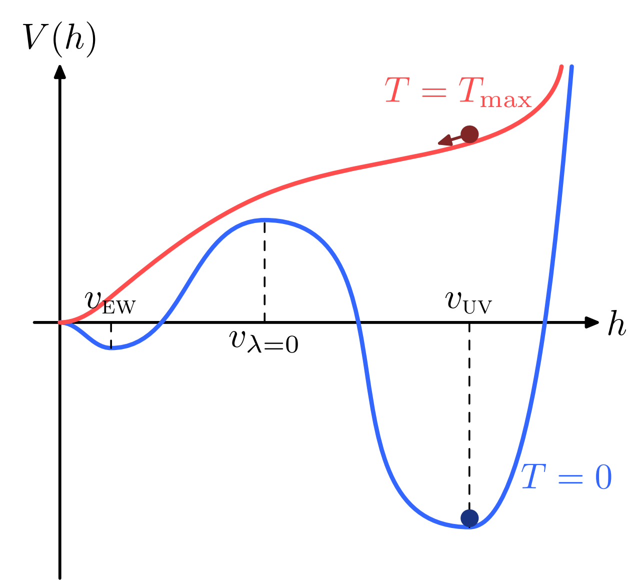
  - *Can we be in a high scale Higgs minimum all along?*

A new Higgstory

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

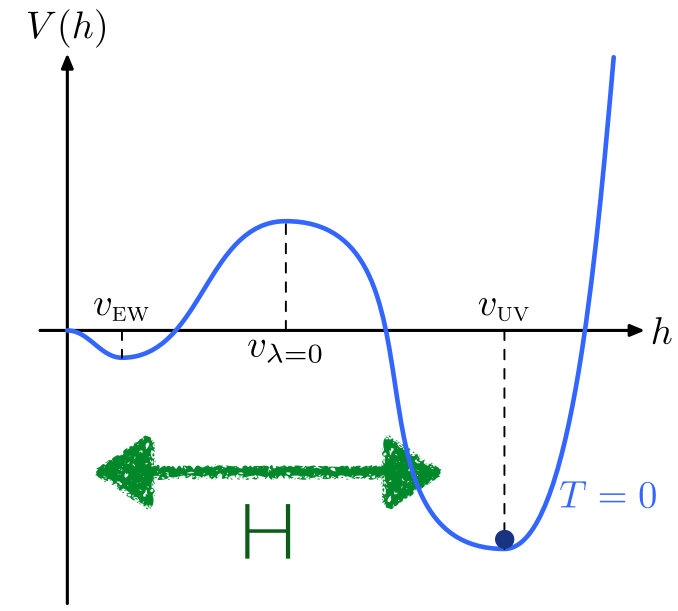


- After inflation:
  - Thermal contribution lift the UV minimum
  - The Higgs rolls back and decays through scattering with background SM radiation
  - *Require*: Reheat to temperatures $T_{\max} > v_{\mathrm{UV}}$

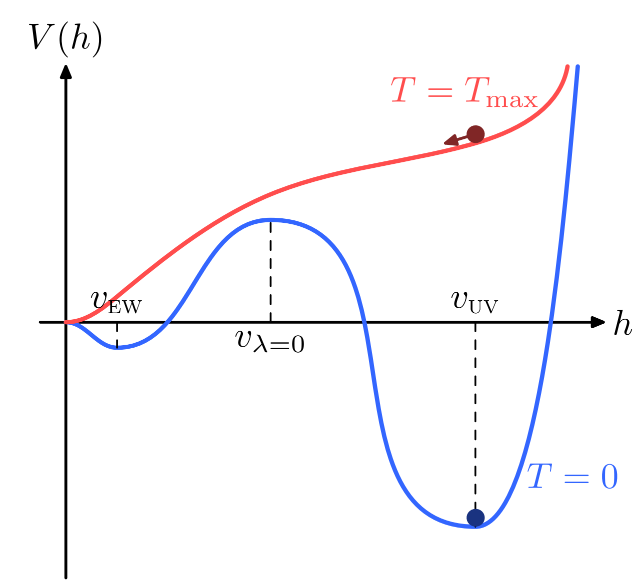


A new Higgstory

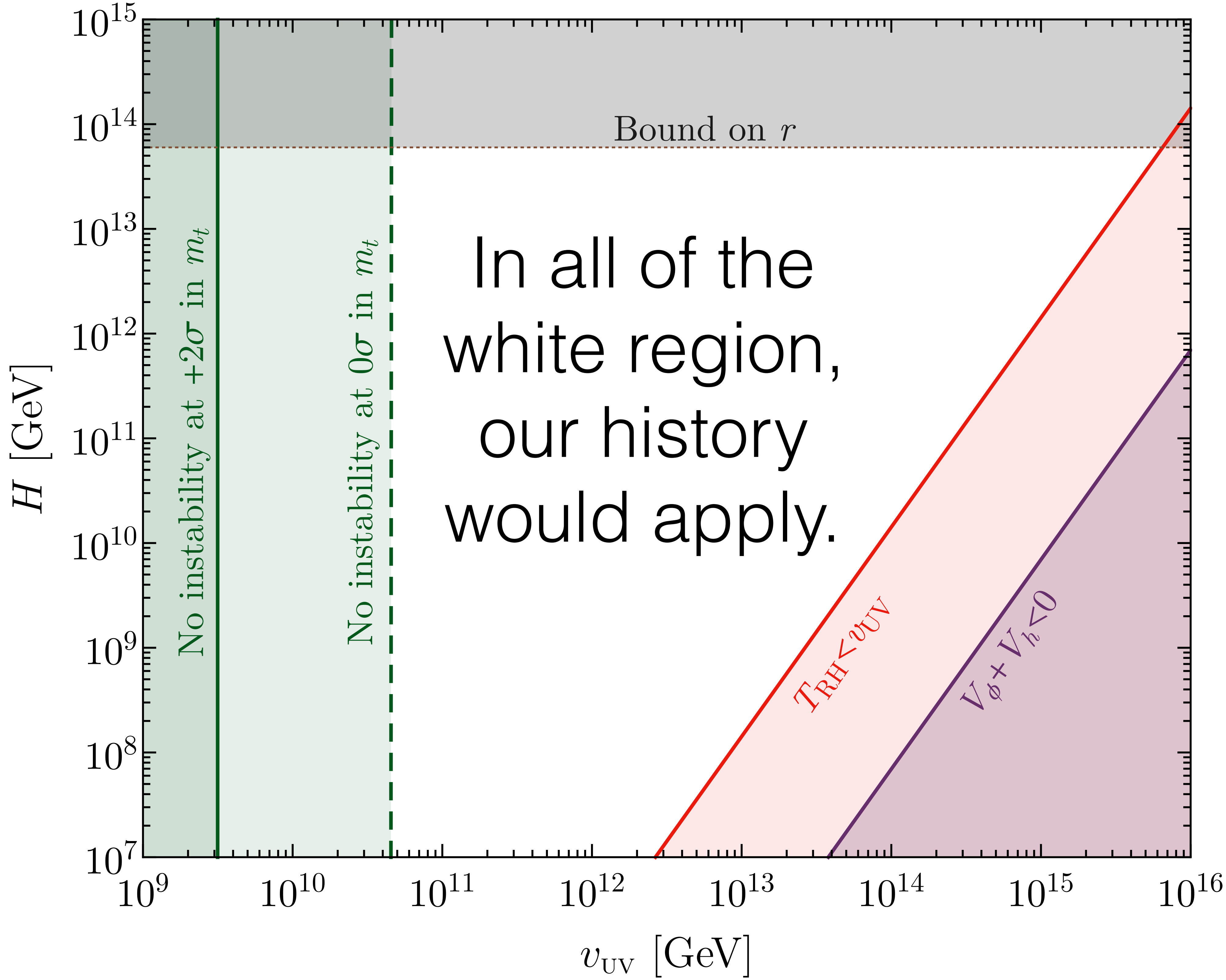
- During inflation
  - Higgs fluctuate over $v_{\lambda=0}$ and roll to the UV minimum.
  - Stay there the whole time when $v_{\mathrm{UV}} > H$
  - *Require*: Stringy/GUT contribution stabilize runaway direction



