Naturally large signals at the Cosmological Collider

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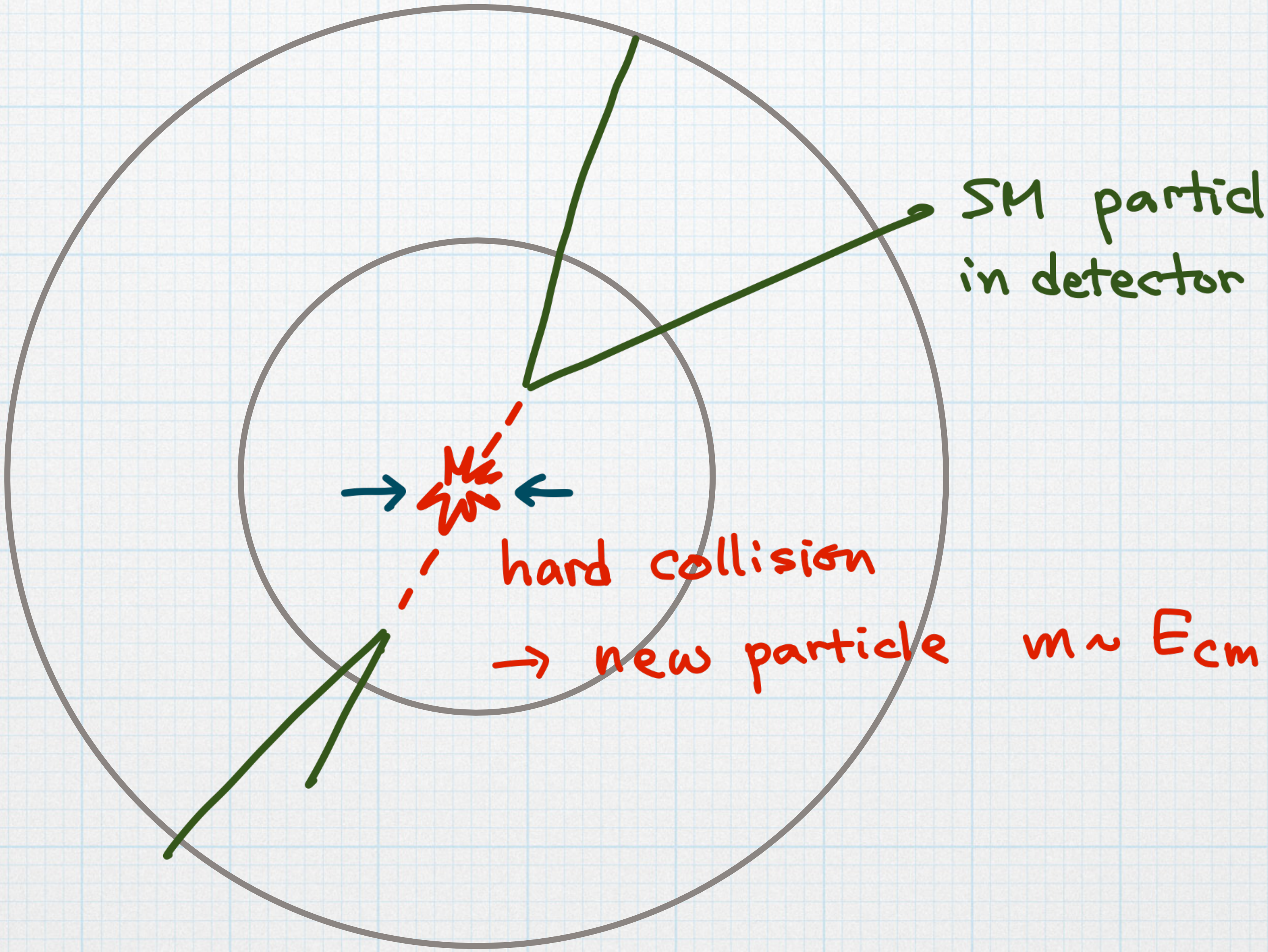
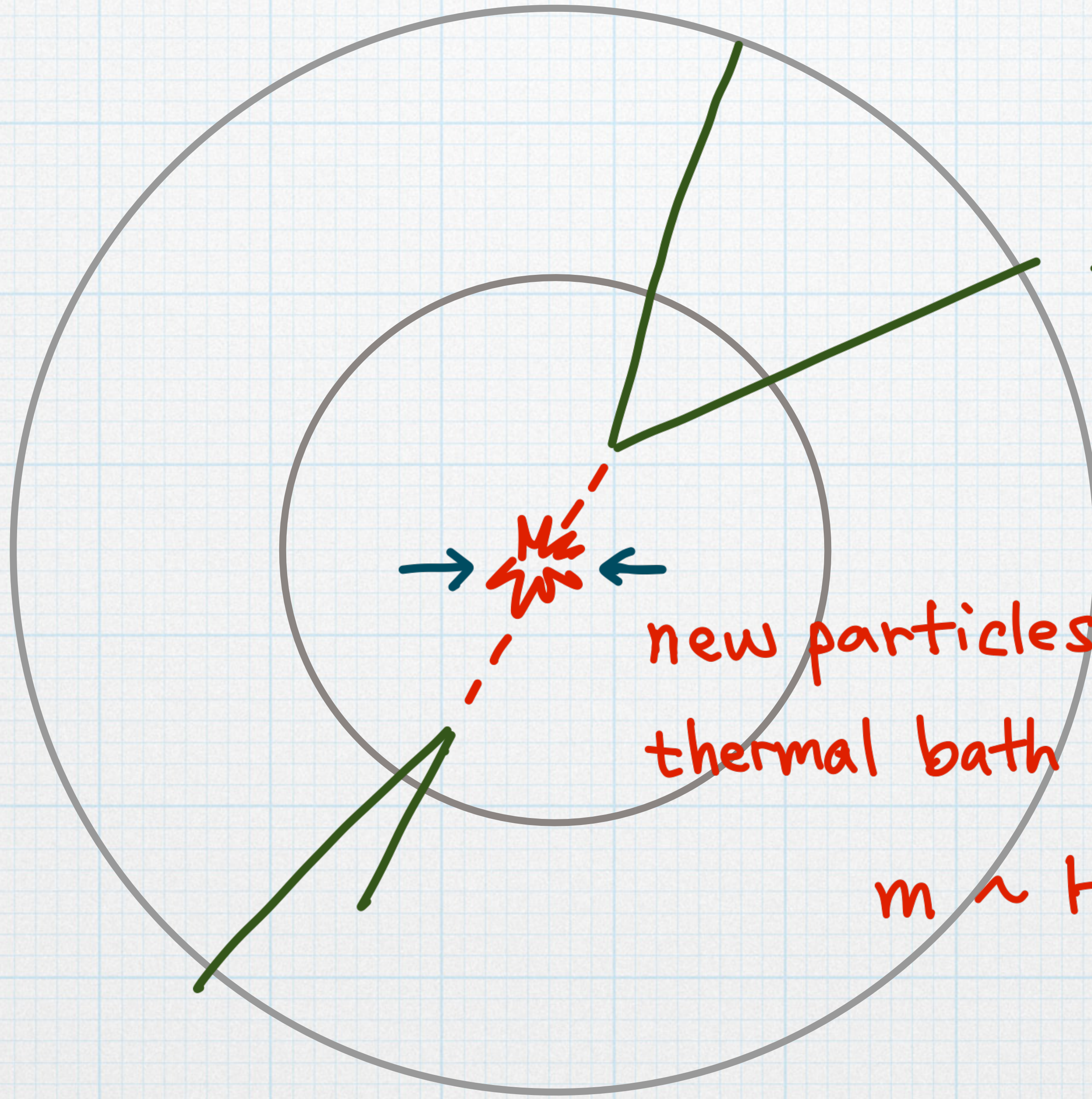
High energy collider



