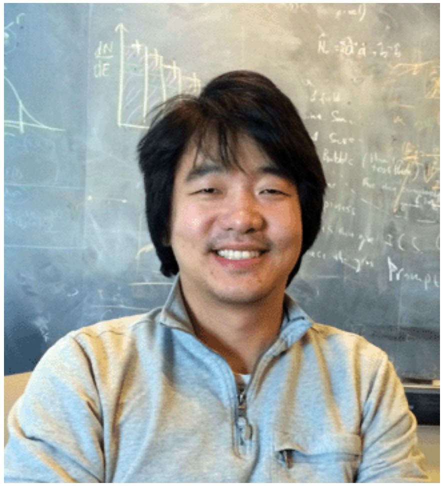
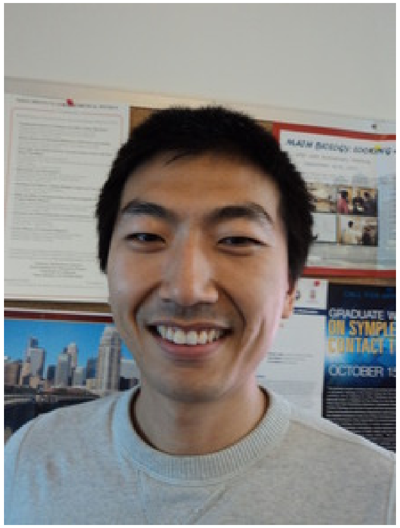
Observing Inflationary Quantum Fluctuations of Fermionic Dark Matter



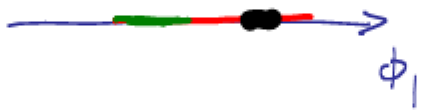


Daniel J. H. Chung

[collaboration: Hojin Yoo and Peng Zhou
1306.1966]

Usual Story

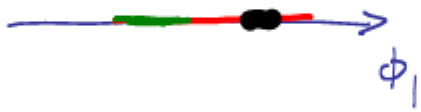
For a review, see e.g. 0809.4944



single field

Quantum fluctuations generate inhomogeneities.

Usual Story



single field

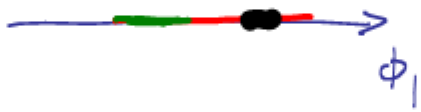
$$\phi_1 = \langle \phi_1(t) \rangle + \delta\phi_1(t,\vec{x})$$

One field → one type of inhomogeneity:

adiabatic perturbations

Observable: $\langle \delta T_{\alpha\beta}(t,\vec{x})\delta T_{\mu\nu}(t,\vec{y})...\rangle$

Usual Story



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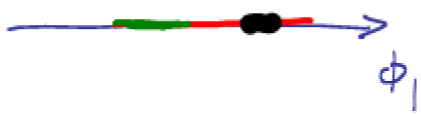
Given what we know about SM, it is very unlikely only one field was dynamical during inflation.

Usual Story



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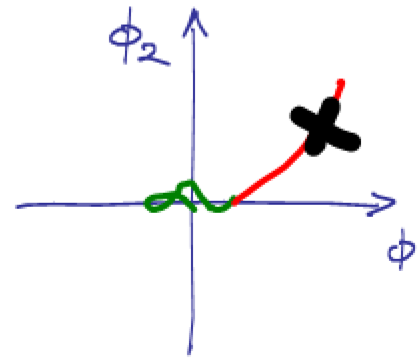


multi-field

$$\phi_1 = \langle \phi_1(t) \rangle + \delta\phi_1(t,\vec{x})$$

$$\phi_2 = \langle \phi_2(t) \rangle + \delta\phi_2(t,\vec{x})$$

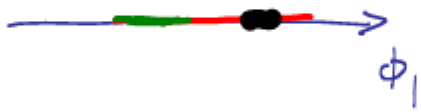
Two linearly independent inhomogeneities:

adiabatic + isocurvature perturbations

Observable: $\langle \delta T^{(i)}_{\alpha\beta}(t,\vec{x}) \delta T^{(j)}_{\mu\nu}(t,\vec{y}) \ldots \rangle$

