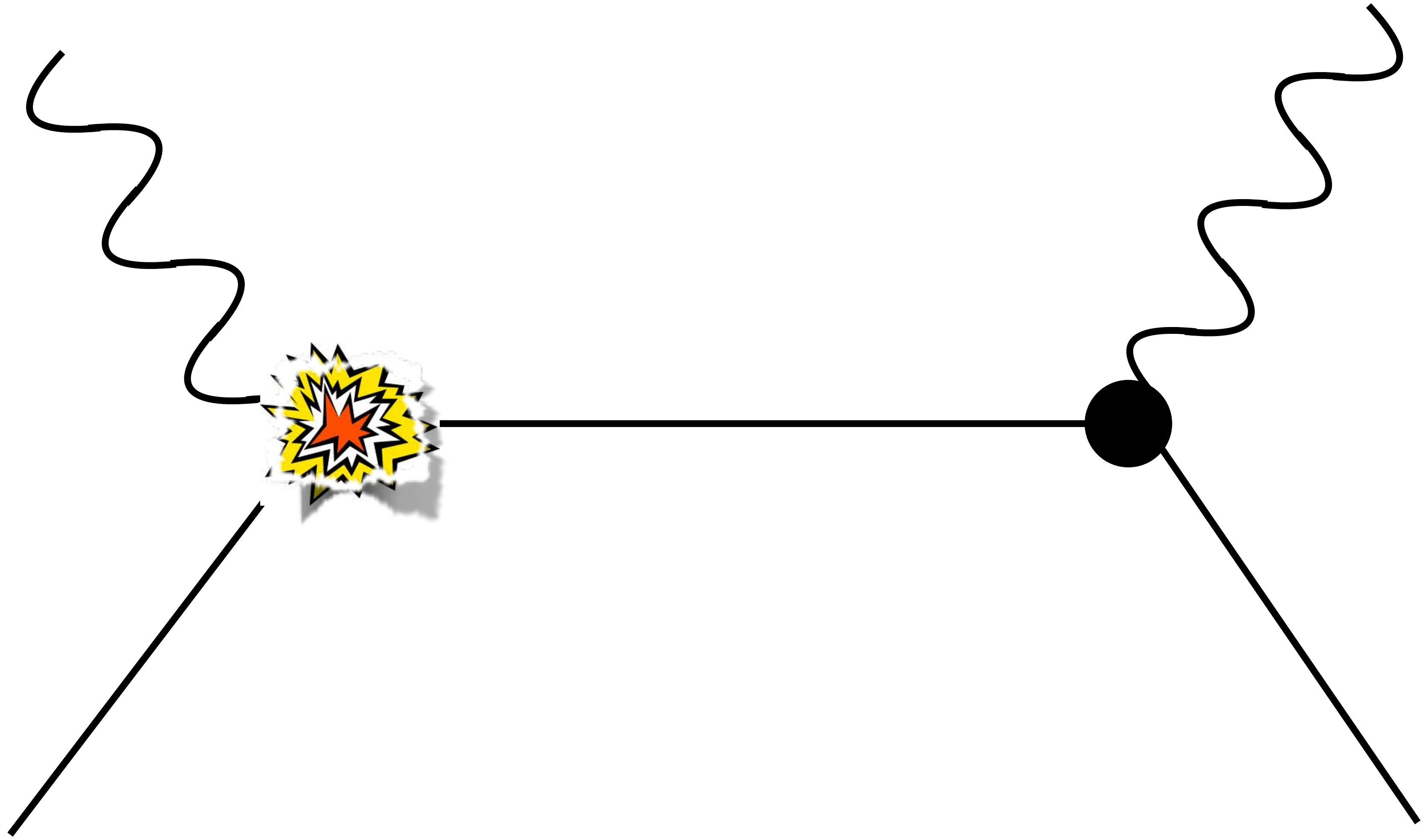
Minimal signatures of the SM at the cosmological collider

Anson Hook
University of Maryland

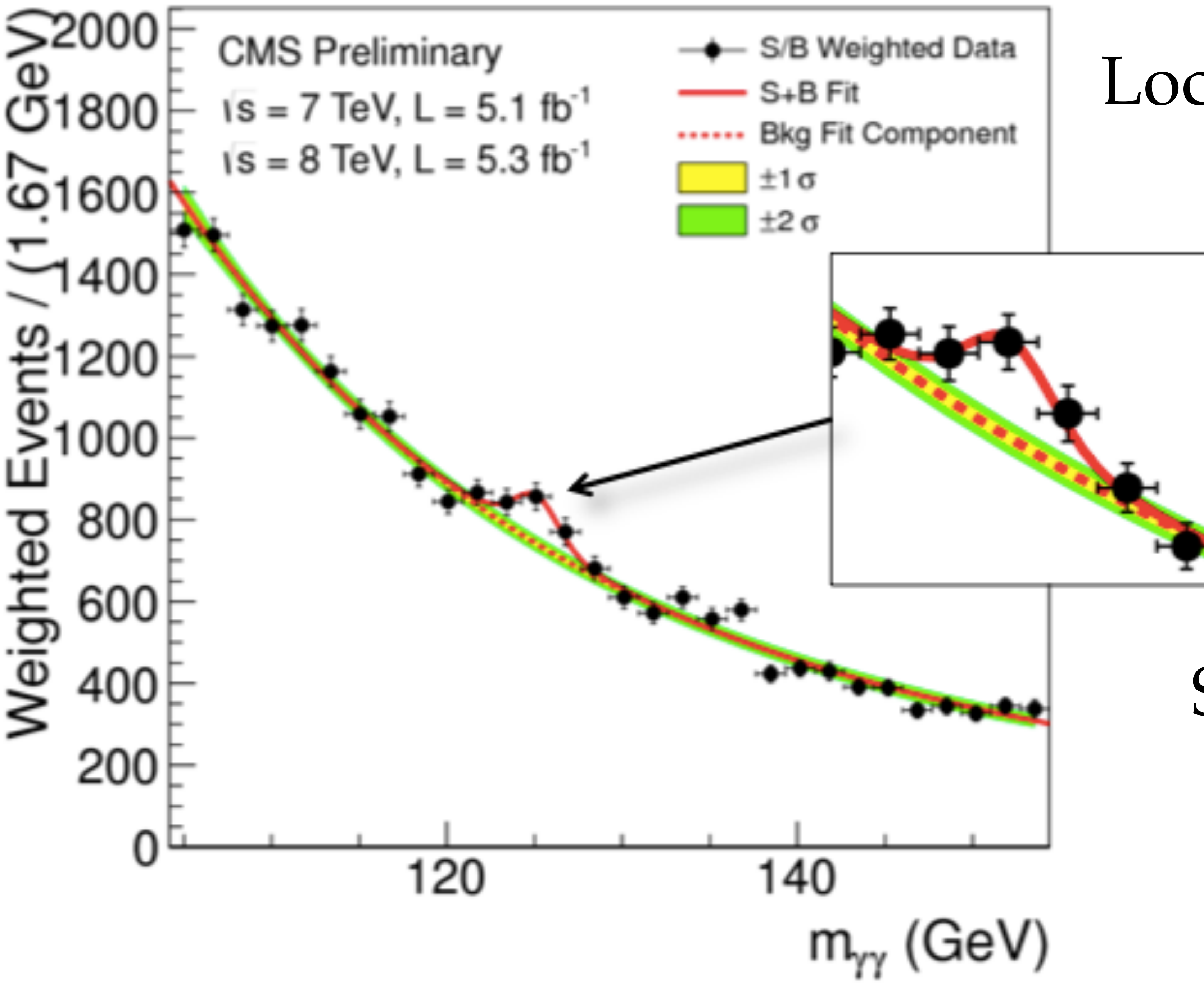
hep-ph/1908.00019 + 1907.10624 : AH/ J. Huang/ D. Racco