Highest foreseeable energy $\sim 10^2$ TeV

Cosmological collider



inflaton fluctuations

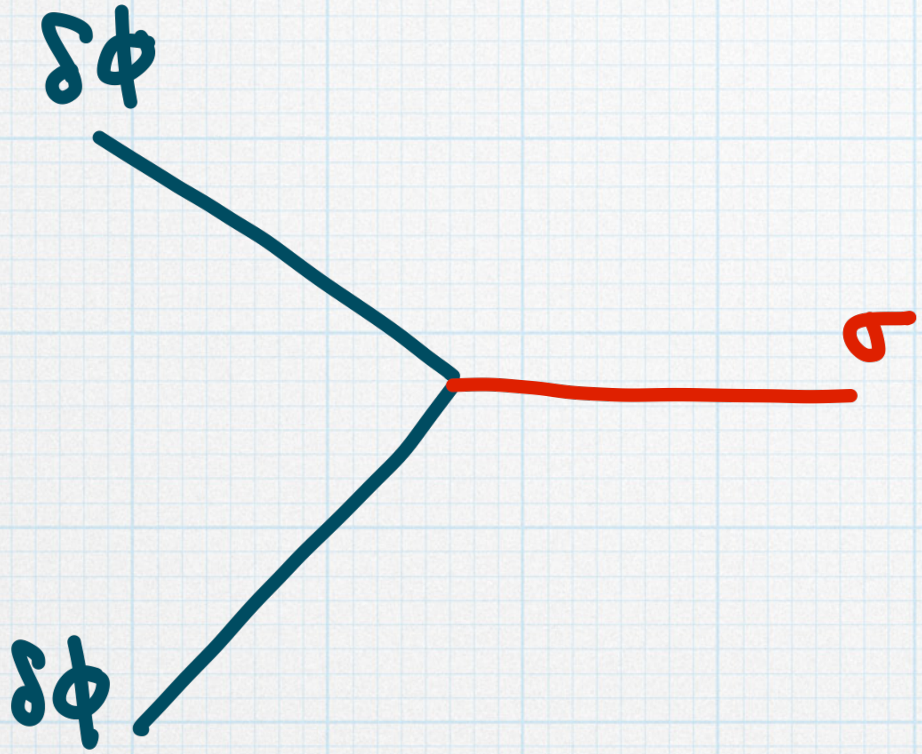
$\longrightarrow$ cosmo observations

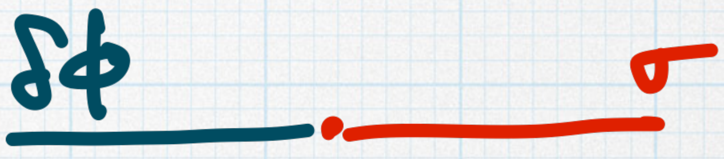
new particles made in the thermal bath of the inflaton

$$m \sim H_{\text{inflation}}$$

Highest possible energy: $H_{\text{inflation}} \sim 10^{13}$ GeV !