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



Summary: parameter space



Cosmological collider
of
SM fermions

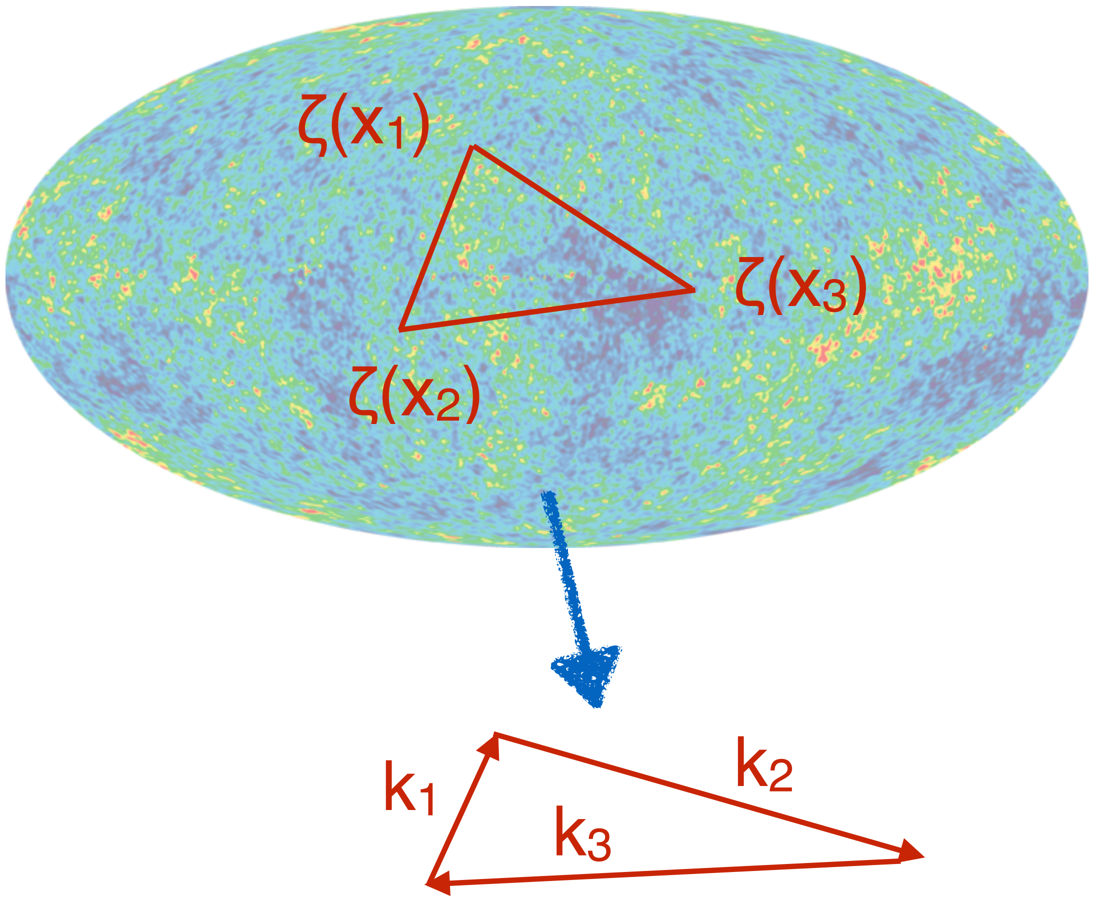
Primordial perturbations (Brief)

- Primordial perturbation ζ(x)

…their correlations $\langle \zeta(x_1)\zeta(x_2)\ldots\zeta(x_n)\rangle$ encodes information of inflation

- Correlation functions (Fourier)

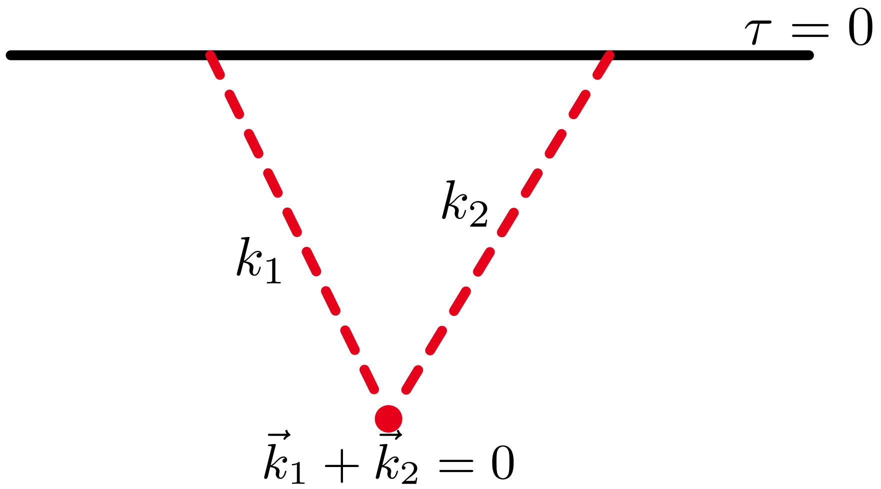
$$\langle \zeta(x_1)\zeta(x_2)\ldots\zeta(x_n)\rangle \to \langle \zeta(k_1)\zeta(k_2)\ldots\zeta(k_n)\rangle$$



Power spectrum (leading effect)

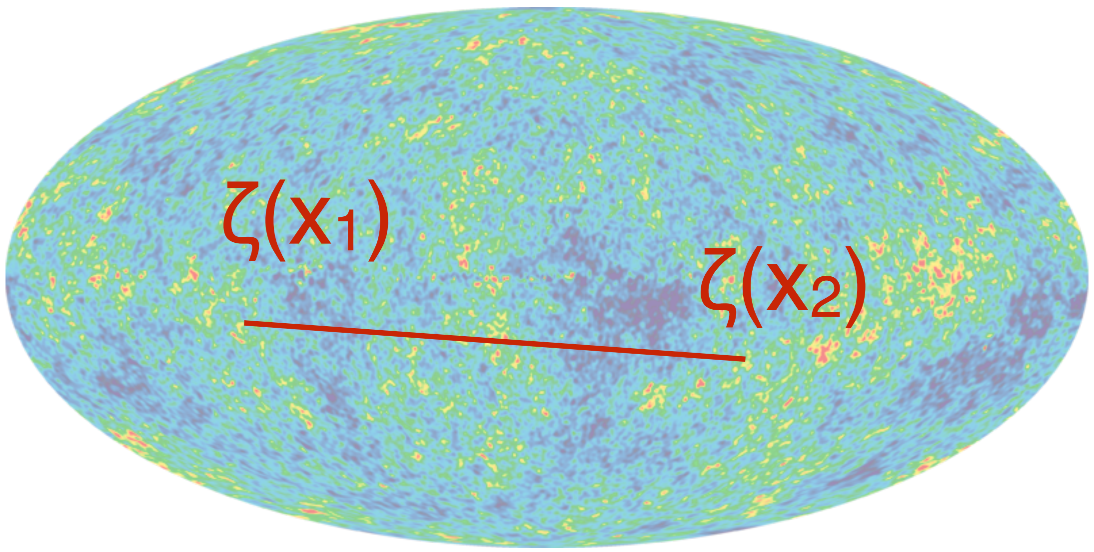
- Power spectrum (leading effect):

$$\langle \delta\phi(k_1)\delta\phi(k_2)\rangle \sim \frac{H^2}{k_1^3}\delta\left(\vec{k}_1 + \vec{k}_2\right)$$



- Density correlation function:

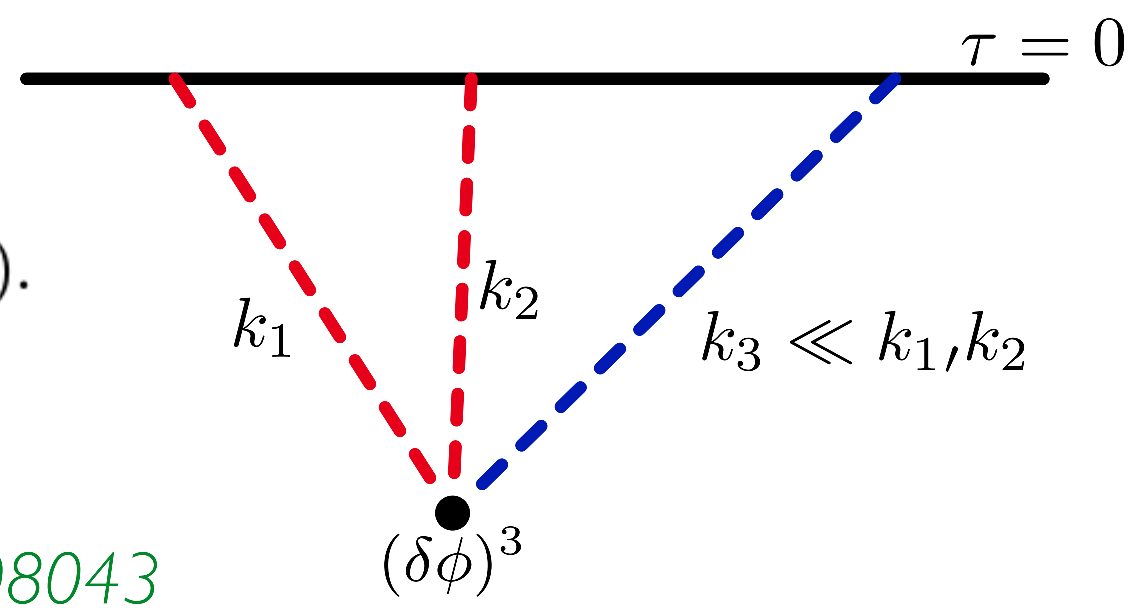
$$\begin{cases} \langle \zeta(k_1)\zeta(k_2)\rangle = (2\pi)^3 \dfrac{2\pi^2 P_\zeta}{k_1^3}\delta\left(\vec{k}_1 + \vec{k}_2\right) \\ \langle \zeta(0)\zeta(x)\rangle \sim H^2 \log|x| \end{cases}$$