Regular Colliders

Colliders produce particles and then we observe the decay products



Regular Colliders

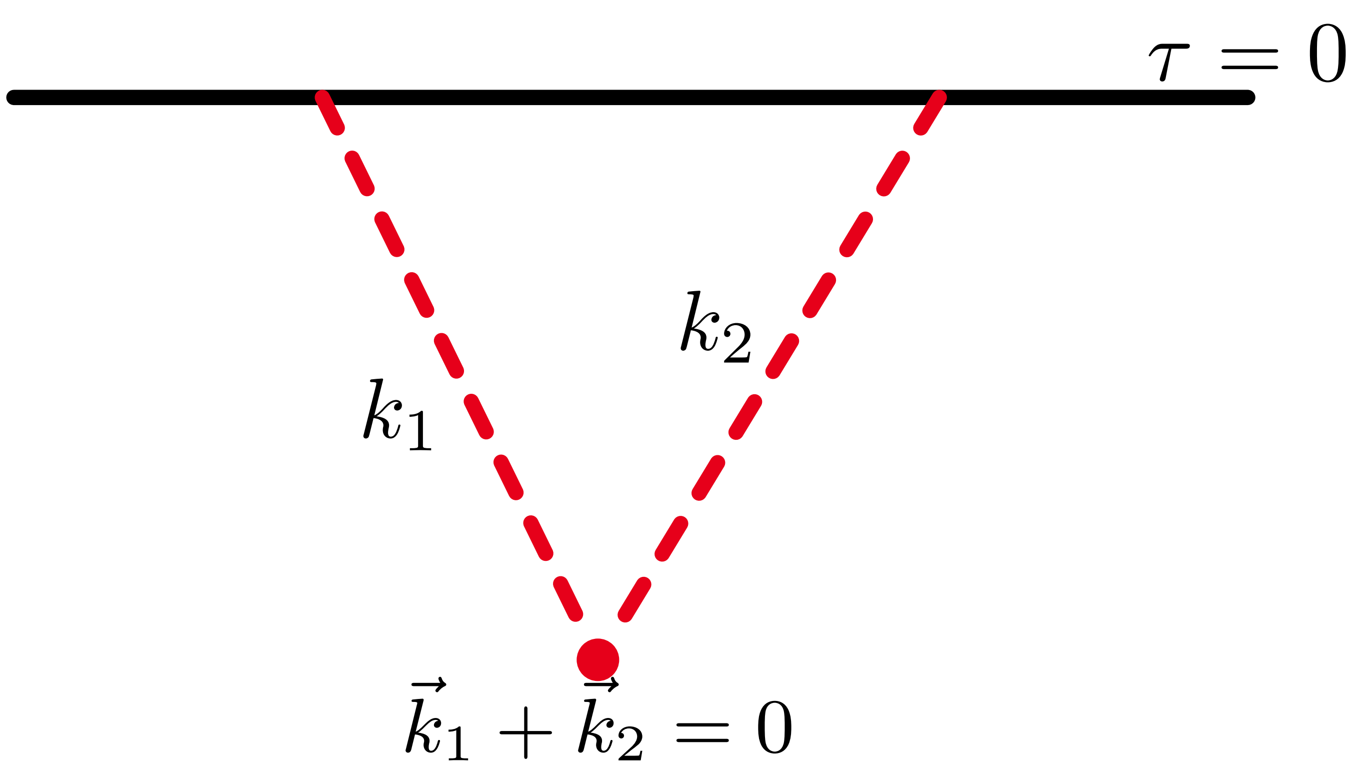


Location of bump gives mass of particle

Size of bump gives coupling constant

Cosmological Colliders

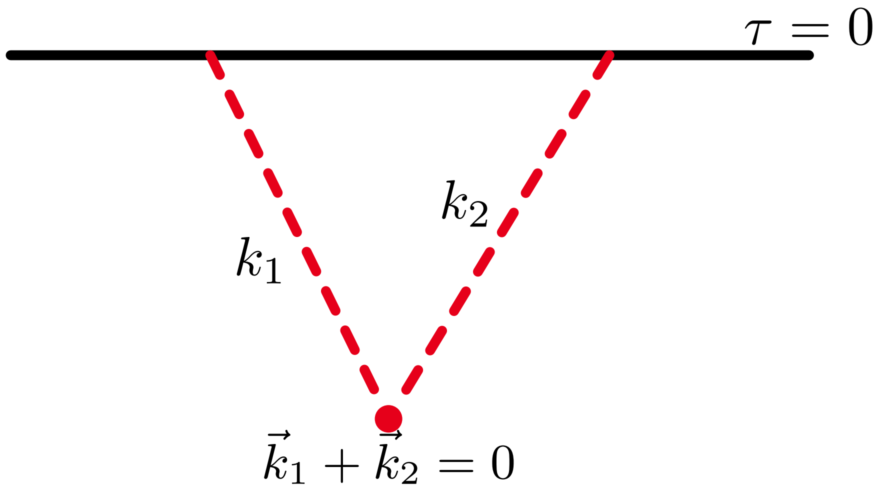
Cosmological Collider produce particles and then we observe the decay products



Cosmological Colliders

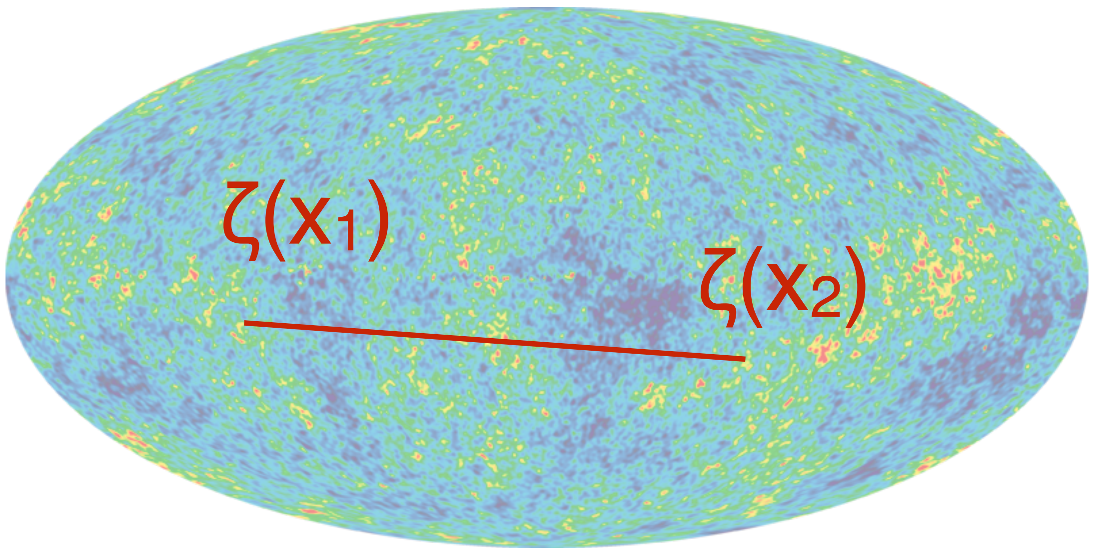
- Power spectrum :

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



- Density correlation function:

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



Cosmological Colliders

Just like at regular colliders
What if there is a new particle?