Basic couplings



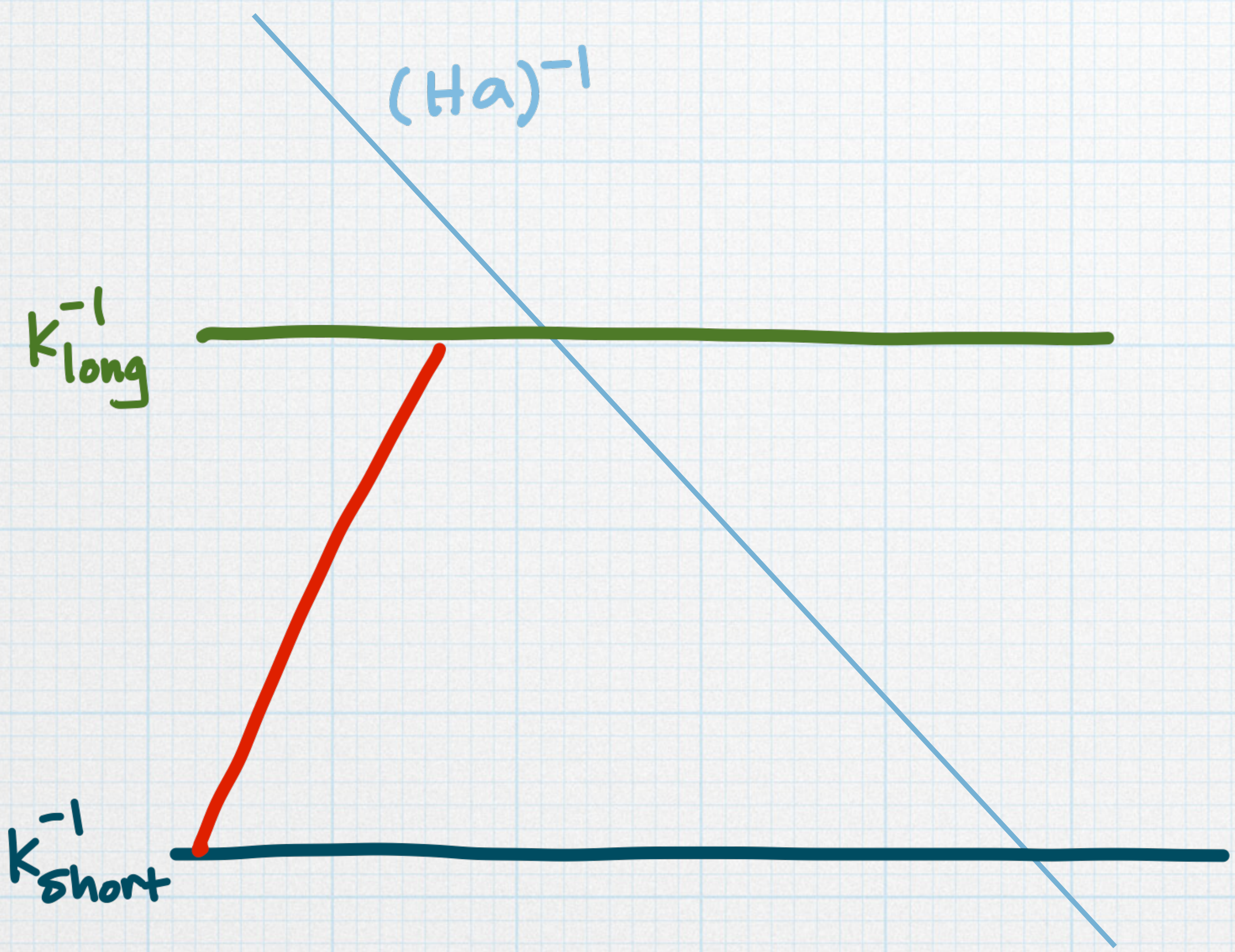


$\delta\phi$: inflaton fluctuations $\qquad E_{\delta\phi} \sim H_{inflation}$

σ: new "matter", for efficient production

need $\qquad m_\sigma \sim H$

Basic signal



Resonance propagates for

$$t = \frac{1}{H} \log \frac{k_{short}}{k_{long}}$$

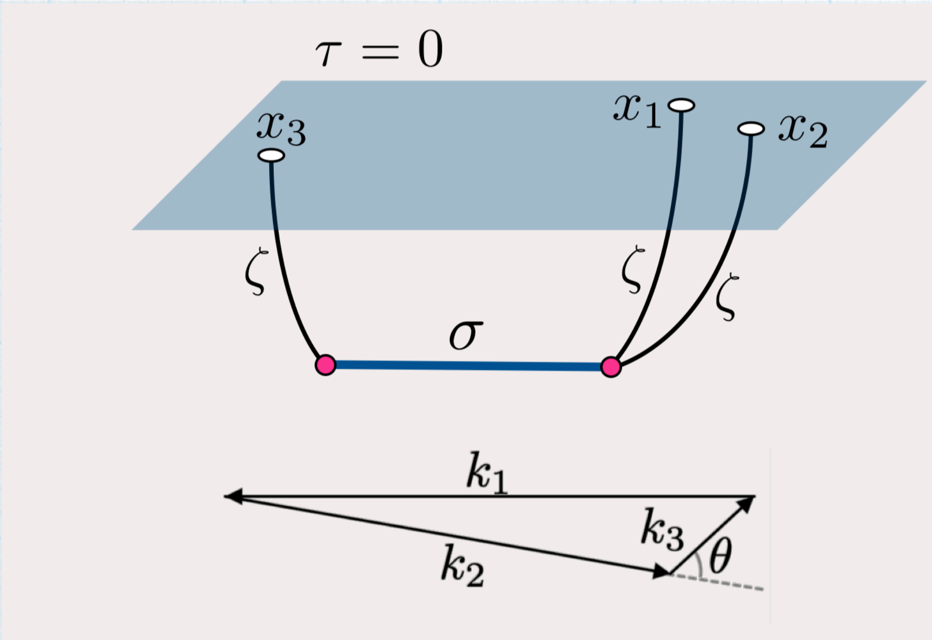
Signal of new particle production

$$\sim \sin(mt) = \underbrace{\sin\left(\frac{m}{H} \log \frac{k_{short}}{k_{long}}\right)}_{\text{oscillatory}}$$

Chen, Wang '09, '12

Arkani-Hamed, Maldacena '15

More specifically



$k_1 \sim k_2 \sim k_{short}$

$k_3 \sim k_{long}$

$$\nu = \sqrt{\frac{m_\sigma^2}{H^2} - \frac{9}{4}}$$

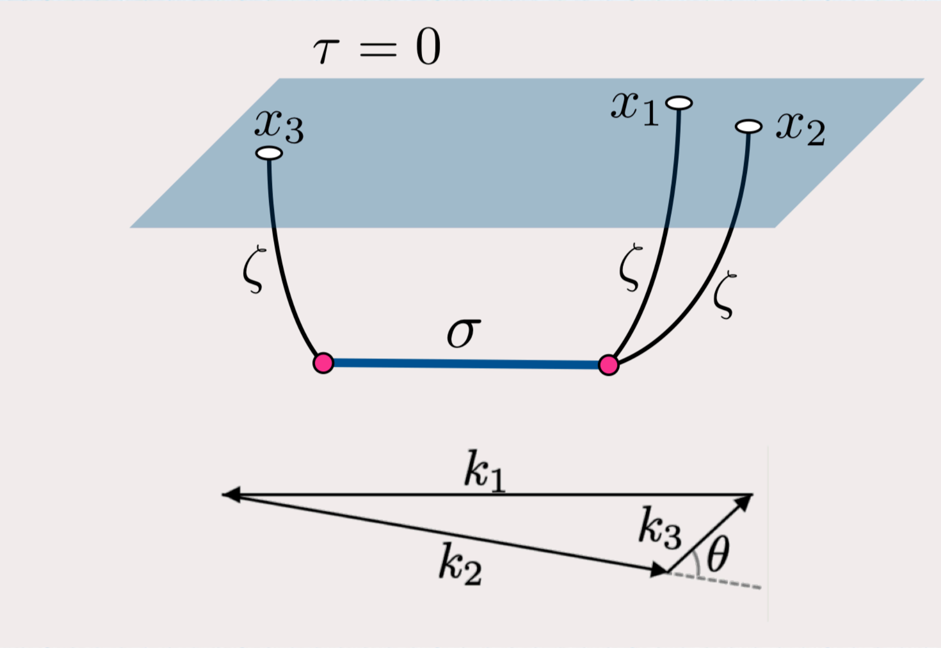
s: spin of σ

$$\frac{\langle \zeta\zeta\zeta \rangle}{\langle \zeta\zeta \rangle_{short} \langle \zeta\zeta \rangle_{long}} \sim e^{-\pi\nu} \cdot \left(f(\nu) \left(\frac{k_{long}}{k_{short}}\right)^{\frac{3}{2}+i\nu} + c.c.\right) P_s(\cos\theta)$$

$e^{-\pi\nu}$: signal Boltzmann suppressed if $m_\sigma \gg H$ $(\nu \gg 1)$

$\left(\frac{k_{long}}{k_{short}}\right)^{3/2+i\nu}$: if $m_\sigma < \frac{3}{2} H$, no osc. signal.

More specifically



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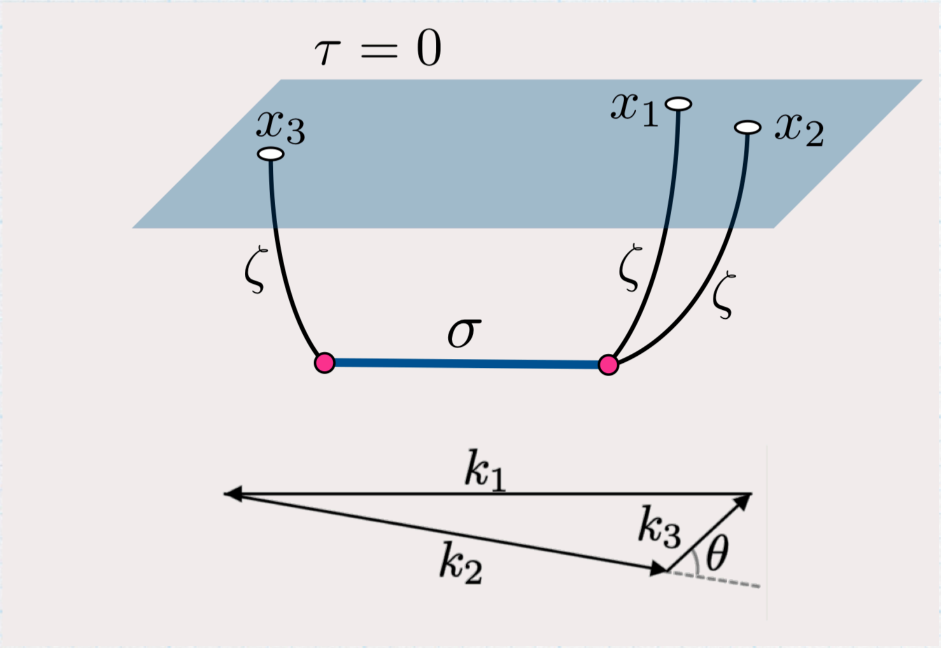
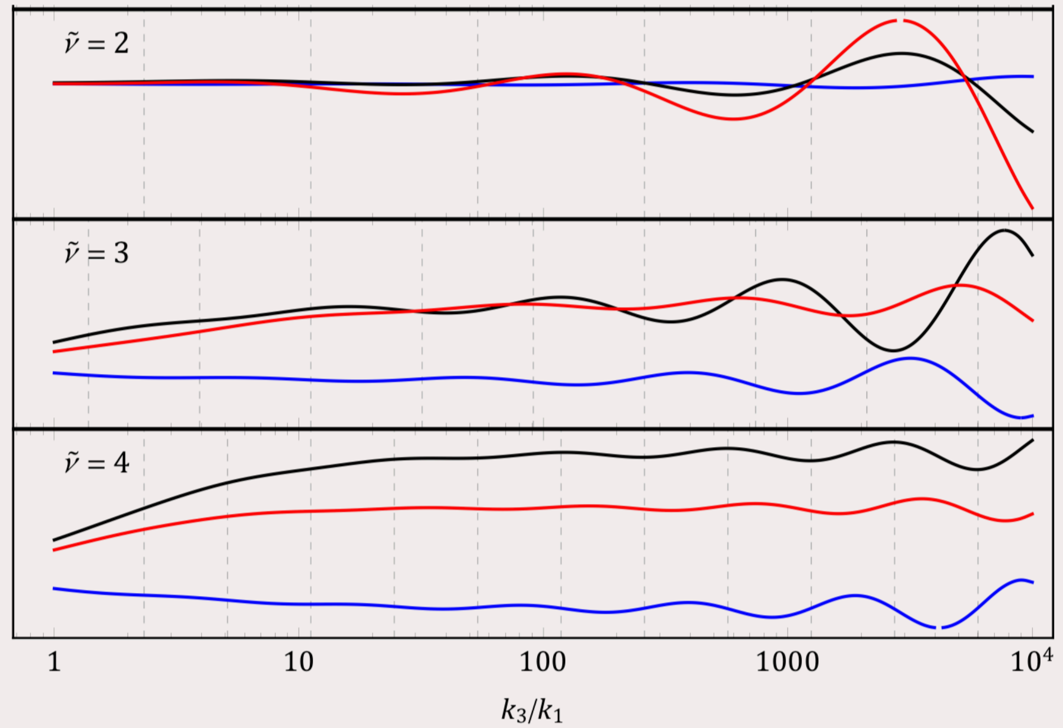
Need $m_\sigma \sim H$