Non-Gaussianity (Brief)

- Non-gaussianity:

$$\langle \zeta(k_1)\zeta(k_2)\zeta(k_3)\rangle' = \frac{(2\pi)^4 \mathcal{P}_\zeta^2}{k_1^2 k_2^2 k_3^2} S(k_1, k_2, k_3).$$



- Cosmological collider

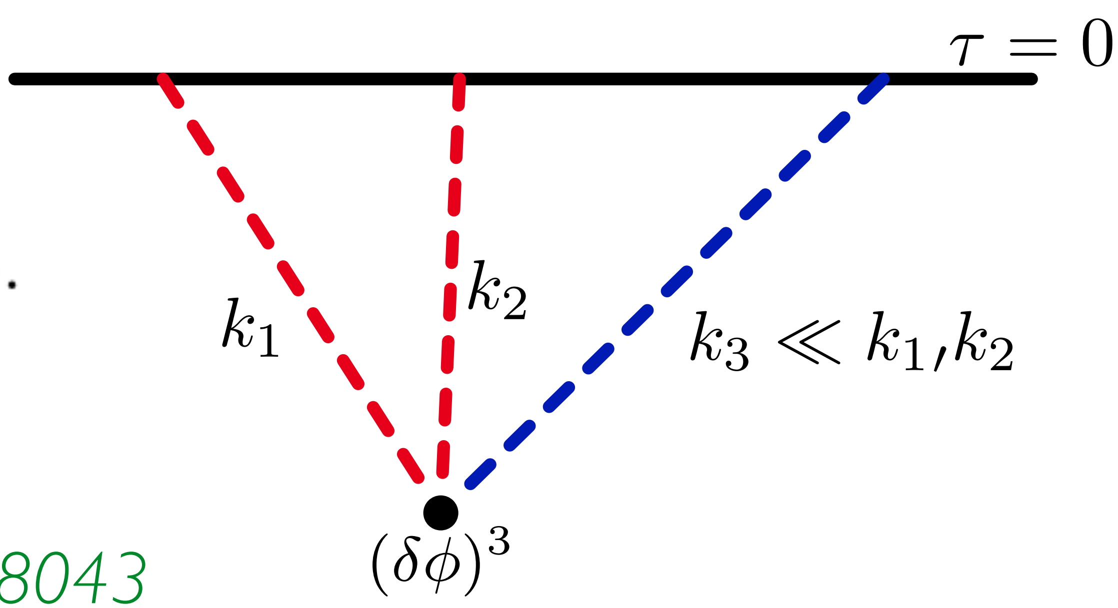
0911.3380, 1503.08043

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

Cosmological collider (Brief)

- Non-gaussianity:

$$\langle\zeta(k_1)\zeta(k_2)\zeta(k_3)\rangle' = \frac{(2\pi)^4\mathcal{P}_\zeta^2}{k_1^2k_2^2k_3^2}S(k_1,k_2,k_3).$$

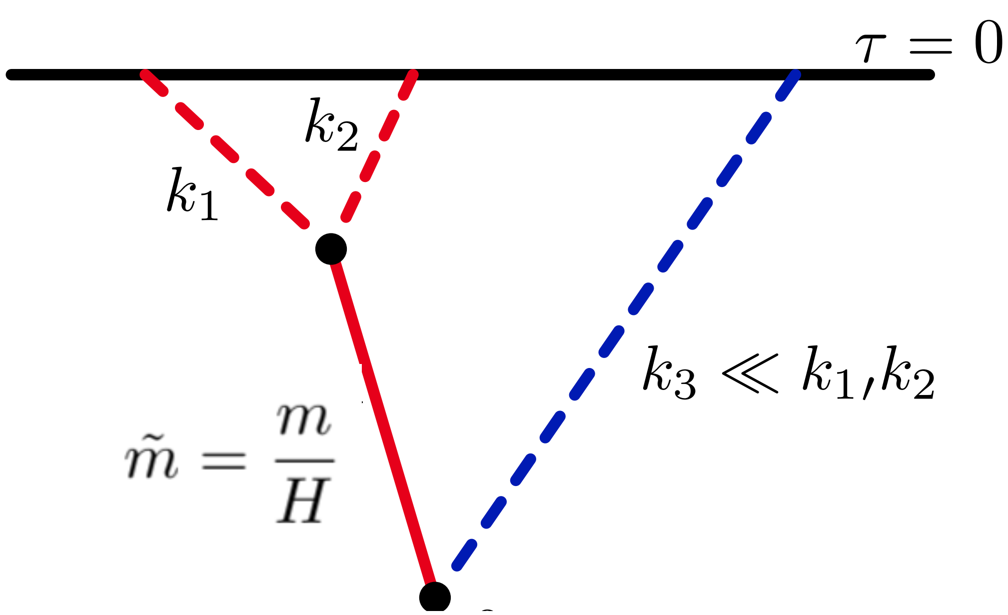


- Cosmological collider

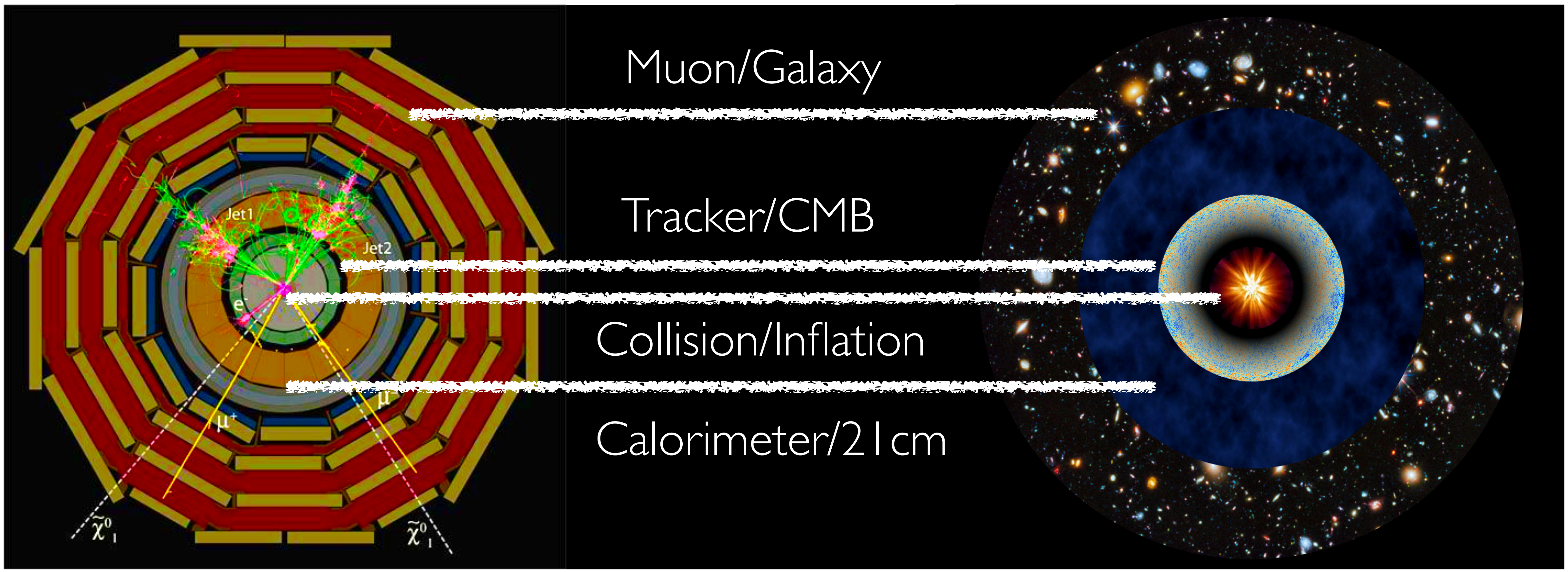
  0911.3380, 1503.08043

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

$$S \propto f_{\rm NL}^{\rm (clock)}\left(\frac{k_3}{k_1}\right)^{2i\tilde{m}}$$



Cosmological collider (Brief)



CMS detector

(Credit: Zhong-Zhi Xianyu)