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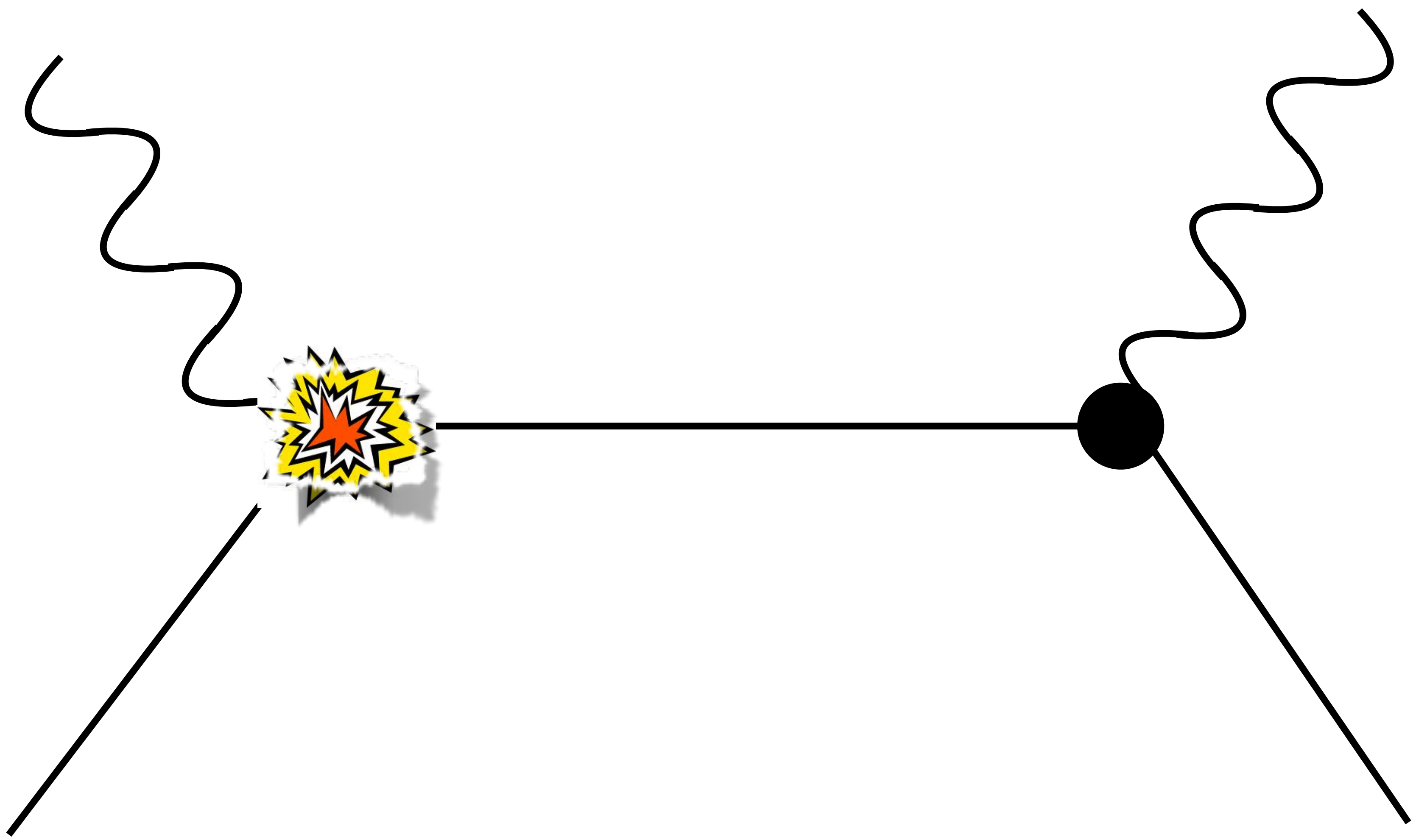
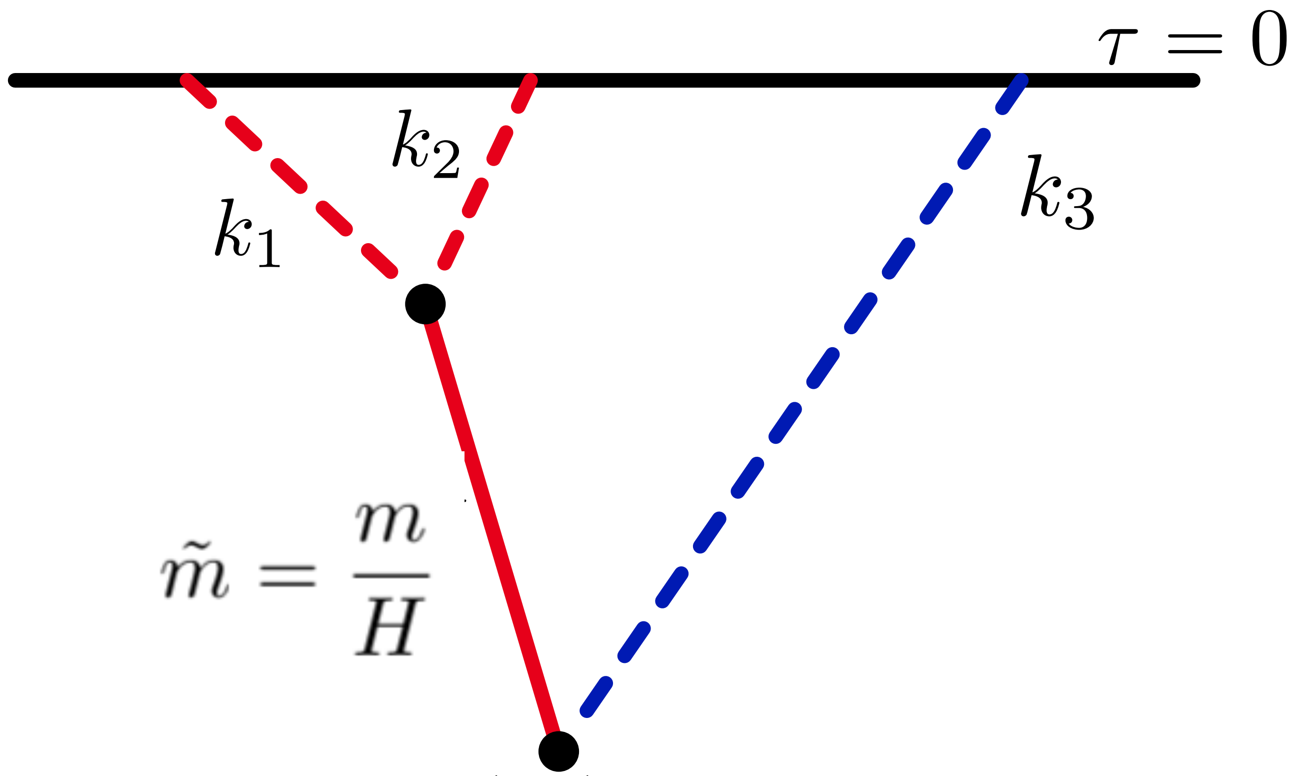
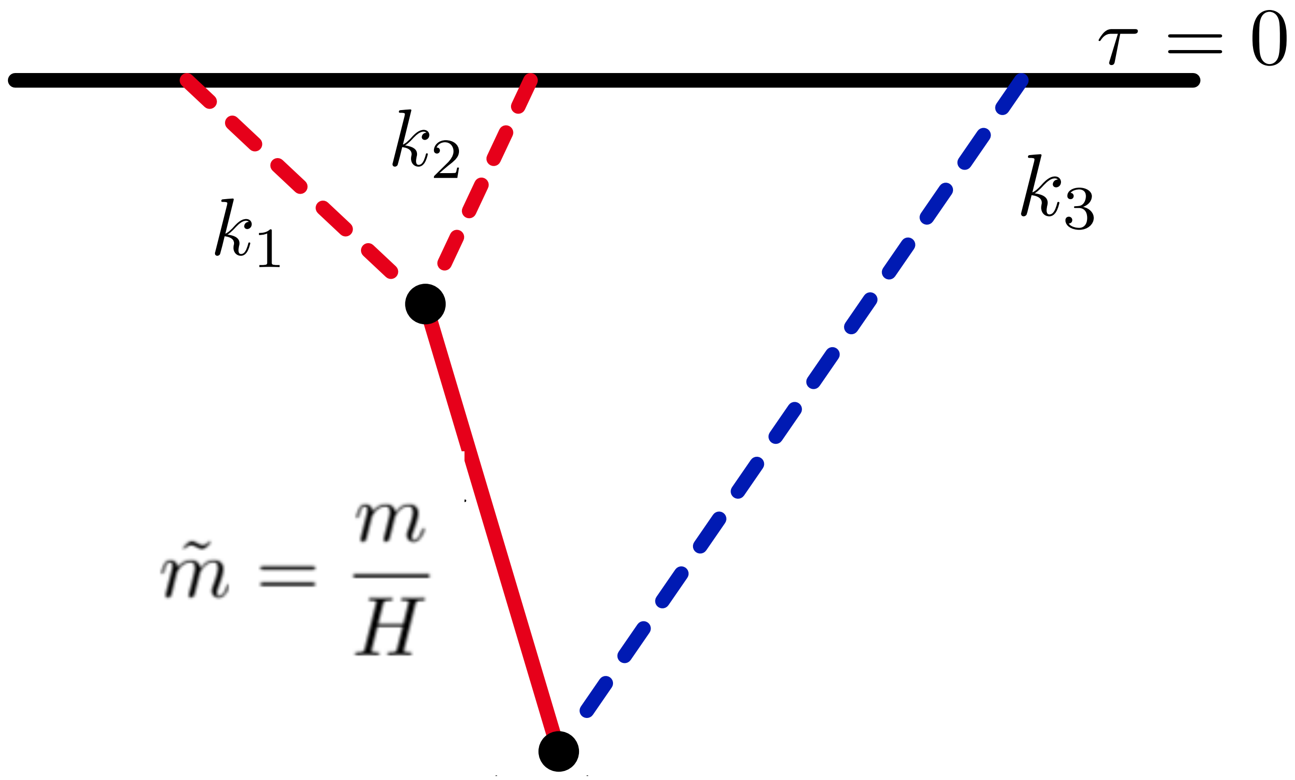


Cosmological Colliders : Mass



How do we get the mass?

Cosmological Colliders : Mass

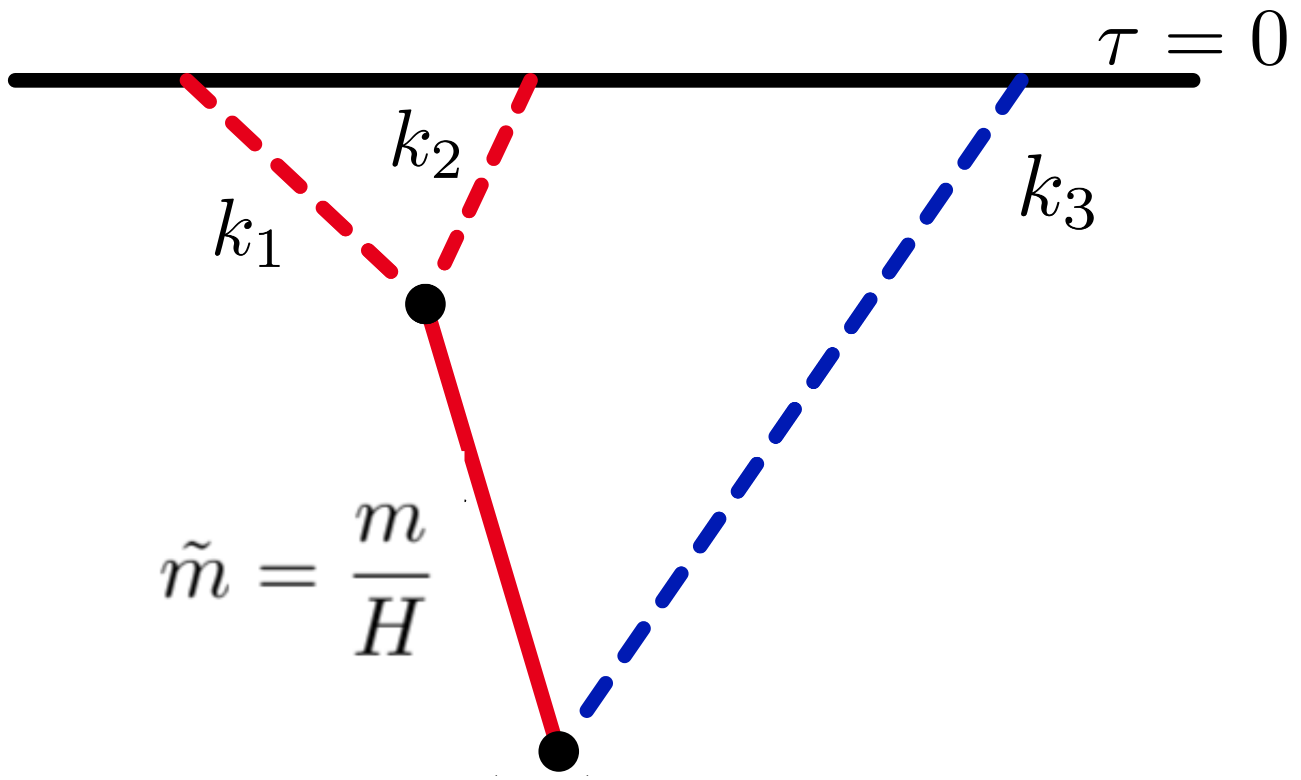


How do we get the mass?

$$e^{imt} \sim \tau^{im}$$

Measure at different values of t and see oscillation!