$\boxed{\text{<i j > info imprinted in dark matter and radiation}}$

Usual Story



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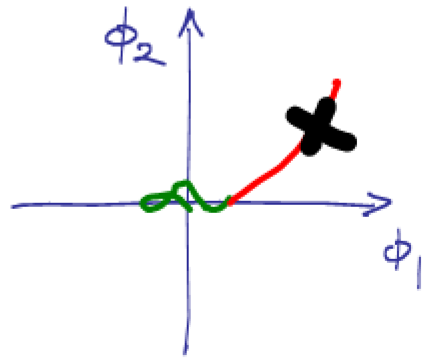
Observable: $\langle \delta T_{\alpha\beta}(t,\vec{x}) \delta T_{\mu\nu}(t,\vec{y}) \ldots \rangle$

Quantum fluctuations becoming
on-shell observables, not
just virtual corrections.



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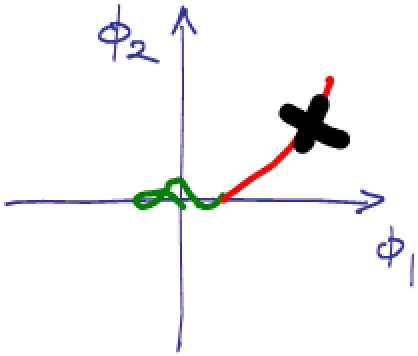
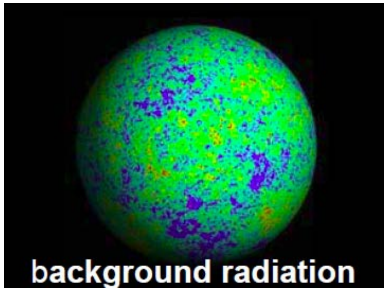
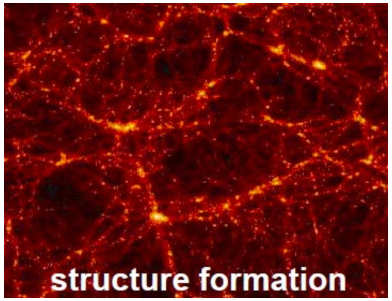


multi-field



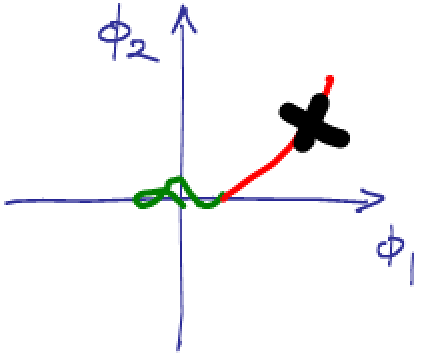


Thus far, scale invariant isocurvature perturbations are observationally constrained to be less than about 3% of the two-point function power on large scales.

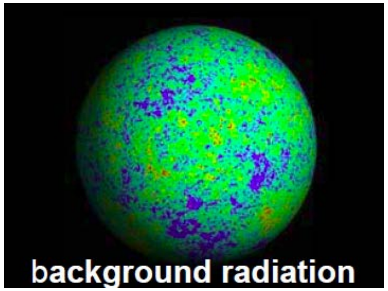
Usual story: Fluctuations on bosonic field space (e.g. scalars and gravitons)

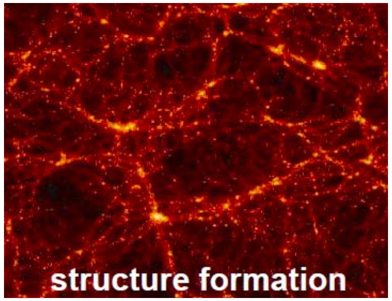
Question

single field



multi-field



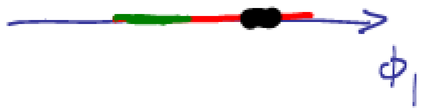


Usual story: Fluctuations on bosonic field space

What about fermion field fluctuations during inflation?