More specifically





Chen, Chua, Guo, Wang, ZZX, Xie, 1803.04412

$$\frac{\langle \zeta \zeta \zeta \rangle}{\langle \zeta \zeta \rangle_{\text{short}} \langle \zeta \zeta \rangle_{\text{long}}} \sim e^{-\pi\nu} \cdot \left(f(\nu) \left(\frac{k_{\text{long}}}{k_{\text{short}}} \right)^{\frac{3}{2}+i\nu} + \text{c.c.} \right)$$

Why cosmological collider?

- Energy scale $\quad E \sim H \gg E_{lab}$

$$H_{max} \sim 10^{13}\ \mathrm{GeV}$$

- A lot more data to come

CMB + LSS + 21 cm

Ultimate sensitivity: $f_{NL} \sim 0.01$

What is the size of the signal?

Estimating the signal

- **Power spectrum**

$$\langle \zeta \zeta \rangle = \frac{2\pi^2}{k^3} P_\zeta$$

For an inflaton rolling at speed $\langle \partial_\mu \phi \rangle = \dot{\phi}_0$

$$P_\zeta = \left(\frac{H}{\dot{\phi}_0}\right)^2 \left(\frac{H}{2\pi}\right)^2$$

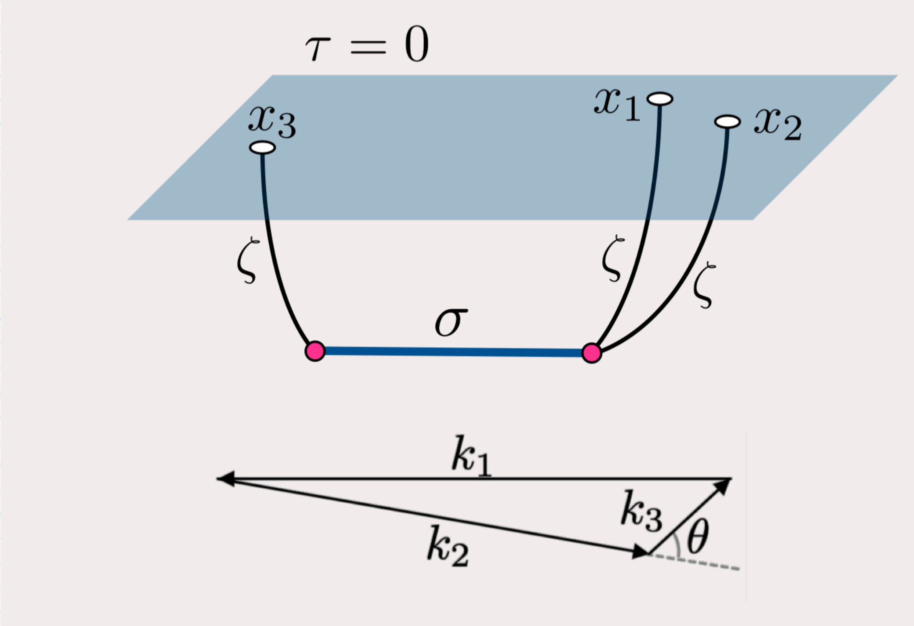
CMB power spectrum

$$\rightarrow P_\zeta \simeq 2 \times 10^{-9} \qquad \rightarrow (\dot{\phi}_0)^{1/2} \doteq 60\,H$$

P_ζ: power in the inflaton, similar to the PDFs.

Estimating the signal

- bispectrum



$$\langle \zeta \zeta \zeta \rangle = (2\pi)^4 P_\zeta^2 \frac{1}{(k_1 k_2 k_3)^2} S(k_1, k_2, k_3)$$

$$S(k_1, k_2, k_3) \sim f_{NL} \sim \frac{1}{2\pi P_\zeta^{1/2}} \times \text{interactions}$$

interactions ~ couplings x loops x propagators

Inflaton interactions with matter

- Classification schemes

  (non)renormalizable, symmetries ...

- A key feature:

  Inflaton coupling will change the spectrum of matter.

  → None trivial to get large signal.

Case 1: non-derivative coupling

For example:

$$\lambda \phi^2 Q^2 + \mu \phi Q^2 \qquad Q: \text{ scalar}$$

To avoid $e^{-m/H}$ suppression, we want $m_Q \sim H$.