Cosmological Colliders : WKB



What determines the time of the events?

Cosmological Colliders : WKB

Particle production in De-Sitter Space

Non-Adiabatic production of
particles from time dependence

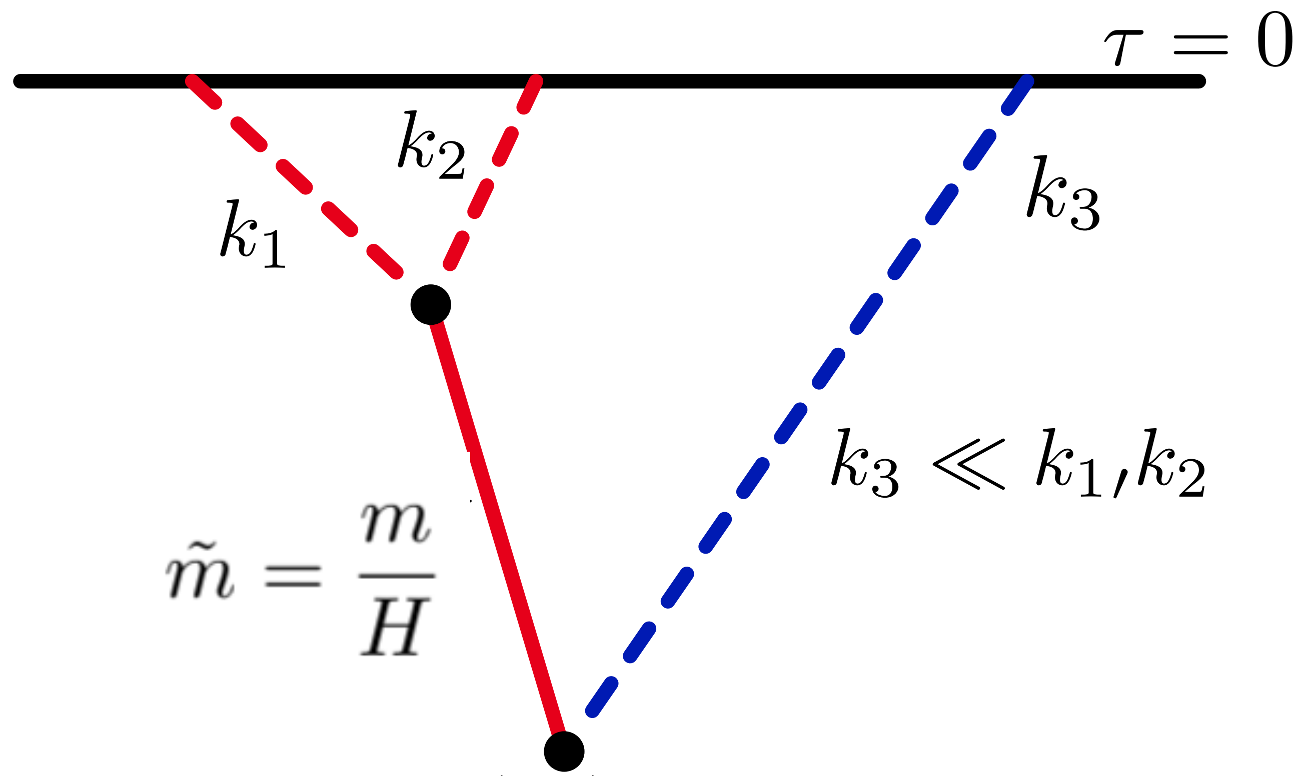
$$P \sim e^{-\omega^2/\dot{\omega}} \sim e^{-m/H}$$

Probability of creating/destroying a
particle maximized when

$$k\tau \sim 1$$

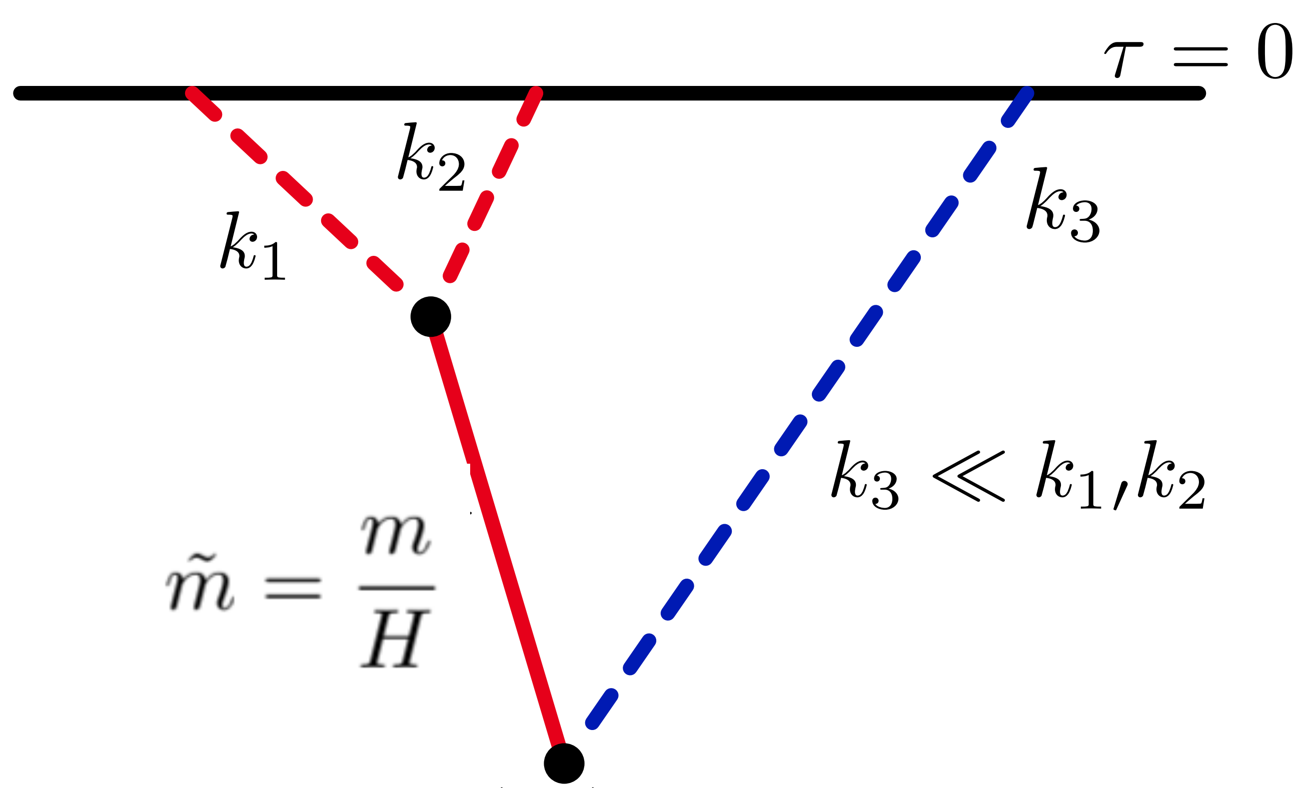
Need mass around Hubble

Cosmological Colliders : WKB



$$e^{im(t-t_0)} \sim (\frac{\tau}{\tau_0})^{im} \sim (\frac{k_3}{k_1})^{im}$$

Cosmological Colliders



Squeezed limit of non-gaussianities

Oscillations give mass of particle

Magnitude gives the coupling

Issues of the Cosmological Colliders

1. Mass and coupling can be explained by any number of theories
2. Non-Gaussianities tend to be small
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Minimally coupled SM actually does a remarkable job addressing all of these problems!