DC, Yoo, Zhou 1306.1966

Fermion Quantum Fluctuations During Inflation



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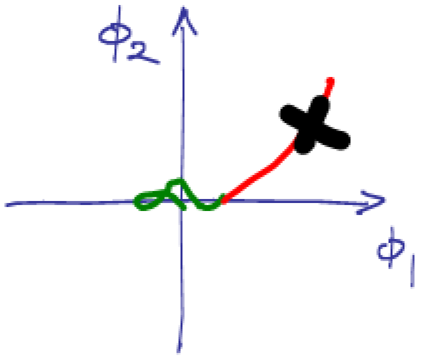
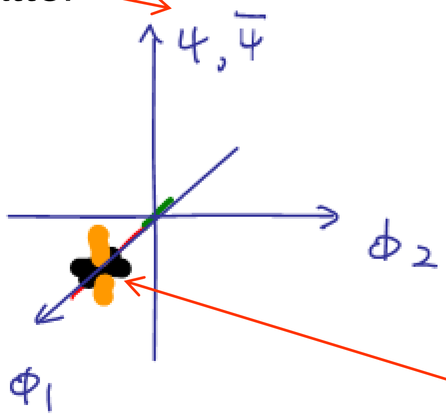


multi-field

What about fermion field fluctuations during inflation?

DC, Yoo, Zhou 1306.1966

e.g. dark matter from hidden sector

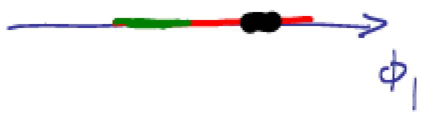


multi-field + fermion

Observable: $\langle \delta T^{(i)}_{\alpha\beta}(t,\vec{x})\delta T^{(j)}_{\mu\nu}(t,\vec{y})\ldots\rangle$

no classical VEV for fermions is an important generic character of this class of isocurvature perturbations

Fermion Fluctuations Questions



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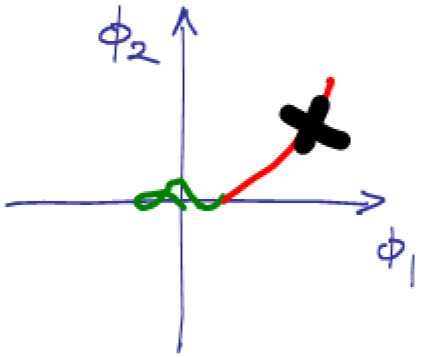

multi-field

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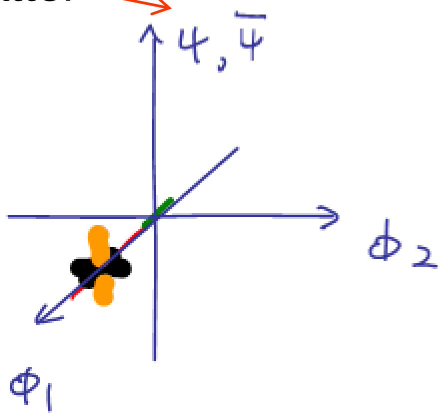

multi-field + fermion

Observable: $\langle \delta T^{(i)}_{\alpha\beta}(t,\vec{x})\delta T^{(j)}_{\mu\nu}(t,\vec{y})\ldots\rangle$

- Minimal coupling necessary for observation?
- Features of 2 and 3 point functions of inhomogeneity observables? For example, is it scale invariant? Bispectrum observable?
- Role of the gravitational Ward identity?

Minimal Coupling?

In the inflaton, scalar isocurvature, and the graviton case, one only needs gravitational interactions to obtain nontrivial observables.

Can one get away with this for the fermion?

Minimal Coupling?

In the inflaton, scalar isocurvature, and the graviton case, one only needs gravitational interactions to obtain nontrivial observables.

Can one get away with this for the fermion?

no

Certainly, fermions still can be produced by the work done by the curvature of the spacetime.

As I will explain, the problem is the dilution of the IR behavior of the free fermionic propagator during inflation.

For the rest of the talk, we will assume that the fermions are stable enough to be dark matter.