Coupling above contributes to m_Q for $\langle \phi \rangle \neq 0$

$$\delta m_Q^2 = \lambda \langle \phi \rangle^2$$

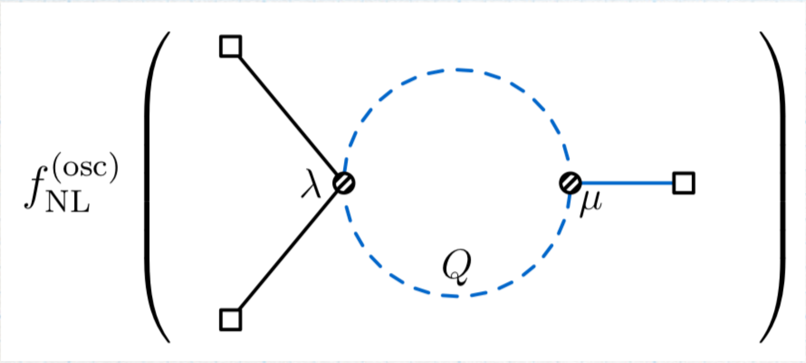
To avoid fine tuning

$$\delta m_Q^2 \lesssim H^2 \quad \rightarrow \quad \lambda \lesssim \frac{H^2}{\langle \phi \rangle^2}$$

Similarly

$$\mu \lesssim \frac{H^2}{\langle \phi \rangle}$$

Case 1: non-derivative coupling



$$\sim \frac{1}{2\pi P_\zeta^{1/2}} \frac{1}{16\pi^2} \lambda \frac{\mu}{H} < \frac{1}{2\pi P_\zeta^{1/2}} \frac{1}{16\pi^2} \left(\frac{H}{\langle\phi\rangle}\right)^3$$

Size of $\langle\phi\rangle$

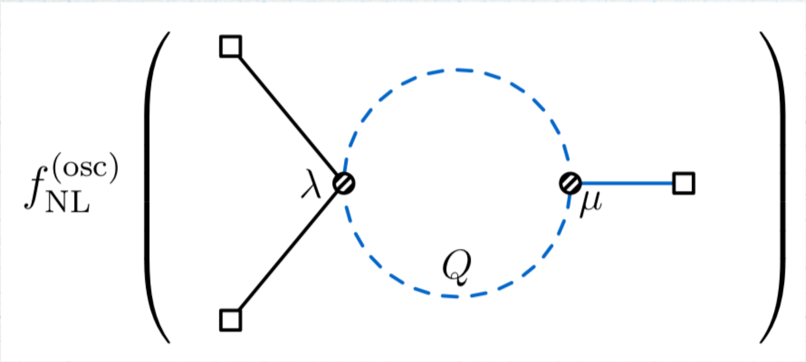
$$N_{e\text{-fold}} = \int d\phi \frac{H}{\dot{\phi}_0} \sim \frac{H}{\dot{\phi}_0} \Delta\phi \simeq O(10)$$

In general, we expect

$$\Delta\phi \sim \langle\phi\rangle \quad \rightarrow \quad \langle\phi\rangle \sim N \frac{\dot{\phi}_0}{H}$$

$$\rightarrow \frac{H}{\langle\phi\rangle} \sim \frac{2\pi P_\zeta^{1/2}}{N} \sim 10^{-5}$$

Case 1: non-derivative coupling

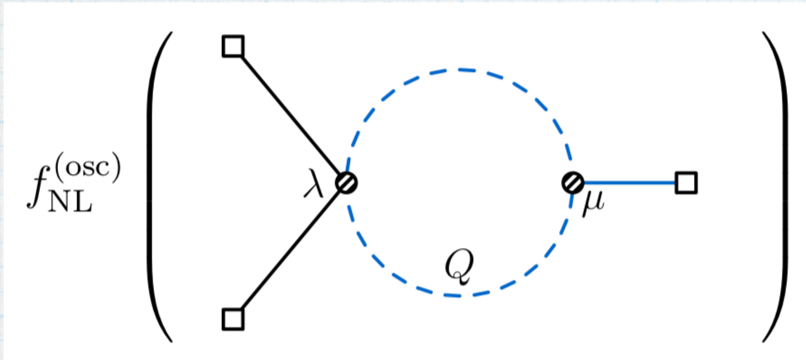


$$\sim \frac{1}{2\pi P_\zeta^{1/2}} \frac{1}{16\pi^2} \lambda \frac{\mu}{H} < \frac{1}{2\pi P_\zeta^{1/2}} \frac{1}{16\pi^2} \left(\frac{H}{\langle\phi\rangle}\right)^3$$

$$\frac{H}{\langle\phi\rangle} \sim \frac{2\pi P_\zeta^{1/2}}{N} \sim 10^{-5}$$

$$\rightarrow f_{NL} \sim \frac{1}{4N^3} P_\zeta$$ tiny !

Case 1: non-derivative coupling



$\sim \frac{1}{4N^3} P_\zeta$ **tiny!**

Key: coupling $\lambda \phi^2 Q^2$ shifts Q mass $\delta m_Q^2 = \lambda \langle \phi \rangle^2$

requiring $\delta m_Q^2 < H^2$ lead to small coupling $\lambda < \frac{H^2}{\langle \phi \rangle^2}$

Get around by fine-tuning m_Q^2 ?

No! Inflaton field excursion sizable

Difficult to tune for the full evolution.

Case 2: derivative coupling

- At $d=6$

$$\frac{c_6}{\Lambda^2}(\partial\phi)^2 Q^\dagger Q$$

- Well motivated, for inflaton with symmetry

$$\phi \rightarrow \phi + c$$

- Validity of EFT

$$\Lambda^2 > \langle \partial_\mu \phi \rangle = \dot{\phi}_0$$

Case 2: derivative coupling

- **Signal estimate**

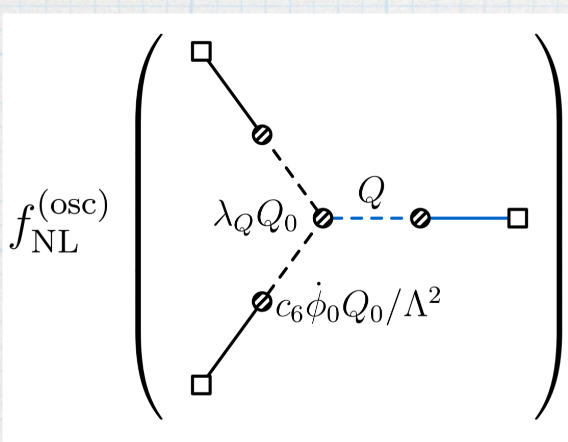
$$\mathcal{L} \supset \frac{c_6}{\Lambda^2} (\partial_\mu \phi)^2 Q^\dagger Q - m_Q^2 Q^\dagger Q - \lambda_Q |Q|^4$$

Correction from rolling inflaton to Q mass

$$\delta m_Q^2 = \frac{c_6}{\Lambda^2} \dot{\phi}_0^2 \quad \rightarrow \quad \frac{c_6}{\Lambda^2} \lesssim \frac{H^2}{\dot{\phi}_0^2} = \frac{2\pi^2 P_\zeta}{H^2}$$

Also, assume Q acquires a VEV

$$\langle Q \rangle = Q_0 \qquad \lambda_Q Q_0^2 \lesssim H^2$$



$$\sim \frac{1}{2\pi P_\zeta} \left(\frac{c_6}{\Lambda^2} \dot{\phi}_0 Q_0 \right)^3 \lambda_Q Q_0 \frac{1}{H^4} \lesssim \frac{1}{\lambda_Q} (2\pi)^2 P_\zeta$$

small unless $\lambda_Q \sim 10^{-8}$

Case 2: derivative coupling

- How about $d=5$?

$$\frac{1}{\Lambda}\partial_\mu\phi\, J^\mu \quad \text{or} \quad \frac{\phi}{\Lambda} F\wedge F$$

Validity of EFT: $\Lambda^2 > \dot{\phi}_0$

Naive estimate:

$$f_{NL} \sim \frac{1}{16\pi^2}\frac{1}{2\pi P_\zeta^{1/2}}\left(\frac{H}{\Lambda}\right)^3 < \frac{1}{16\pi^2}\frac{1}{2\pi P_\zeta^{1/2}}\left(\frac{H}{\dot{\phi}_0^{\frac{1}{2}}}\right)^3 = \frac{1}{16\pi^2}\sqrt{2\pi}\, P_\zeta^{1/4}$$

However, this is too naive.