Minimal Signatures of the SM

New particle : SM particle

Mass and coupling : Determined by a single interaction

The single interaction is the most relevant operator allowed by symmetries connecting a shift symmetric inflaton to the SM

Minimal Coupling

$$\frac{c_\psi}{\Lambda_f}\partial_\mu\phi\overline{\psi}\gamma^\mu\gamma^5\psi \qquad \frac{\phi}{\Lambda_F}F\tilde{F}$$

Most relevant operators connecting a shift symmetric inflaton to the SM

Minimal Coupling

$$\frac{c_\psi}{\Lambda_f}\partial_\mu\phi\overline{\psi}\gamma^\mu\gamma^5\psi$$

$$\frac{\phi}{\Lambda_F}F\tilde{F}$$

Most relevant operators connecting a shift symmetric inflaton to the SM

Already exist tight constraints on this coupling

Minimal Coupling

$$\frac{c_\psi}{\Lambda_f}\partial_\mu\phi\overline{\psi}\gamma^\mu\gamma^5\psi$$

$$\frac{\phi}{\Lambda_F}F\tilde{F}$$

Most relevant operators connecting a shift symmetric inflaton to the SM

Focus instead on this guy

Minimal Coupling

$$\frac{c_\psi}{\Lambda}\partial_\mu\phi\overline{\psi}\gamma^\mu\gamma^5\psi = \partial_\mu\phi J^\mu$$

Inflaton has exponentially small spatial gradients but decent sized time derivatives

$$\partial_\mu\phi J^\mu \to \dot{\phi}J^0 = \mu Q$$

Leading order coupling of inflaton to SM is a chemical potential for spin

Minimal Coupling : Size

How large of a chemical potential can we have?

$$\dot{\phi} < \Lambda^2$$

Consistent EFT

$$\mu = \frac{\dot{\phi}}{\Lambda} = H \left(\frac{2\pi\dot{\phi}}{H^2} \right)^{1/2} \sqrt{\frac{\dot{\phi}}{2\pi\Lambda^2}} \lesssim 60H$$

Minimal Coupling

$$\frac{c_t}{\Lambda_t}\partial_\mu\phi\bar{t}\gamma^\mu\gamma^5 t$$

What are the effects of a chemical potential for spin?

$$\omega^2 = (|k| \pm \lambda)^2 + m^2 \qquad \lambda = \frac{\dot{\phi}}{\Lambda_t}$$

Modified Dispersion

Minimal Coupling : WKB

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

Modified Dispersion

$$P \sim e^{-\omega^2/\dot{\omega}} \sim e^{-\frac{m^2}{\lambda H}}$$

In large chemical potential limit, no exponential suppression of particle production

$$k\tau \sim \lambda$$

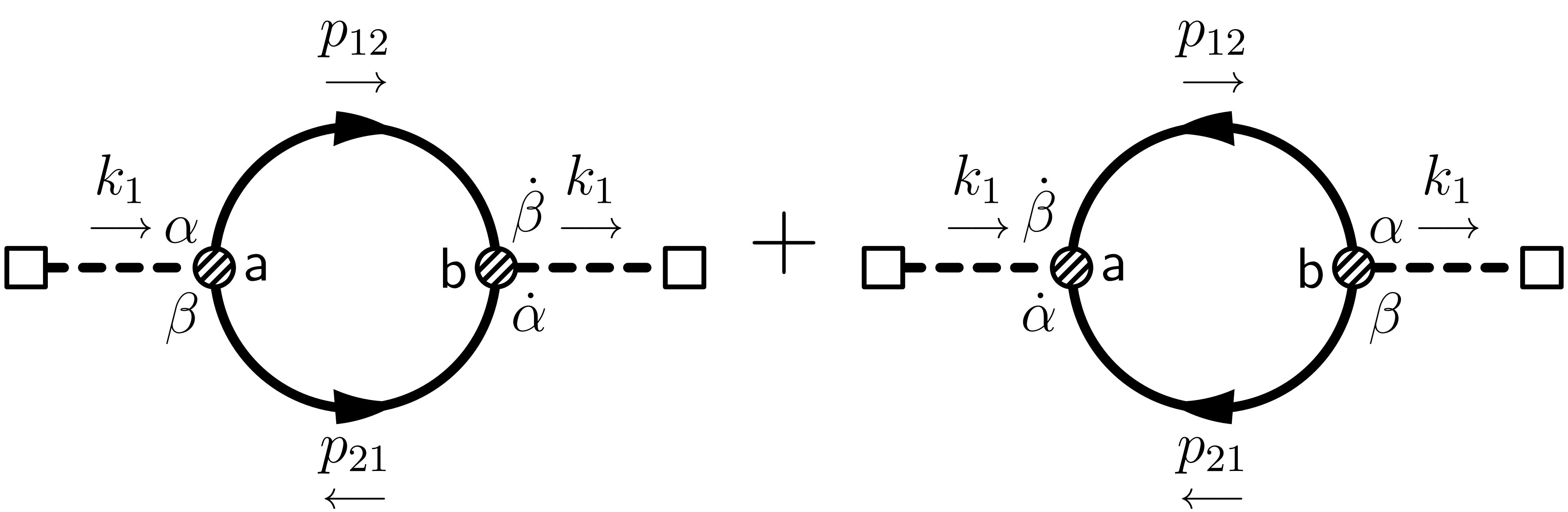
$$n \sim k^2 \delta k \sim m\lambda^2$$

Minimal Coupling : WKB

$$n \sim k^2 \delta k \sim m\lambda^2$$

Large number of top quarks effects
Higgs Potential which in turn effects
top quark mass which effects
number of top quarks

Top quark back reaction



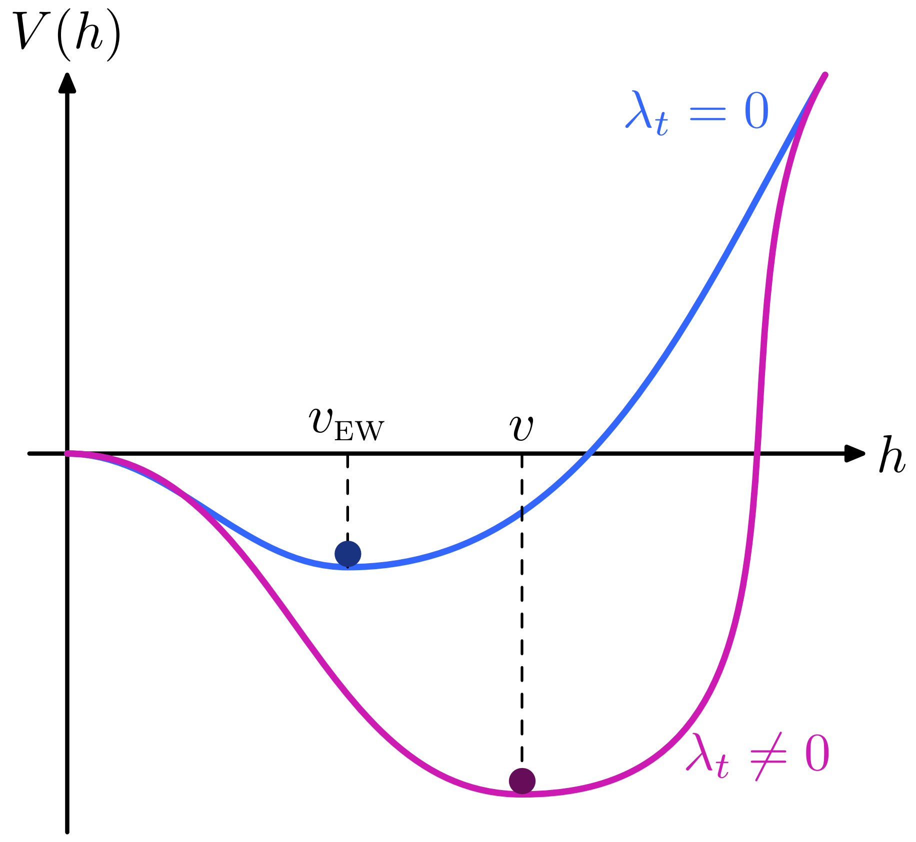
$$\delta V_{\mathbf{H}} \sim -\frac{N_c y_t^2}{\pi^2}\lambda^2|\mathbf{H}|^2 \exp\left[-\frac{\pi y_t^2|\mathbf{H}|^2}{\lambda H}\right]$$

Top quark back reaction

$$\delta V_{\mathbf{H}} = -m_h^2|\mathbf{H}|^2 + \lambda_h|\mathbf{H}|^4 - \frac{N_c y_t^2}{\pi^2}\lambda^2|\mathbf{H}|^2 \exp\left[-\frac{\pi y_t^2|\mathbf{H}|^2}{\lambda H}\right]$$