Local Conformal Symmetry

Key differences between free fermions and {scalars, gravitons}:

massless limit of free fermions coupled to gravity is invariant under local conformal transformations

spin 1/2

$$g_{\mu\nu}(x) \to \lambda(x) g_{\mu\nu}(x) \qquad \Psi \to \lambda^{-3/2}(x)\Psi$$

$$\sqrt{g} i \bar{\Psi} \gamma^a \nabla_{e_a} \Psi \to \sqrt{g} i \bar{\Psi} \gamma^a \nabla_{e_a} \Psi$$

massless spin 0: no, not with minimal coupling (e.g. scalar perturbations)
massless spin 2: no (i.e. tensor perturbations – BICEP2)

massless spin 1: yes

Local Conformal Symmetry

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$$\sqrt{g} i\bar{\Psi}\gamma^a \nabla_{e_a}\Psi \to \sqrt{g} i\bar{\Psi}\gamma^a \nabla_{e_a}\Psi$$

Important because FRW background (relevant for linearized perturbations) is conformally flat.

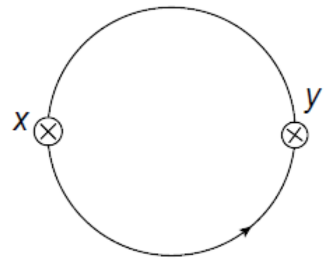
$$\lambda = a^{-1}(t) \qquad g_{\mu\nu} \to \eta_{\mu\nu}$$

m << H corresponds to effectively massless dynamics.

Since free correlators in Minkowski space are fixed by conformal dimensions, can read off m<<H free correlator from conformal dimension.

Conformal Symmetry Implication 1

$$\delta\rho_\psi(x) \propto \bar{\psi}\psi(x)$$



1

$$\langle \bar{\psi}\psi_x \bar{\psi}\psi_y \rangle_{LO} = \begin{cases} \frac{1}{\pi^4 a_x^6 |\vec{x}-\vec{y}|^6} \left(1 + O\left[\left(\frac{m_\psi}{H_{inf}}\right)^2\right]\right) & (m_\psi \ll H_{inf}) \\ \frac{1}{\pi^4 a_x^6 |\vec{x}-\vec{y}|^6} (4\pi) \left(\frac{m_\psi}{H_{inf}}\right)^3 \exp(-2\pi \frac{m_\psi}{H_{inf}}) & (m_\psi \gg H_{inf}) \end{cases}$$

6 = large suppression power from conformal dimension

Note that this by itself does not say that the correlator is suppressed. One can divide by objects that scale the same way. But the number 6 will persist to be important in suppressing the final result.

Conformal Symmetry Implication 2

1

$$\langle \bar{\psi}\psi_x \bar{\psi}\psi_y \rangle_{LO} = \begin{cases} \frac{1}{\pi^4 a_x^6 |\vec{x}-\vec{y}|^6} \left(1 + O\left[\left(\frac{m_\psi}{H_{inf}}\right)^2\right]\right) & (m_\psi \ll H_{inf}) \\ \frac{1}{\pi^4 a_x^6 |\vec{x}-\vec{y}|^6} (4\pi) \left(\frac{m_\psi}{H_{inf}}\right)^3 \exp(-2\pi \frac{m_\psi}{H_{inf}}) & (m_\psi \gg H_{inf}) \end{cases}$$

Fermion particle production ends when m=H after inflation. This is also connected with conformal symmetry but at the mode decomposition level..

[DC, Everett, Yoo, Zhou 12]

$$\frac{\langle \delta\rho_x \delta\rho_y \rangle}{\langle \bar{\rho}_\psi \rangle^2} \sim \frac{m_\psi^2/(\pi^4 a^6 r_{CMB}^6)}{m_\psi^2 m_\psi^6 (a_*^6/a^6)} \sim \left(\frac{1}{a_* m_\psi r_{CMB}}\right)^6 \sim \boxed{e^{-6N(k_{CMB})}\left(\frac{H_e}{m_\psi}\right)^2}$$

2

Free fermionic inhomogeneities are too suppressed on long wavelengths to be interesting.

There is effectively a volume dilution that occurs for the fermion modes due to its conformal behavior which cannot be offset by the denominator which does not start diluting until after inflation during the coherent oscillation period.

Can Gravitational Fluctuations Save This?

The scaling arguments essentially fix the two-point correlator in the near conformal limit and make in unobservable.

Coupling to propagating fields in a conformal symmetry breaking (large breaking) sector is necessary for preventing this generic feature of the fermion correlator.

Recall gravity sector is non-conformal, and thus far we only looked at background gravitational fields.