Couplings of this type modifies dispersion relations.

$\longrightarrow$ Can lead to additional enhancement.

Modification of dispersion relation.

- Enhancement through non-adiabiticity

particle production $\propto \frac{\dot{\omega}}{\omega^2}$ $\quad \omega$ = particle energy

"usual" dispersion relation for free particle

$$\omega^2 = k_{phys}^2 + m^2 \qquad k_{phys} = \frac{k}{a(t)} \qquad k\text{: comoving}$$

Looking for modifications which can further enhance the signal.

Modification of dispersion relation.

- What does not work

Current of complex scalar

$$\frac{1}{\Lambda} \partial_\mu \phi J^\mu \qquad J^\mu = (Q^\dagger \overleftrightarrow{\partial}^\mu Q)$$

$$\langle \partial_\mu \phi \rangle = \dot{\phi}_0 \quad \text{and define} \quad \mu = \dot{\phi}_0 / \Lambda$$

$$\rightarrow \mathcal{L} = |(\partial_0 - i\mu) Q|^2 - |\nabla Q|^2 + m^2 |Q|^2 + \cdots$$

A shift in energy $\omega \rightarrow \omega - \mu$.

Not physical, can be eliminated by $Q \rightarrow e^{i\mu t} Q$.

Similar conclusion for coupling to vector-like fermion current

$$\frac{1}{\Lambda} \partial_\mu \phi J^\mu \qquad J^\mu = \bar{\psi} \gamma^\mu \psi .$$

Modification of dispersion relation.

– What can work

- We learned that $(\omega \pm \mu)^2 = k_{phys}^2 + m^2$ does not work

- Look for modification of the form

$$\omega^2 = k_{phys}^2 \pm \underbrace{2\mu k_{phy}} + m^2 + \cdots \qquad \left(k_{phys} = \frac{k}{a(t)}\right)$$

$$\frac{\dot{\omega}}{\omega^2} \sim \frac{\mu}{\omega^2}$$ additional enhancement.

Modification of dispersion relation.

– What can work

$$\omega^2 = k_{phys}^2 \pm 2\mu k_{phy} + m^2 + \cdots \qquad \left(k_{phys} = \frac{k}{a(t)}\right)$$

- This type of term comes from $\vec{k} \cdot \vec{n}$, $\vec{n}$ = another vector.
- Origin of the other vector $\vec{n}$

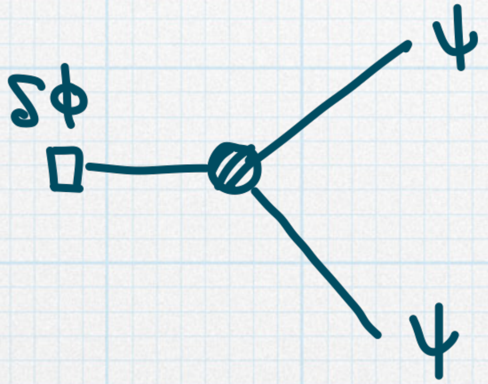
$\vec{n}$ = spin : $\quad J^\mu = \bar{\Psi} \gamma^5 \gamma^\mu \psi, \quad \epsilon^{\mu\nu\rho\sigma} A_\nu \partial_\rho A_\sigma$

Not for scalar. $\qquad$ Or, broken rotational invariance.

Coupling to chiral fermion

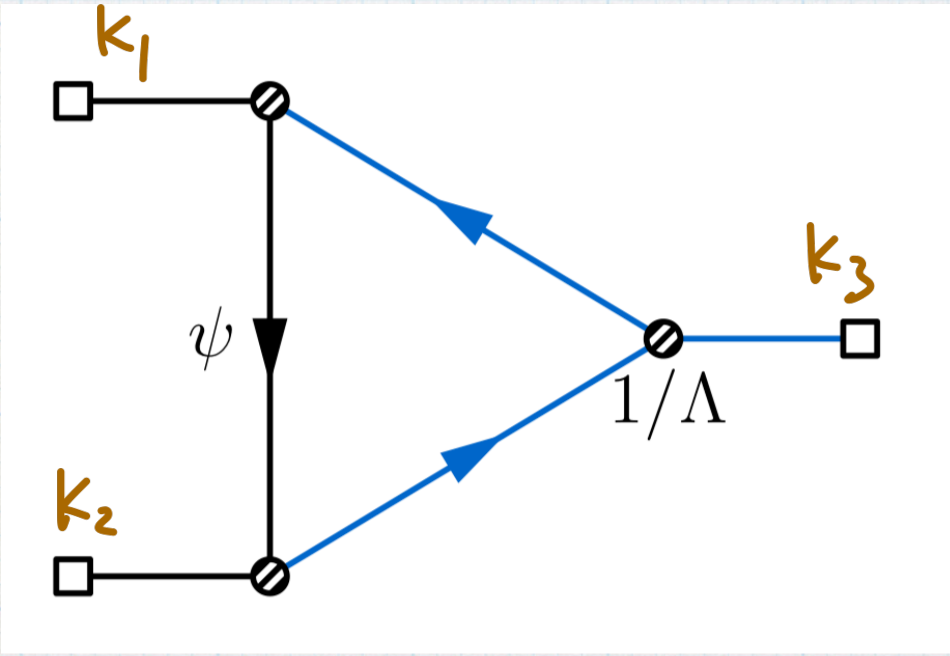
Inflaton with a single Majorana fermion

$$\mathcal{L} = \sqrt{-g}\left(i\psi^\dagger \bar{\sigma}^\mu D_\mu \psi - \frac{1}{2}m(\psi\psi + \psi^\dagger\psi^\dagger) + \underbrace{\frac{1}{\Lambda}(\partial_\mu\phi)\psi^\dagger\bar{\sigma}^\mu\psi}\right)$$