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

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

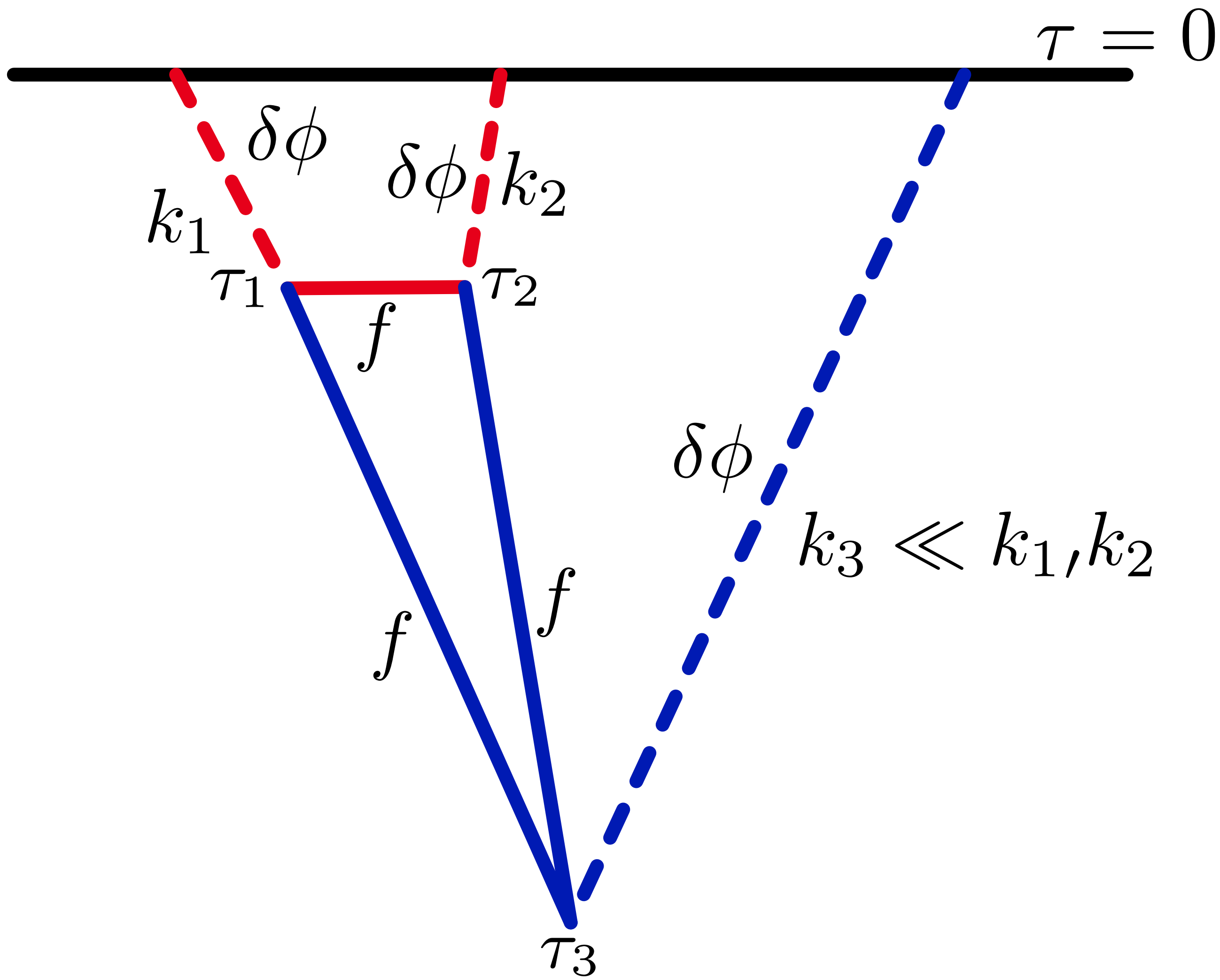


Top quark back reaction

Mass and coupling determined by a single parameter!

Non-gaussian signature

What about the signature in non-Gaussianities?



Non-gaussian signature

Mass and coupling determined by a single parameter!

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

$$S = S(k_1, k_2, k_3)^{\text{non-analytic}}\Big|_{k_3 \ll k_1 \sim k_2}$$

$$\sim \frac{m^2}{\Lambda_t^3} m \lambda^2 \left(\frac{k_3}{k_1}\right)^{2-2i\omega} e^{-\frac{m^2}{\lambda H}}$$

Non-gaussian signature

$$S = S(k_1, k_2, k_3)^{\text{non-analytic}}\Big|_{k_3 \ll k_1 \sim k_2}$$

$$\sim \frac{m^2}{\Lambda_t^3} m\lambda^2 \left(\frac{k_3}{k_1}\right)^{2-2i\omega} \quad e^{-\frac{m^2}{\lambda H}}$$

Fermion loop = number density

Non-gaussian signature

$$S = S(k_1, k_2, k_3)^{\text{non-analytic}}\Big|_{k_3 \ll k_1 \sim k_2}$$

$$\sim \frac{m^2}{\Lambda_t^3} m\lambda^2 \left(\frac{k_3}{k_1}\right)^{2-2i\omega} e^{-\frac{m^2}{\lambda H}}$$

Coupling Cubed

Non-gaussian signature

$$S = S(k_1, k_2, k_3)^{\text{non-analytic}}\Big|_{k_3 \ll k_1 \sim k_2}$$

$$\sim \frac{m^2}{\Lambda_t^3} m\lambda^2 \left(\frac{k_3}{k_1}\right)^{2-2i\omega} e^{-\frac{m^2}{\lambda H}}$$

Coupling of Inflaton is to mass due to integration by parts

Non-gaussian signature

$$S = S(k_1, k_2, k_3)^{\text{non-analytic}}\Big|_{k_3 \ll k_1 \sim k_2}$$

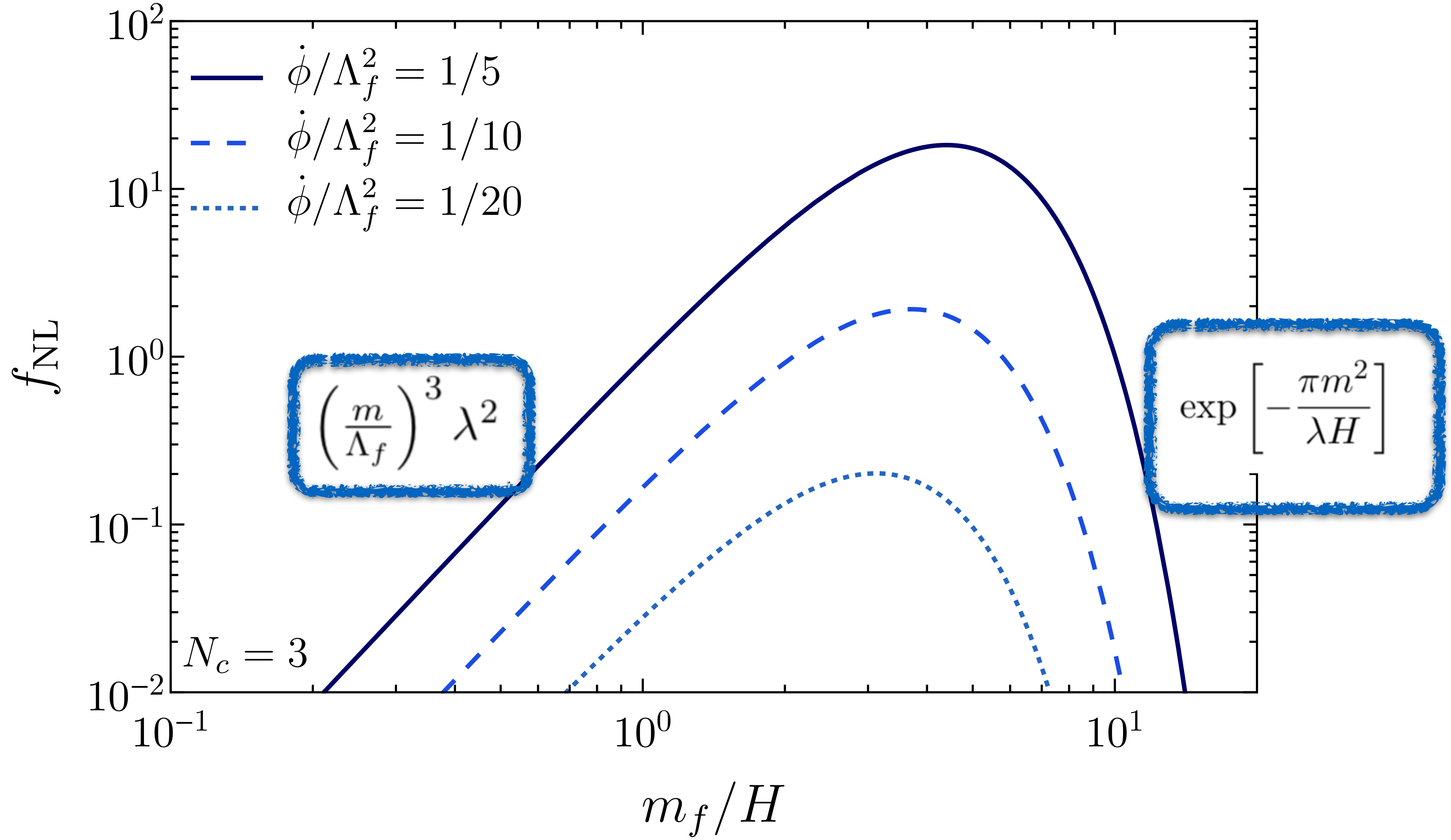
$$\sim \frac{m^2}{\Lambda_t^3} m\lambda^2 \left(\frac{k_3}{k_1}\right)^{2-2i\omega} e^{-\frac{m^2}{\lambda H}}$$

Number density dilutes away as a^3 so inflaton 3 point function has $(k_3/k_1)^3$ but definition of S removes a k_3/k_1