Using SM Fermions

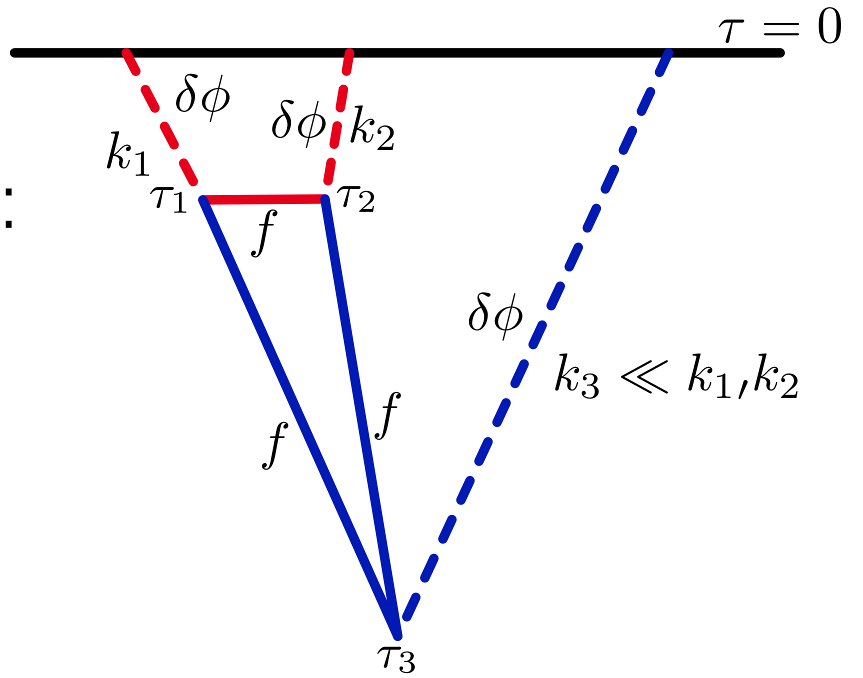
- Why fermions?
  - SM fermion masses scan many order of magnitude
  - Fermions have no hierarchy problem
  - *Fermions enhance EW symmetry breaking*

*Anson Hook, **JH**, Davide Racco, arXiv:1908.00019*

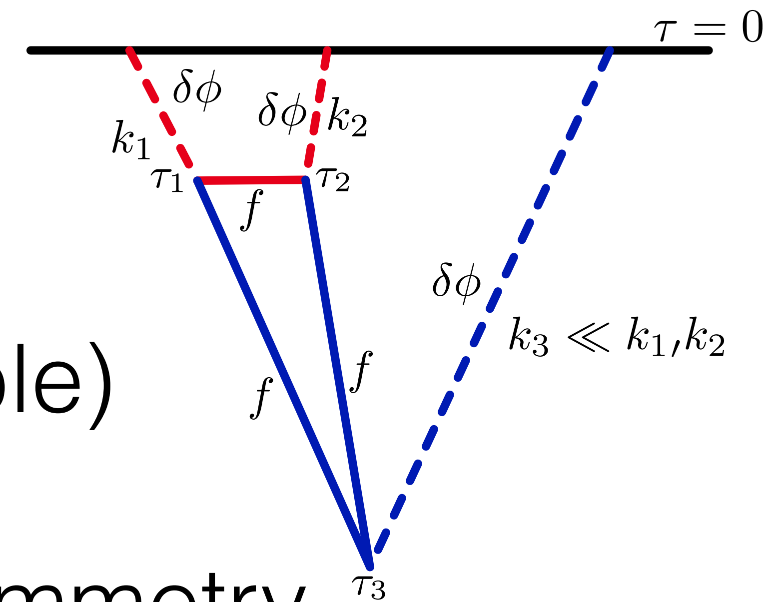
- How to use SM fermions?
  - Couple them to inflaton (shift symmetric):

$$-\frac{c_{f_i}}{\Lambda_f}\partial_\mu\phi\,\overline{f_i}\gamma^\mu\gamma^5 f_i$$

1805.02656



A fermion story



- Fermion dispersion relation (small Hubble)
  - Rolling inflaton ($\dot{\phi}$) breaks Lorentz Symmetry

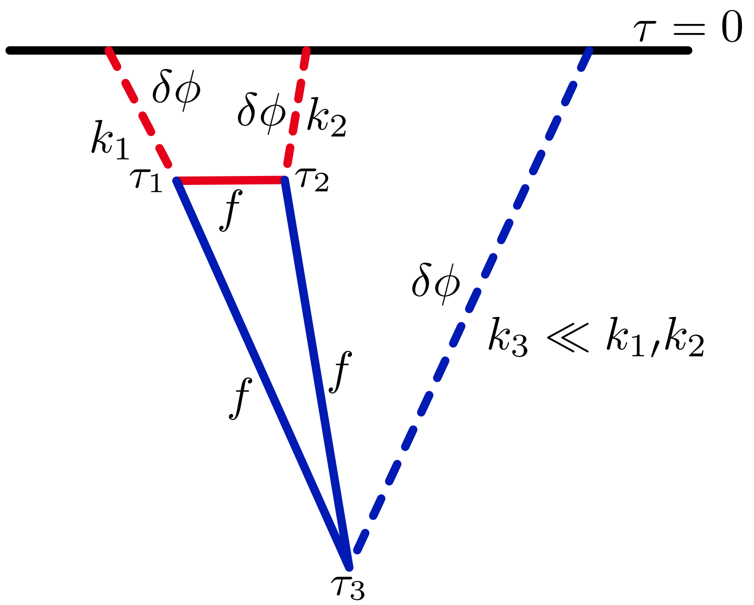
$$-\frac{c_{f_i}}{\Lambda_f}\partial_\mu\phi\,\overline{f_i}\gamma^\mu\gamma^5 f_i \longrightarrow \omega^2 = (|k| \mp \lambda)^2 + m^2 \qquad \lambda = \frac{\dot{\phi}}{\Lambda_f}$$

- Fermion production ($H \ll m \ll \lambda$)
  - Fermion mode: $\left(\omega \sim m, k \sim \pm\lambda\right)$
  - Production rate:
  - Effective density:

$$\left(k_3 \sim \omega(\tau_3) \sim m\right)$$

- Fermion redshift
- Fermion annihilation

A fermion story



- Fermion dispersion relation

$$\omega^2 = (|k| \mp \lambda)^2 + m^2$$

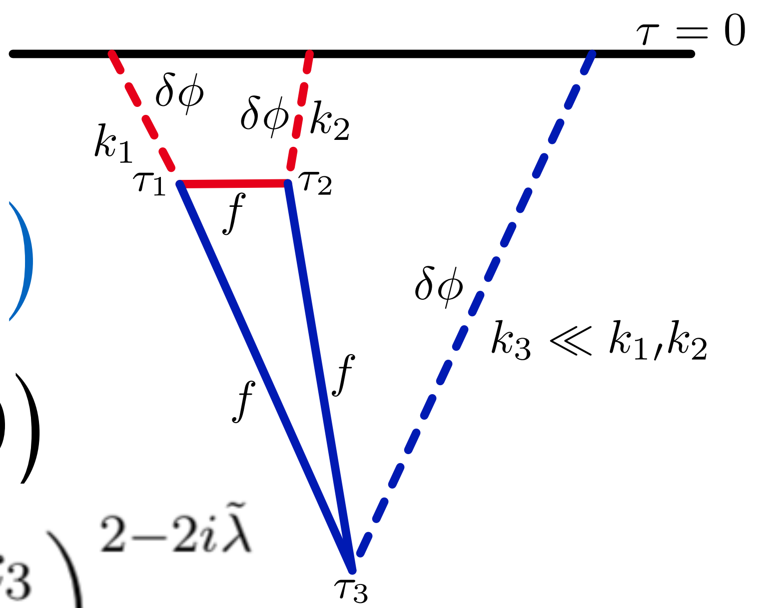
- Fermion production ($H \ll m \ll \lambda$)
  - Fermion mode: $\left(\omega \sim m, k \sim \pm\lambda\right)$
  - Production rate: $\Gamma \propto e^{-\frac{\omega^2}{\dot{\omega}}} \sim e^{-\frac{m^2}{\lambda H}}\Big|_{\sqrt{\lambda H} \ll m \ll \lambda}$
  - Effective density: $n \sim k^2 \delta k \sim m\lambda^2\Big|_{m \ll H}$

Non-adiabatic particle production

- Fermion redshift
- Fermion annihilation

A fermion story

- Fermion dispersion relation: $\omega^2 = (|k| \mp \lambda)^2 + m^2$
- Fermion production
- Fermion redshift: $\left(k_3 \sim \omega(\tau_3) \sim m\right)$
  - From $\left(\omega \sim m, k \sim \lambda\right)$ to $\left(\omega \sim \lambda, k \sim 0\right)$
  - $\omega \sim \lambda$ sets oscillation frequency $\left(\frac{k_3}{k_1}\right)^{2-2i\tilde{\lambda}}$



- Fermion annihilation
  - Fermions $\left(\omega \sim \lambda, k \sim 0\right)$ can only pair annihilate