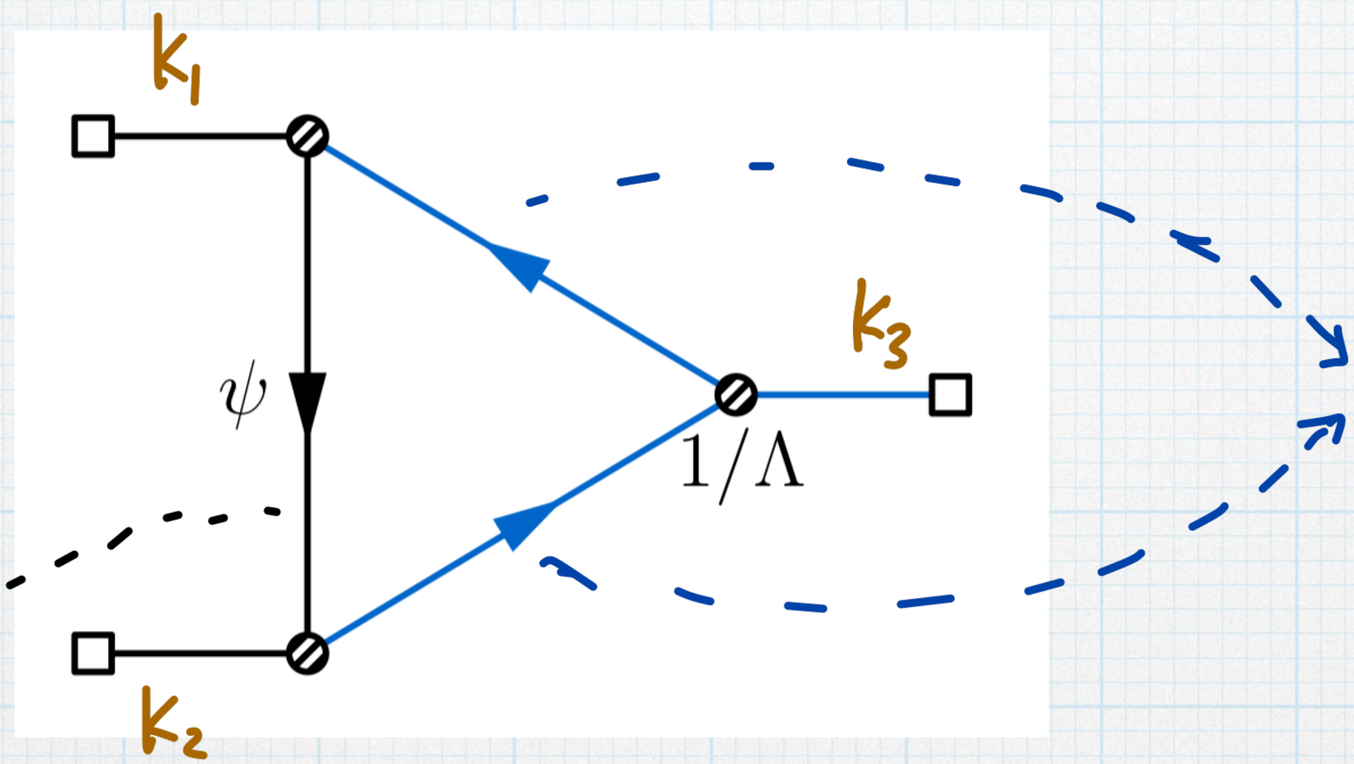
$$\mu\, \psi^\dagger \bar{\sigma}^0 \psi$$

$$\mu = \frac{\dot{\phi}_0}{\Lambda}$$



Coupling to chiral fermion

"hard" $\frac{1}{m}$



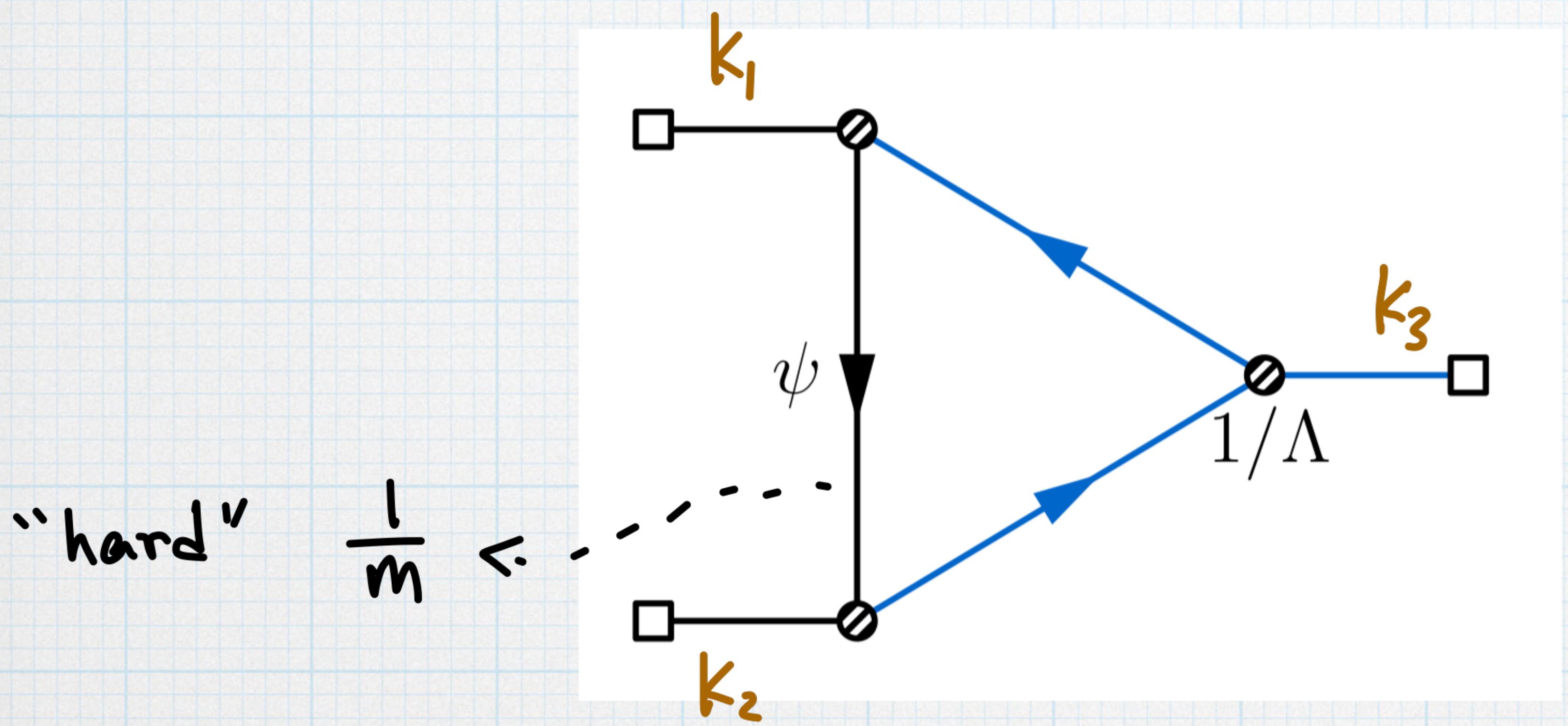
$e^{\pi\mu/H}$ enhancement

Together with overall Boltzmann factor

$$e^{-\pi\sqrt{m^2+\mu^2}/H}\, e^{\pi\mu/H} \xrightarrow{\mu \gg 1 \gg H} e^{-\pi m^2/H\mu}$$

No overall suppression as $\mu \gg m \gg H$.

Coupling to chiral fermion



overall factor

$e^{-\pi m^2/\mu H}$

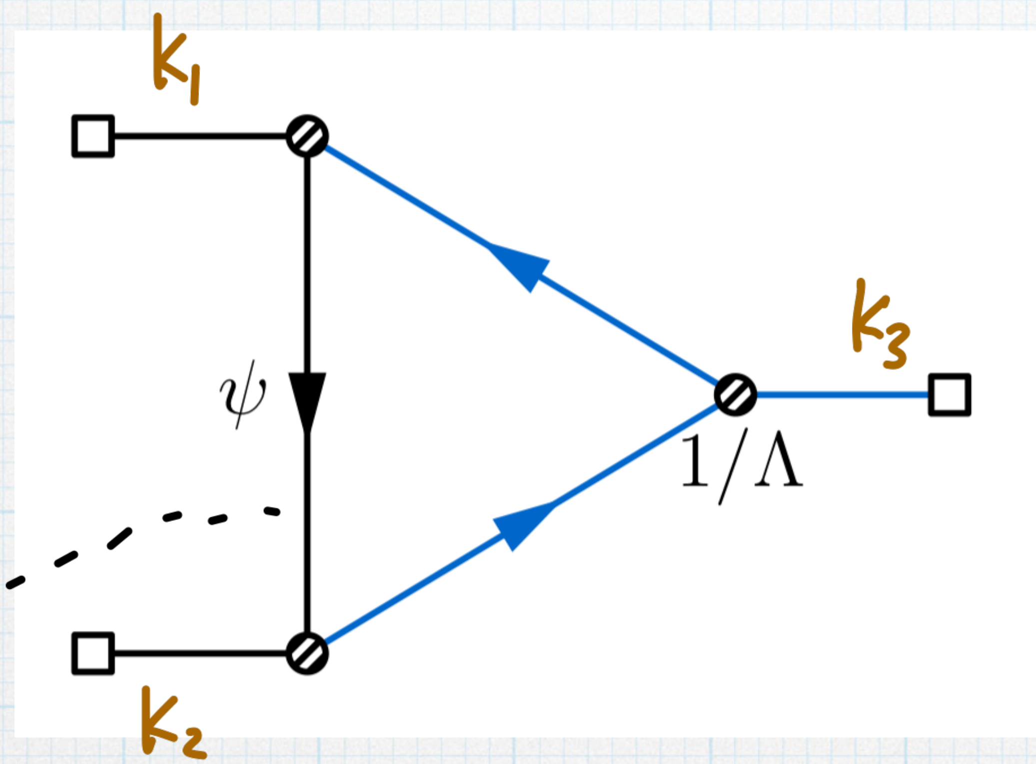
Enhanced modes for $\omega^2 = (k_{phys} \pm \mu)^2 + m^2$