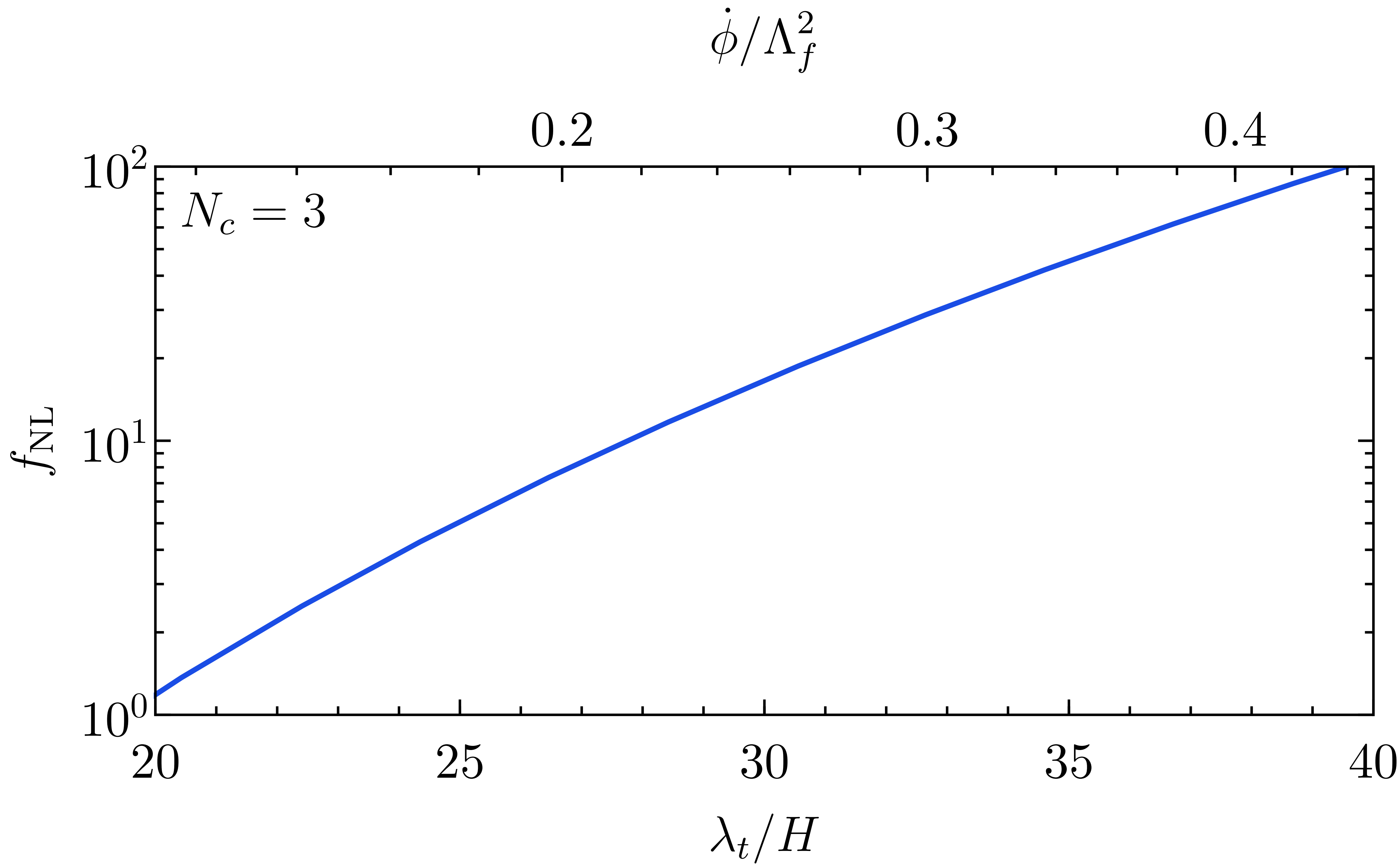
Oscillation due to e^{imt}

General Fermion @ Cosmological Collider

$$S(k_1, k_2, k_3) \overset{\lambda \gg m}{\underset{k_3 \ll k_1 \sim k_2}{\simeq}} f_{\rm NL}^{(\rm clock)} \left(\frac{k_3}{k_1}\right)^{2-2i\tilde{\mu}} + \cdots$$



Minimal SM @ Cosmological Collider



Issues of the Cosmological Colliders

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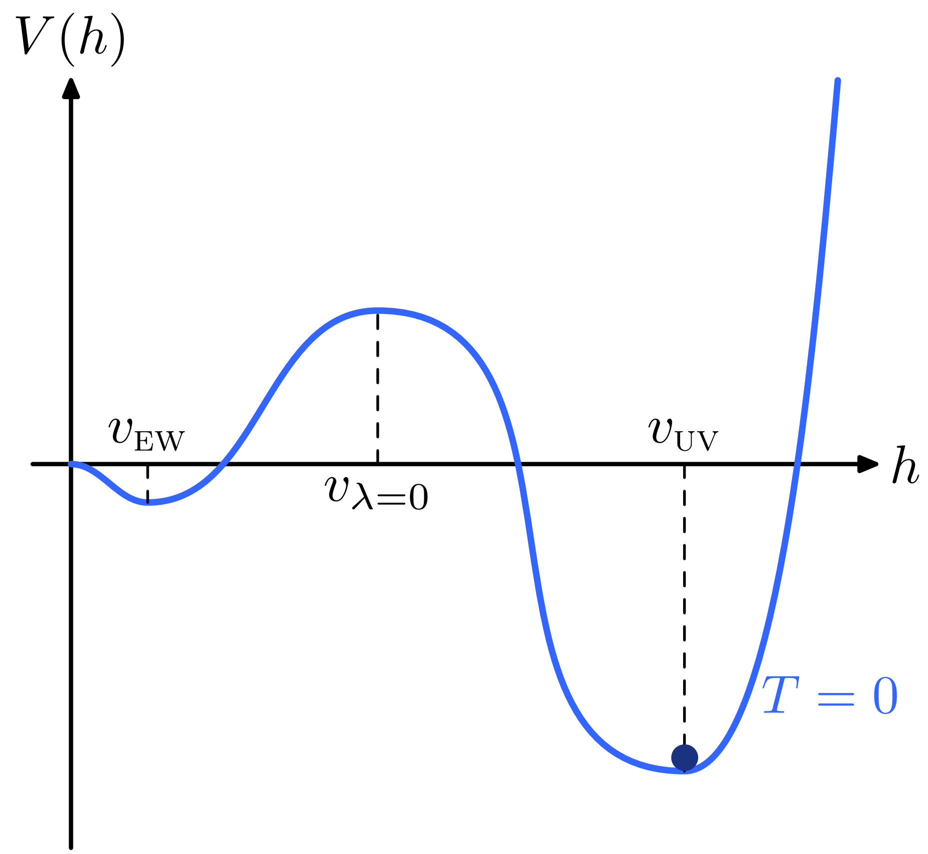
All issues mitigated by fermion coupling!

What about the Higgs?

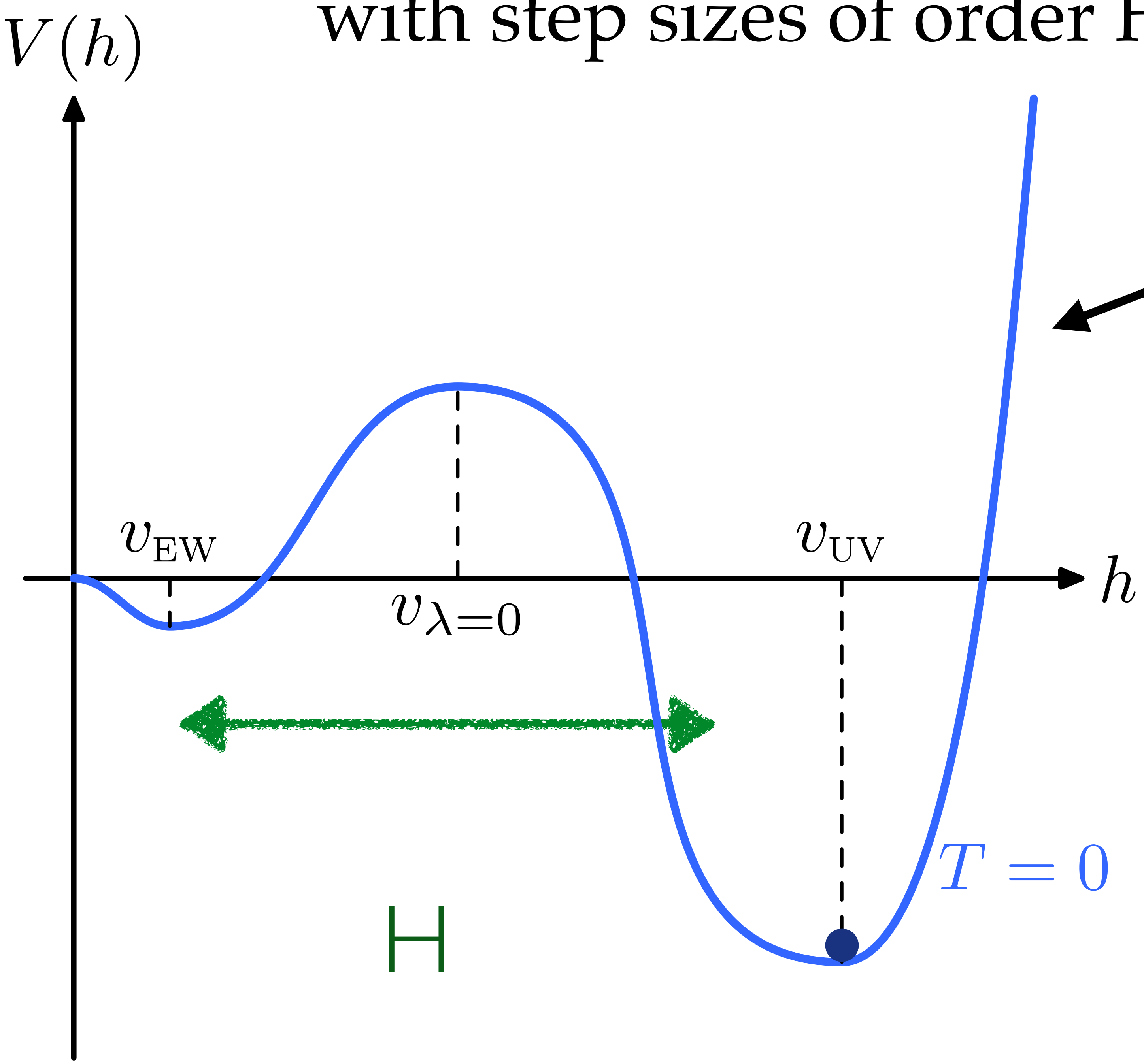
SM Higgs Instability



- Higgs quartic goes negative at ~ 10^{11} GeV
- True minimum of the Higgs is at very high scales
- Inflation occurs at these high scales, maybe the Higgs is in the true minimum?