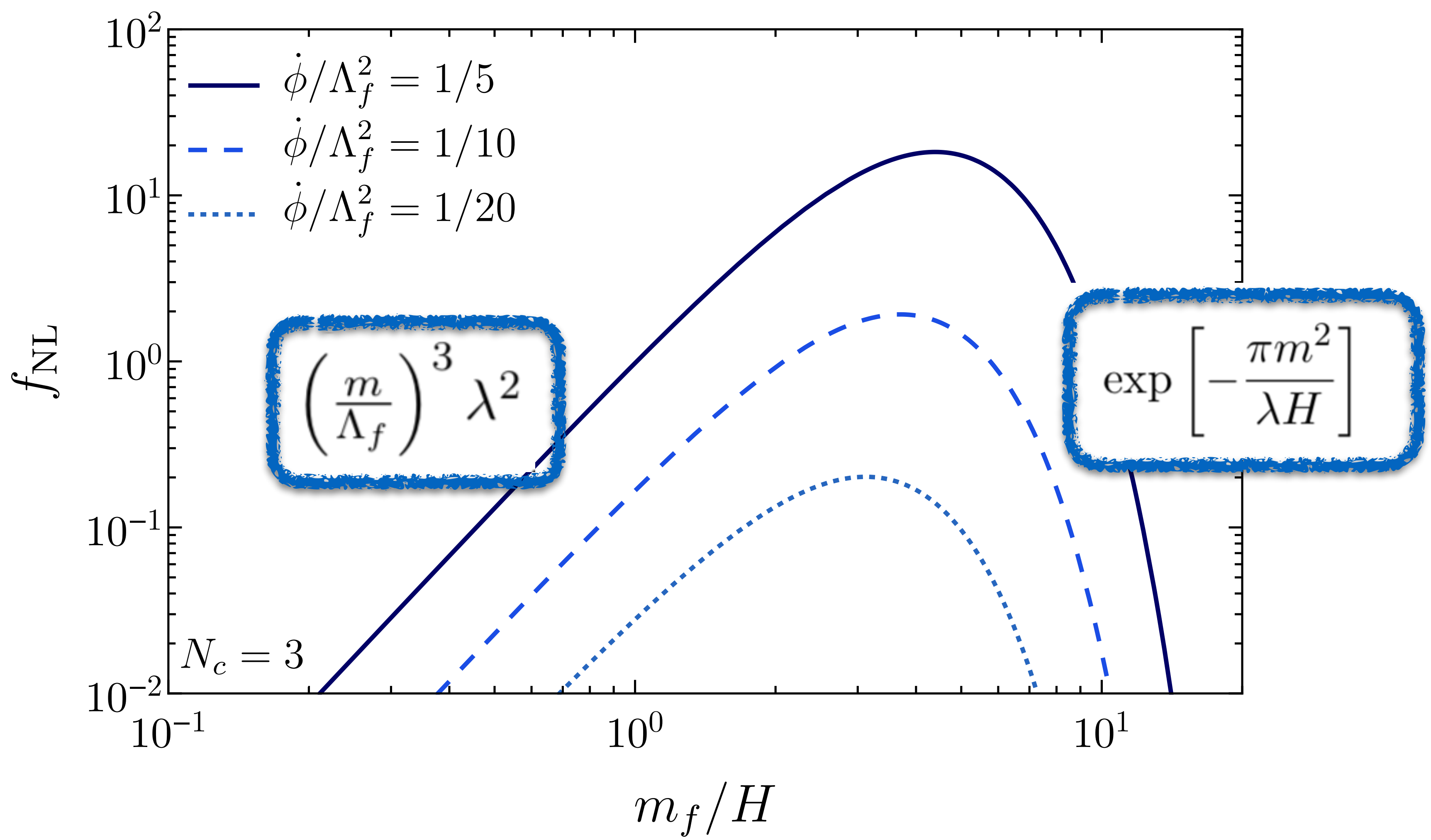
$$\left(k_2 \sim k_1 \sim \omega(\tau_1) \sim \lambda\right)$$

$$\frac{k_3}{k_1} \sim \frac{m}{\lambda}$$

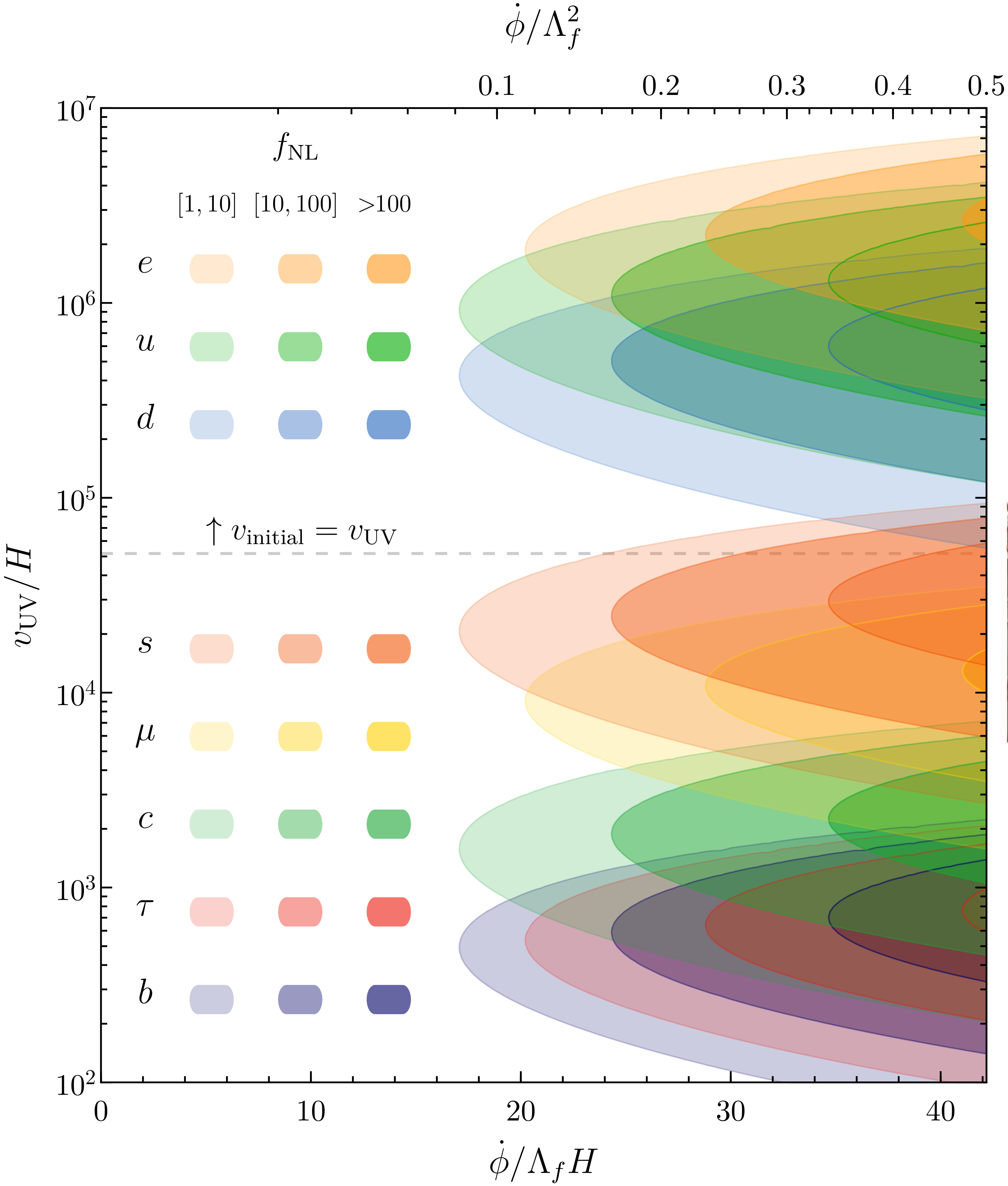
Results
&
implications

Signal strength

- Signal from a fermion loop: $\mu = \sqrt{\lambda^2 + m^2} \sim \lambda \gg m$
  - Shape: $S(k_1, k_2, k_3) \overset{\substack{\lambda \gg m \\ k_3 \ll k_1 \sim k_2}}{\simeq} f_{\rm NL}^{\rm (clock)} \left(\frac{k_3}{k_1}\right)^{2-2i\tilde{\mu}} + \cdots$
  - Amplitude: $f_{\rm NL}^{\rm (clock)} \approx \frac{N_c}{6\pi} \mathcal{P}_\zeta^{-1/2} \left(\frac{m}{\Lambda_f}\right)^3 \widetilde{\lambda}^2 \frac{e^{\pi \widetilde{\lambda}} \widetilde{\mu} \Gamma(-i\widetilde{\mu})^2 \Gamma(2i\widetilde{\mu})^3}{2\pi \Gamma(i(\widetilde{\lambda} + \widetilde{\mu}))^3 \Gamma(i(\widetilde{\mu} - \widetilde{\lambda}) + 1)}$