$\frac{\dot{\omega}}{\omega^2}$: tiny for very early and late times

peak at $k_{phys} \sim \mu$, width: $\Delta k_{phys} \sim m$

phase space with enhancement $\sim 4\pi m \mu^2$.

Coupling to chiral fermion



"hard" $\frac{1}{m}$

overall factor

$e^{-\pi m^2/\mu H}$

phase space

$4\pi m \mu^2$

$$f_{NL} \sim \frac{1}{2\pi P_\zeta^{1/2}} \frac{1}{16\pi^2} \left(\frac{m}{\Lambda}\right)^3 \frac{H}{m} \, 4\pi m \mu^2 \, e^{-\pi m^2/\mu H}$$

$$\sim \frac{P_\zeta}{2} \left(\frac{m}{H}\right)^3 \left(\frac{\mu}{H}\right)^5 e^{-\pi m^2/\mu H}$$

Signal can be large if $\mu > m > H$

Coupling to vector

- axion like coupling

$$\frac{\phi}{\Lambda} F \wedge F \qquad \mu = \frac{\dot{\phi}_0}{\Lambda}$$

dispersion relation: $\omega^2 = k_{phys}(k_{phys} \pm 2\mu) + m^2 - \frac{H^2}{4}$

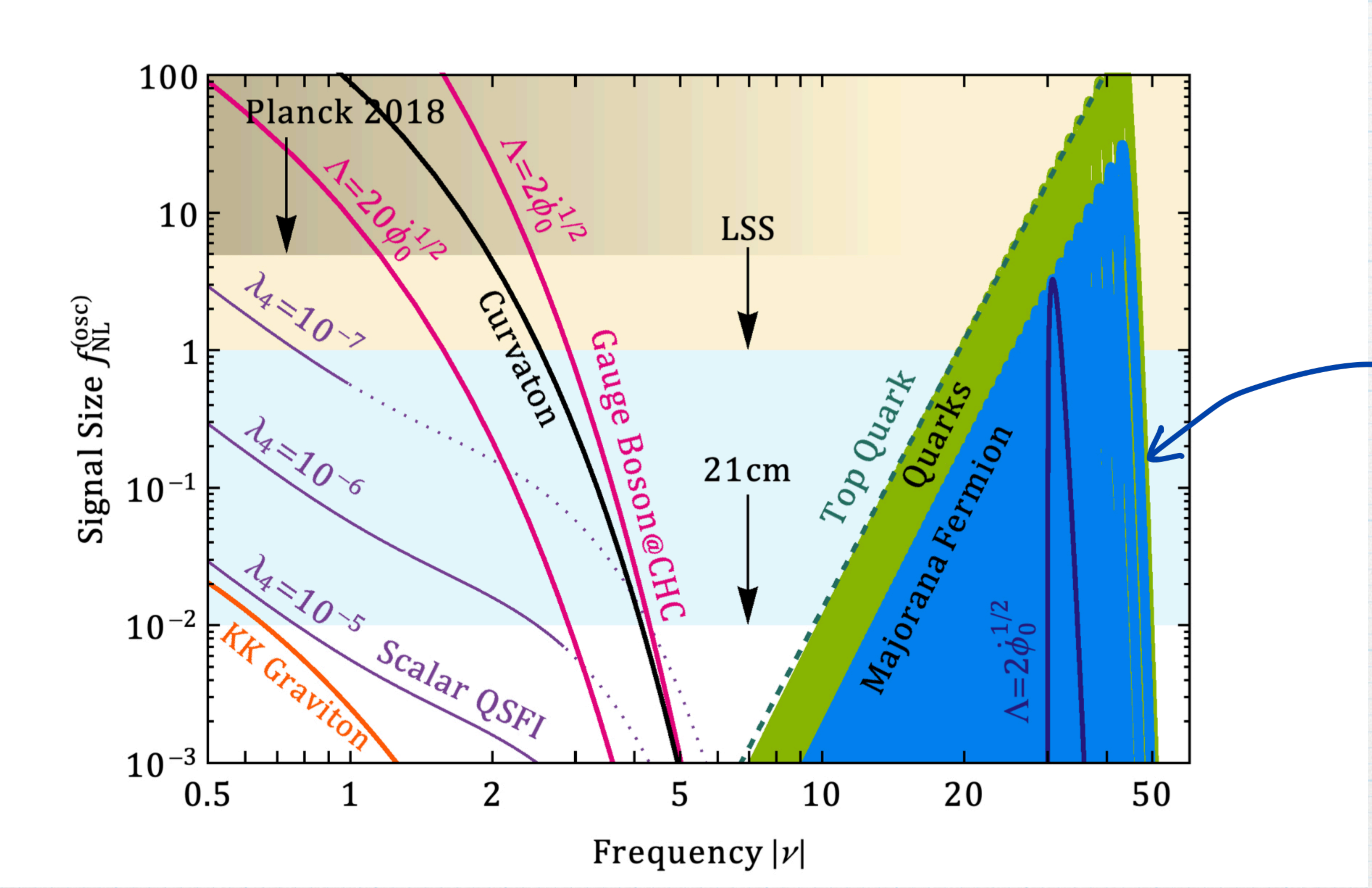
Overall factor $\sim e^{\pi(\mu - m)}$

large enhancement possible for $\mu > m$

However, can have tachyon mode if $\mu \gg m$

Needs further study (on-going)

Signals at cosmological collider



scan Λ

$$\nu = \left(\frac{9}{4} - \frac{m^2}{H^2}\right)^{1/2}, \quad \left(\frac{1}{4} - \frac{m^2}{H^2}\right)^{1/2}, \quad (m^2+\mu^2)^{1/2}/H$$

scalar vector fermion.

Conclusions

- Cosmological collider gives a unique window to physics at very high energies

$$E \sim 10^{13}\ \text{GeV} \,!$$

- Not all new physics lead to sizable signals. Very sensitive to coupling to the inflaton.

Conclusions

- Much more work needed to fully understand its physics potential.

  - Natural model space.

    Models of $\partial_\mu \phi J^\mu \ldots$ Why $m \sim H$?

  - Better predictions for $f_{NL}(k_1, k_2, k_3)$.

  ...