SM Higgs During Inflation

Light fields can be kicked around
with step sizes of order Hubble

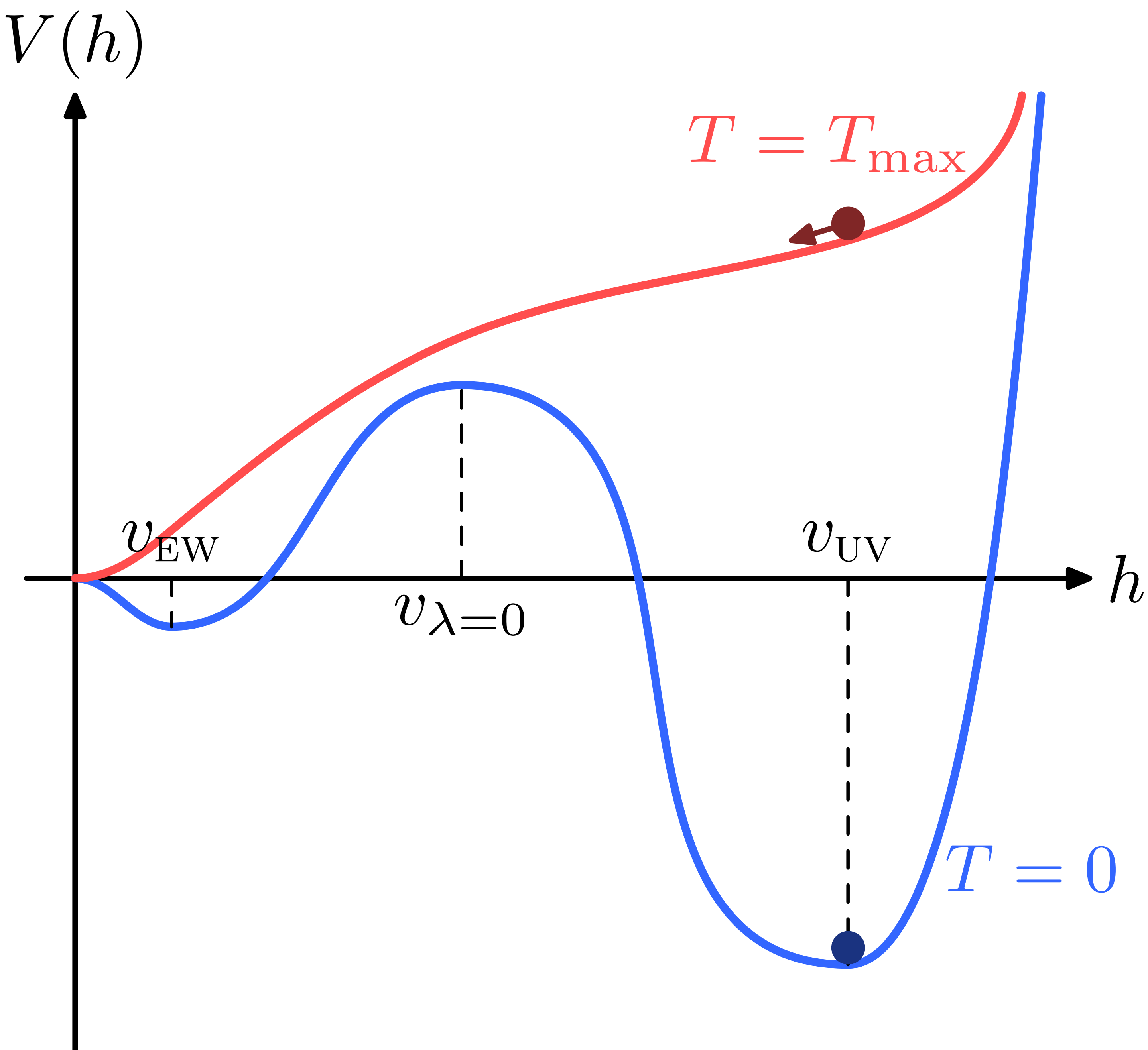


Planck Slop stabilization

Higgs random walk itself
into the new minima!

Higgs heavy in new minima
doesn't random walk out

SM Higgs After Inflation



Thermal effects rescue the Higgs after inflation

Possible only because

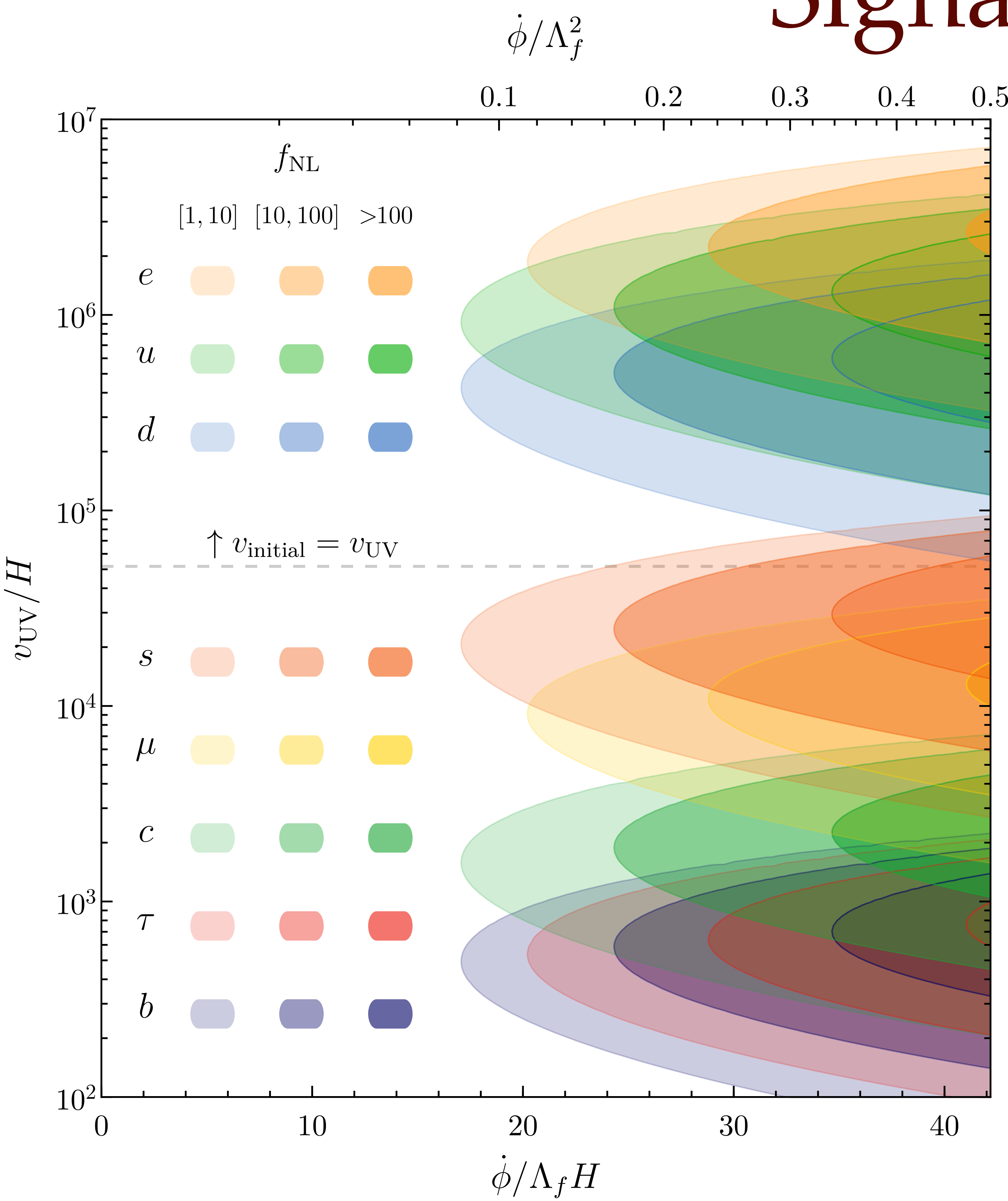
$$T^4 \sim M_p^2 H^2 \gg H^4$$

How do we see this?

SM has many fermions that scan many decades of energy

Natural to expect one or more of them is accidentally close to the Hubble scale

Signal



Take home:

1. SM fermions scan Hubble
2. Multiple SM fermions can be observed together

Signal Interpretation

Utilize amplitude of f_{NL} and oscillation to give mass and coupling

Ratio of fermion masses to discover that it is the SM all over again

Could be an observational discovery of another minimum where the Higgs mass is very different!

Conclusion

The Cosmological Collider is a new exciting collider that will give us access to super high energies

Gives the mass and coupling of new particles

The most minimal situation is actually very predictive

Can probe alternative minima where the Higgs mass is very large