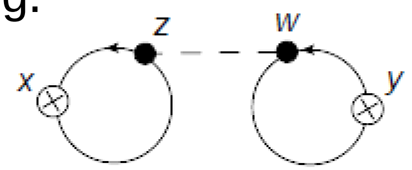
Can gravitational field fluctuations about the background break conformality sufficiently to leading order in perturbation theory?

no

Ward Identity

One can show that the gravitational coupling to the inflaton-gravitational scalar potential sector is suppressed due to diffeomorphism invariance. i.e. Ward identity

e.g.



$$a^2\zeta\delta_{ij}T_{\psi}^{ij} \in \mathcal{H}_{int}$$

$$I_{\zeta\psi\psi}(x,y) \approx (i)^2\langle\zeta_{\{z_0}\zeta_{w_0\}}\rangle\left[\int_{t_r}^{t} dt_z \int d^3z\, a^3(t_z)\langle[\bar\psi\psi_x, T_{\psi\,i}^{\,i}(z)]\rangle\right]$$
$$\times\left[\int_{t_r}^{t} dt_w \int d^3w\, a^3(t_w)\langle[\bar\psi\psi_y, T_{\psi\,i}^{\,i}(w)]\rangle\right] + O\left(\frac{a^2(t_r)}{a^2(t)}\right)$$

$\lambda\int(dz)T_{\psi\,i}^{\,i}$ generates $x^i \to (1+\lambda)x^i$

$\int_{-\infty}^{t} dt_z \int d^3z\, a^3(t_z)\langle[\bar\psi\psi_x, T_{\psi\,i}^{\,i}(z)]\rangle = 0$ $\quad$ $\bar\psi\psi$ is a diffeomorphism scalar

For the tensor perturbations, estimates indicate a similar suppression.

Minimal Feature Necessary

Coupling to a conformal symmetry breaking (large breaking) sector different from gravity is necessary for preventing this generic feature of the fermion correlator.

renormalizable operator choices to couple fermions to conformal symmetry breaking sector:

1) couple fermions to scalars through Yukawa coupling (simplest → this talk)
2) couple fermions to spontaneously broken gauge theories

Yukawa coupling to inflaton directly makes fermions heavy and decouple for large field inflation. [particularly relevant in light of BICEP2 result]

Introduce a second scalar sector coupled to only the fermions: e.g. second scalar and fermions are in a hidden sector from the inflaton

Concrete Model

inflaton

$$S = \int d^4x\sqrt{g}\,\{\mathcal{L}_{inf}[g_{\mu\nu},\phi] + \mathcal{L}_{SM+CDM+\ldots}[g_{\mu\nu},\{\Psi\}] + \mathcal{L}_{RH}[g_{\mu\nu},\phi,\{\Psi\}]$$

$$-\frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - \frac{1}{2}m_{\sigma^2}\sigma^2 + \mathcal{L}_{in}[g_{\mu\nu},\sigma,\{h\}] + \bar{\psi}(i\gamma^a\nabla_{e_a} - m_\psi)\psi - \lambda\sigma\bar{\psi}\psi\Big\}$$

second scalar

fermions are stable through a U(1): $\boxed{\text{dark matter}}$

DM fermions
fluctuating
during inflation

Concrete Model

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fermions are stable through a U(1): $\boxed{\text{dark matter}}$

parameters can be chosen to make the computation simple:

long-range force (including screening effects) consistent with other constraints:

$$\boxed{m_\sigma < m_\psi} \xrightarrow[\text{gravitational particle prod}]{} \boxed{m_\sigma < H(t_*) < H_{inf}}$$

since $H(t_*) \approx m_\psi$

detach results from inflationary details: $\boxed{m_\psi < H_e}$

choose λ and y

suppress $\sigma\sigma \to \bar{\psi}\psi$ compared to $H \to \bar{\psi}\psi$

$\sigma + \text{gravity} \to \bar{\psi}\psi$

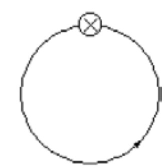
$$\boxed{\lambda^\kappa \frac{H_e/(2\pi)}{m_\psi} \lesssim 1}$$