Signal strength

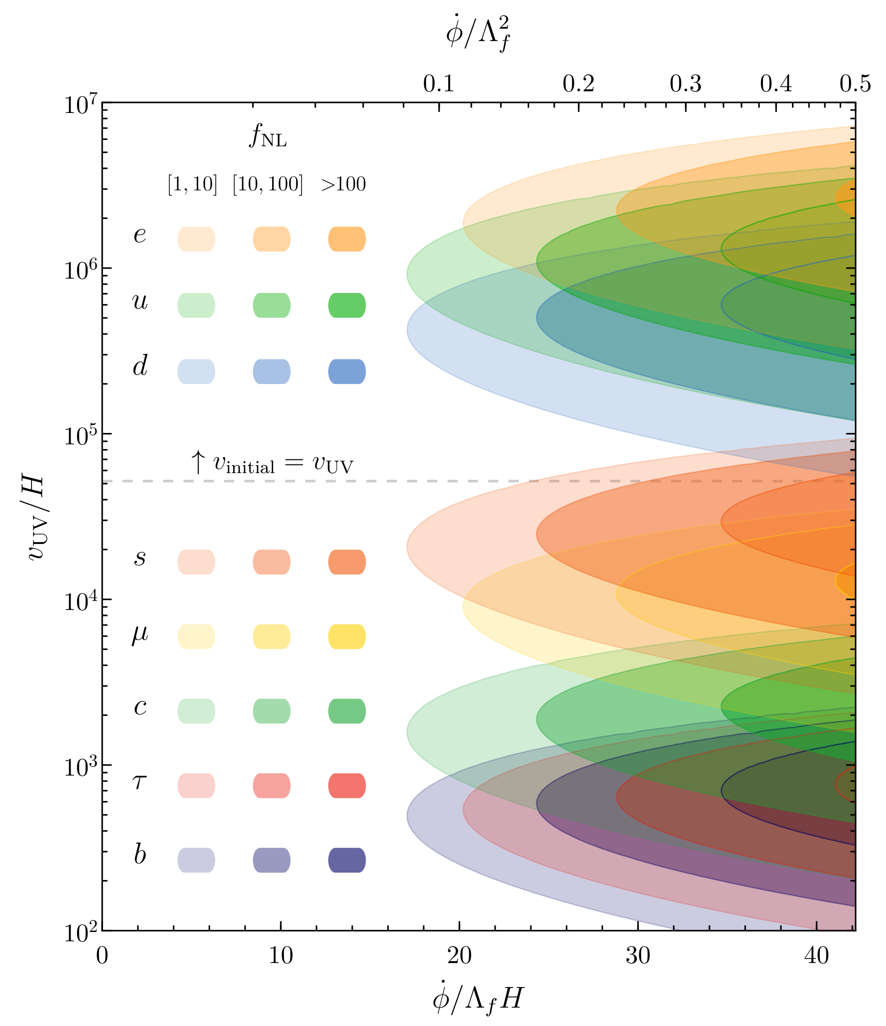


Take home:

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 -> Mass (m/H) & Coupling (λ/H)
  - Two/multiple fermions:
    - Ratio of fermion masses: $\frac{\widetilde{m}_i}{\widetilde{m}_j} = \frac{y_i}{y_j}$



- Implications:
  - A new minimum!
  - New probe of GUT, string theories…
  - No two Higgs doublet, no new coloured states…

Implications

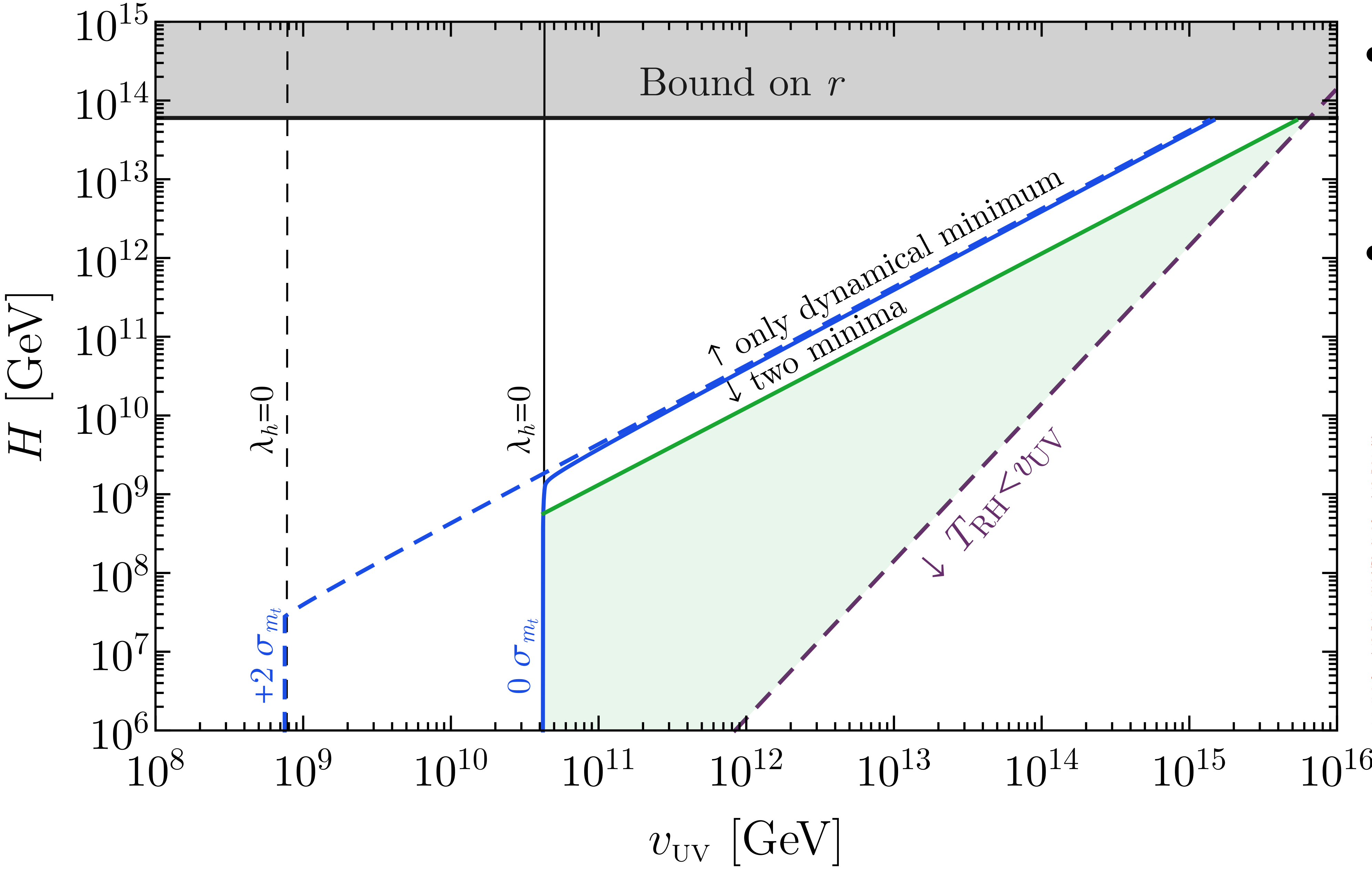
- How to distinguish the signal:
  - Amplitude (f_{NL}) and frequency -> Mass (m/H) & Coupling (λ/H)
  - Two/multiple fermions:
    - Ratio of fermion masses: $\frac{\widetilde{m}_i}{\widetilde{m}_j} = \frac{y_i}{y_j}$
- Implications:
  - A new minimum!
  - UV: New probe of GUT, string theories…
  -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

We can look for the landscape, directly!

Low(er) risk
&
low(er) reward

*Anson Hook, **JH**, Davide Racco*
arXiv:1908.00019

Parameter space II



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

How does the SM fermion density affect Higgs potential?

Dynamical Higgs minimum

- Fermions produced (effective density):

$$n \sim k^2 \delta k \sim m\lambda^2\Big|_{m \ll H} \xrightarrow{?} m_f n_f \sim y_f^2 \lambda_f^2 h^2 \gg H^2 h^2$$

Top quark density affect Higgs potential!

- Fermions impact the Higgs potential

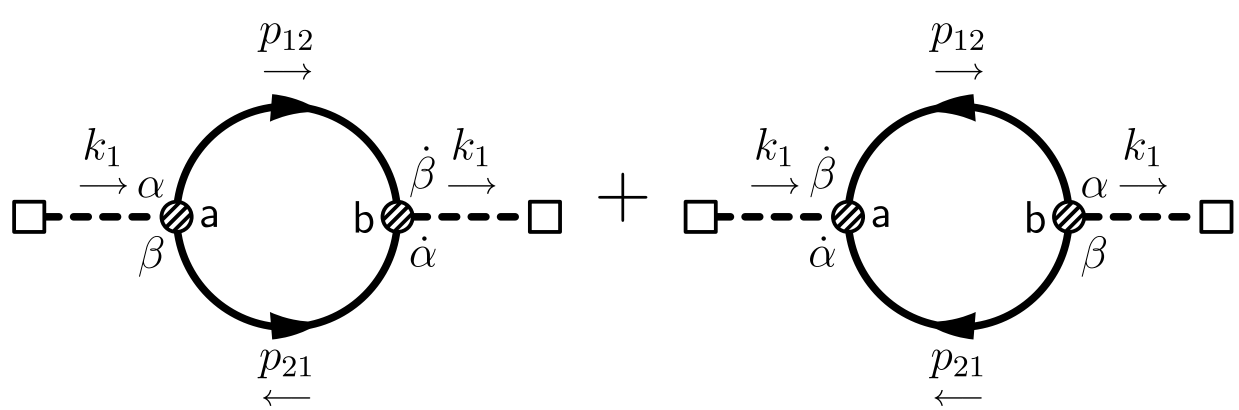
- Correction to mass (small mass limit):

Dynamical Higgs minimum

- Fermions produced (effective density):

$$n \sim k^2 \delta k \sim m\lambda^2\Big|_{m \ll H} \xrightarrow{?} m_f n_f \sim y_f^2 \lambda_f^2 h^2 \gg H^2 h^2$$

- Fermions impact the Higgs potential



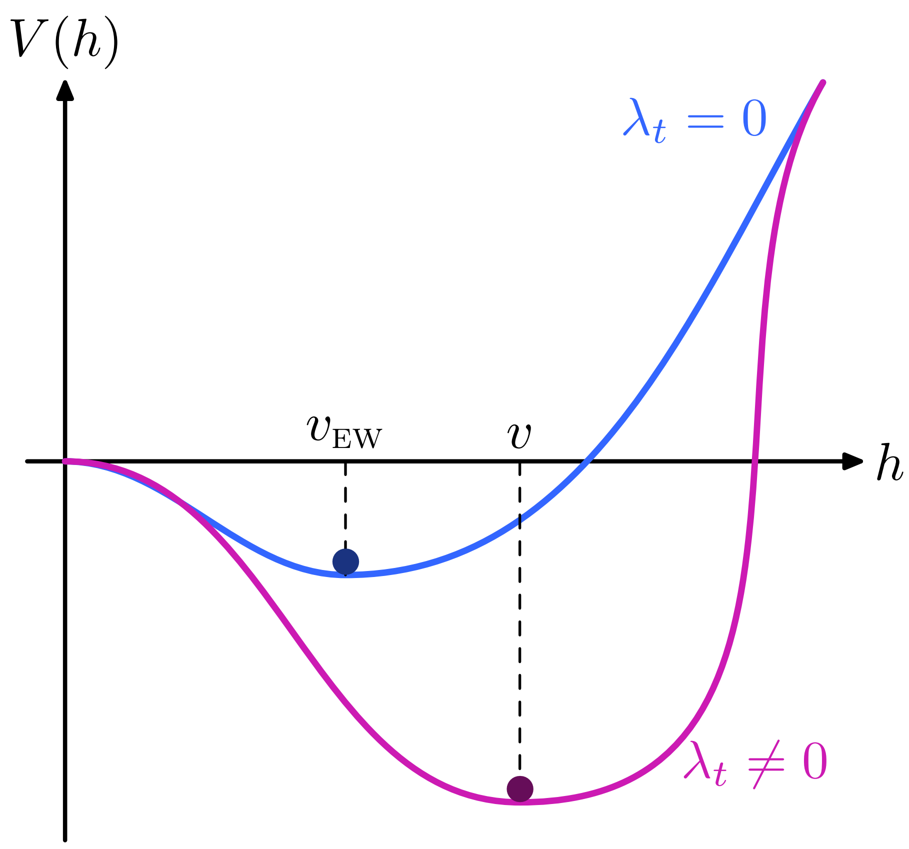
- Correction to mass (small mass limit):

$$\delta V_h = -\frac{y_f^2}{2\pi^2}\lambda_f^2 h^2$$

Especially the top quark

Dynamical Higgs minimum

- Dynamical equilibrium:



1. Fermion production
2. Higgs roll to the minimum
3. Fermions become heavy
4. Particle production shuts off

$$\Gamma \propto e^{-\frac{\omega^2}{\dot{\omega}}} \sim e^{-\frac{m^2}{\lambda H}}\Big|_{1 \ll m^2/\lambda H \ll \lambda/H}$$

- 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

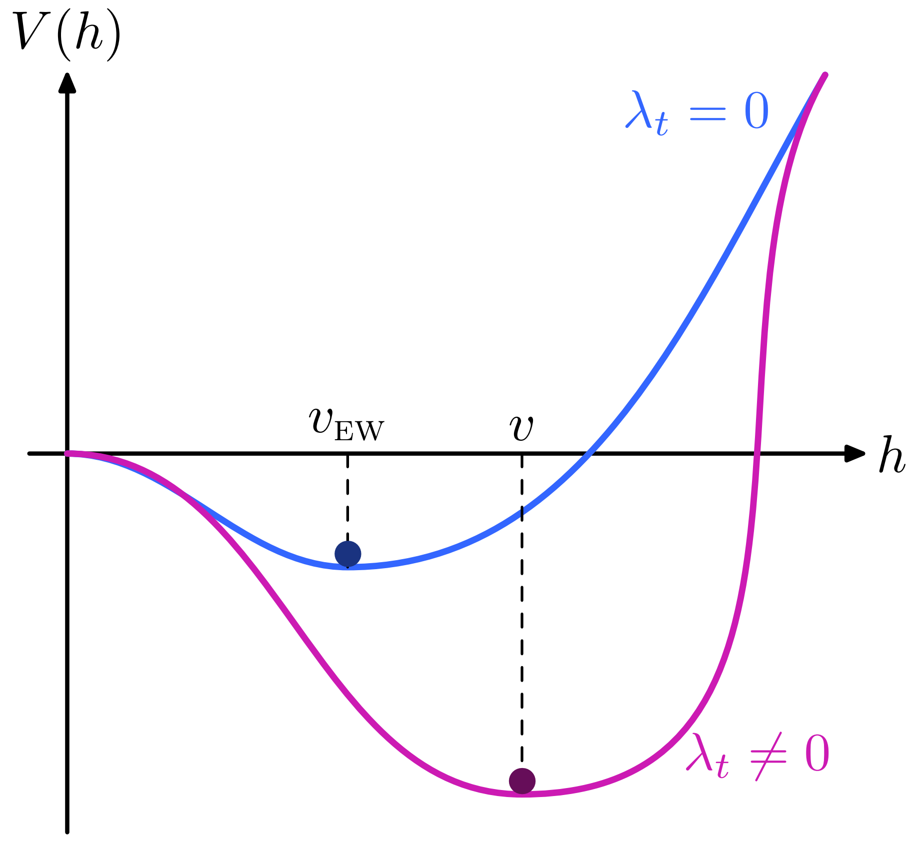
- The resulting Higgs potential:

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

- The dynamical Higgs minimum:

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

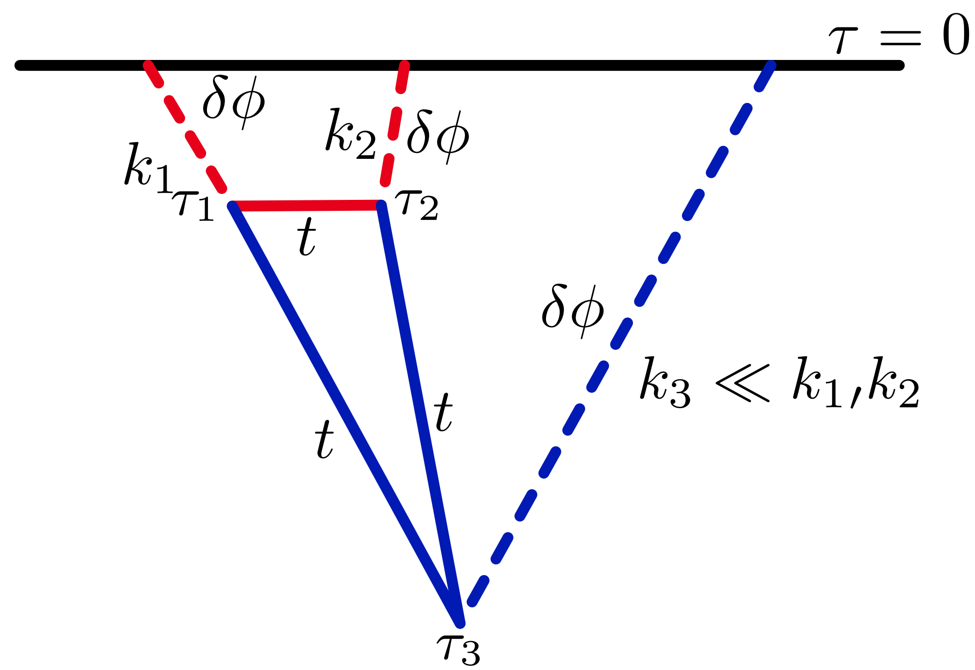
$$\frac{m_t}{H} = \left(\frac{\lambda_t}{\pi H}\right)^{1/2}$$



One parameter signal

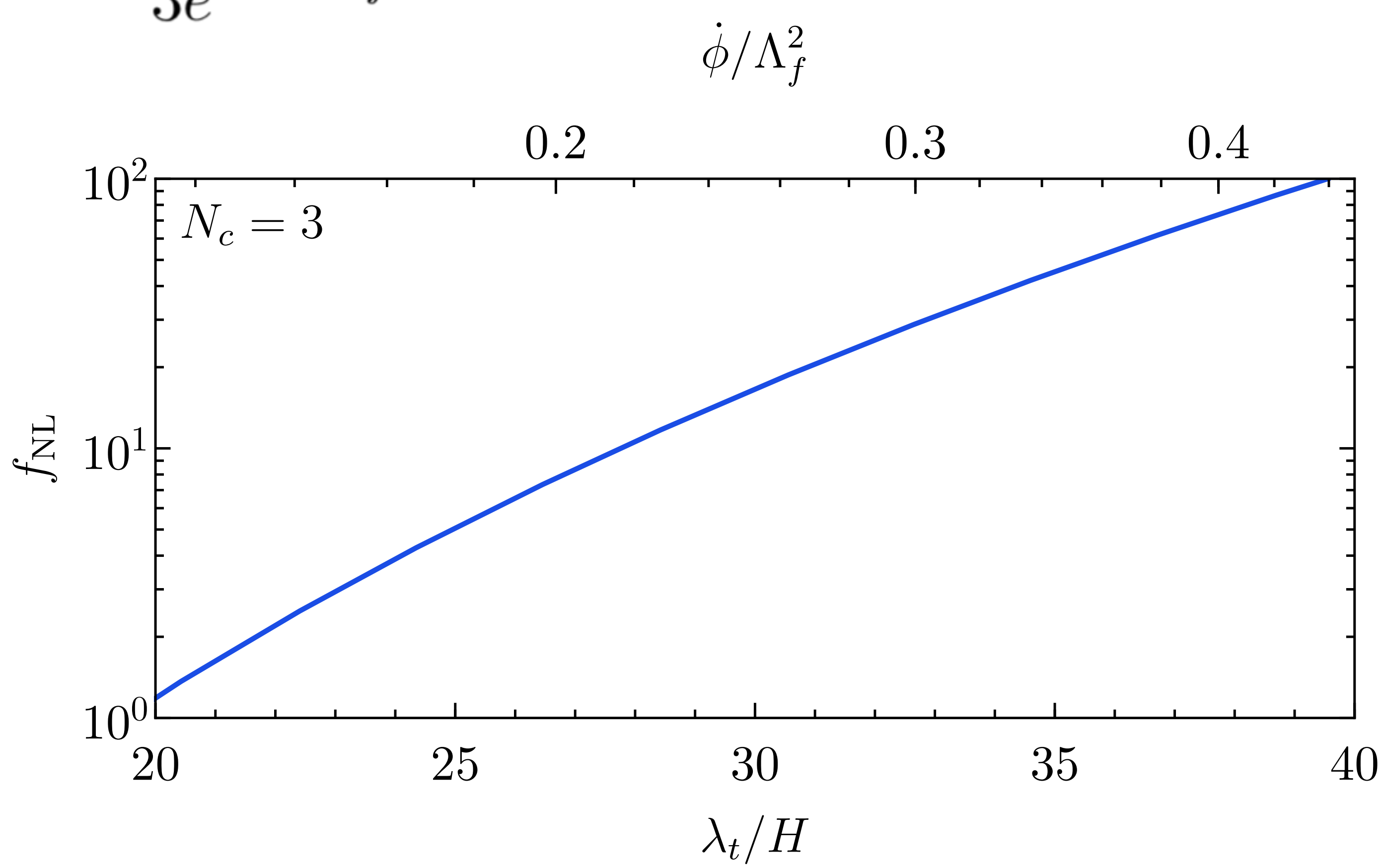
- The signal shape:

$$S(k_1,k_2,k_3) \overset{k_3\ll k_1\sim k_2}{\simeq} f_{\rm NL}^{\rm (clock)} \left(\frac{k_3}{k_1}\right)^{2-2i\widetilde{\lambda}_f}$$

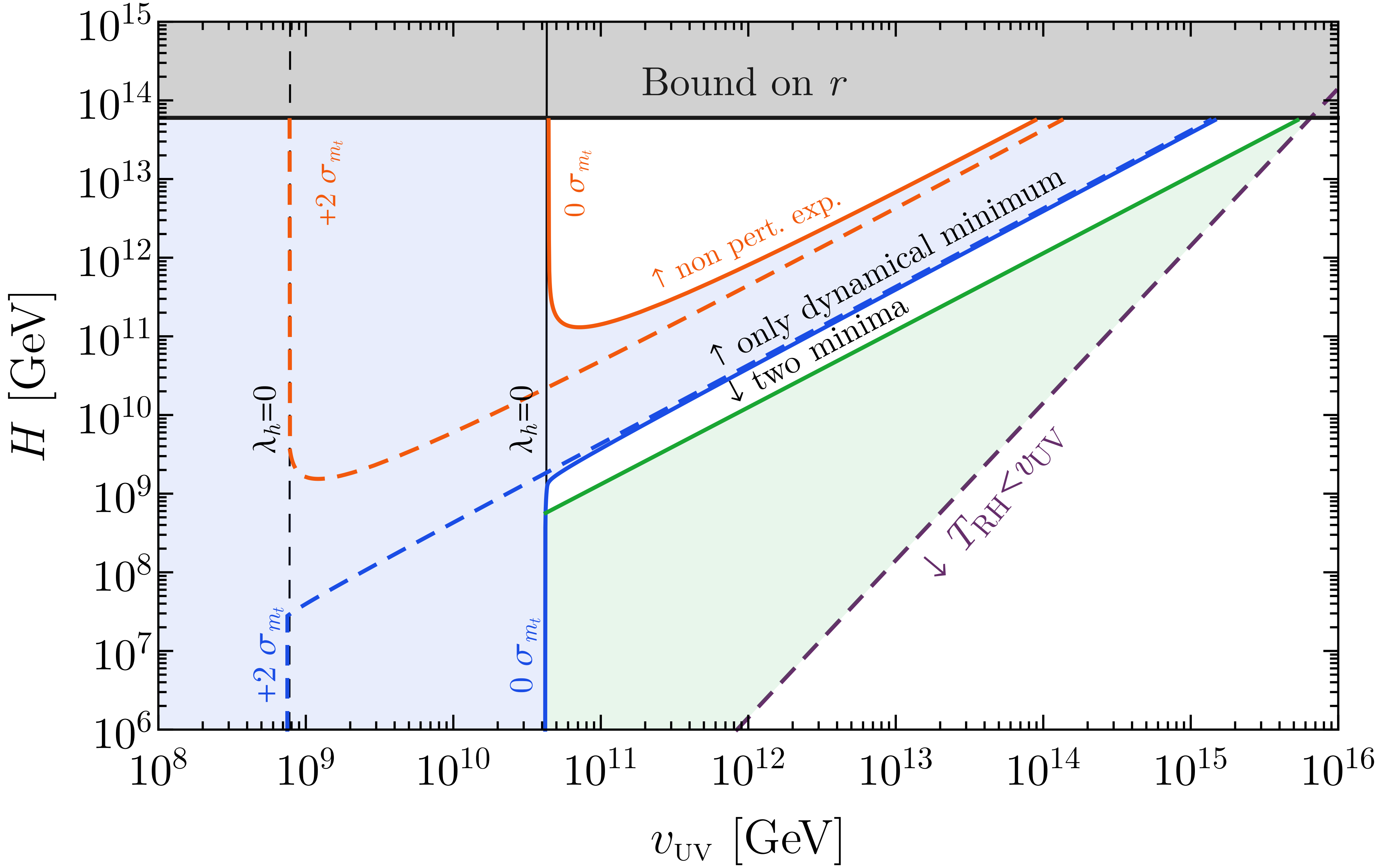


- The signal amplitude:

$$f_{\rm NL}^{\rm (clock)} \approx \frac{4\sqrt{2}N_c\mathcal{P}_\zeta}{3e}\tilde{\lambda}_f^{13/2}$$



One parameter signal



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

Conclusion

- Higgs can be in a distinct minimum during inflation
- Cosmological collider physics offers a way to tell
- The minimum can be a physical one, and we can measure signals from light SM quarks
- The minimum can be generated dynamically, and the top quark can be looked for

Does one new minimum hint multiverse? Would a few of them convince you?