Composite Operator Renormalization in Curved Spacetime

$\langle(\bar{\psi}\psi)_{x,r}(\bar{\psi}\psi)_{y,r}\rangle$ density correlator

$$(\bar{\psi}\psi)_{x,r} = (\bar{\psi}_x)_r(\psi_x)_r(1+\delta Z_1) + \delta Z_2(\sigma_{x,r})^3 + \delta Z_3(\sigma_{x,r})^2$$
$$+\delta Z_4\sigma_{x,r} + \delta Z_5 + \delta Z_6\Box\sigma_{x,r} + \delta Z_7 R + \delta Z_8 R\sigma_{x,r}$$

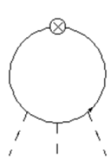
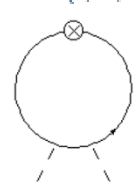
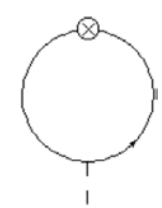
$$\psi \to \psi + \sum_n \psi_n, \qquad \sigma \to \sigma + \sum_n \sigma_n$$ Pauli-Villars fields implicit

δZ_5 flat space has no real particles δZ_5 +  = 0

$\delta Z_2, \delta Z_3, \delta Z_4$ $\sigma \to \sigma + c$ = shift in the fermion mass

$$\bar{\psi}(i\gamma^a\nabla_{e_a} - m_\psi)\psi - \lambda\sigma\bar{\psi}\psi$$

$$\langle vac|(\bar{\psi}\psi)_{x,r}|vac\rangle_{flat} = \langle vac|\left[(\bar{\psi}\psi)_{x,r} + \Delta(\bar{\psi}\psi)_{x,r}\right]|vac\rangle_{flat,\mathcal{L}_I=-\lambda c\bar{\psi}_y\psi_y}$$

δZ_2 +  = 0 δZ_3 +  = 0 δZ_4 +  = 0

Composite Operator Renormalization in Curved Spacetime

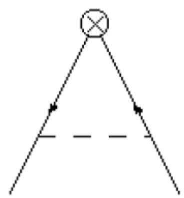
$$\langle (\bar{\psi}\psi)_{x,r} (\bar{\psi}\psi)_{y,r} \rangle$$

$$\begin{aligned}(\bar{\psi}\psi)_{x,r} \;=\; & (\bar{\psi}_x)_r (\psi_x)_r (1 + \delta Z_1) + \delta Z_2 (\sigma_{x,r})^3 + \delta Z_3 (\sigma_{x,r})^2 \\ & + \delta Z_4 \sigma_{x,r} + \delta Z_5 + \delta Z_6 \Box \sigma_{x,r} + \delta Z_7 R + \delta Z_8 R \sigma_{x,r}\end{aligned}$$

δZ_1 normalized to count on-shell particles in flat space

$\vec{p}_{comp} = 0$

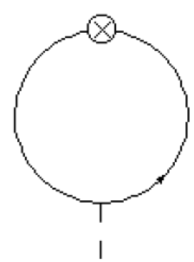
δZ_1 +



= 0

δZ_6 no tadpole for on-shell scalar

$\delta Z_4 - p^2 \delta Z_6$ +



= 0

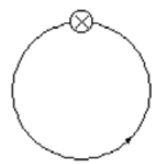
Composite Operator Renormalization in Curved Spacetime

$$\langle(\bar\psi\psi)_{x,r}(\bar\psi\psi)_{y,r}\rangle$$

$$\begin{aligned}(\bar\psi\psi)_{x,r} &= (\bar\psi_x)_r(\psi_x)_r(1+\delta Z_1)+\delta Z_2(\sigma_{x,r})^3+\delta Z_3(\sigma_{x,r})^2\\ &\quad +\delta Z_4\sigma_{x,r}+\delta Z_5+\delta Z_6\Box\sigma_{x,r}+\delta Z_7 R+\delta Z_8 R\sigma_{x,r}\end{aligned}$$

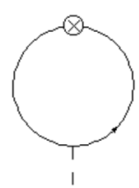
δZ_7 adiabatic prescription for particle production in curved spacetime

$$\begin{aligned}n_\psi &\equiv \langle in|\bar\psi\psi(x)|in\rangle+\sum_{n=1}\langle in|\bar\psi_n\psi(x)_n|in\rangle+\delta Z_5+\delta Z_7 R(x)\\ &= \langle in|\bar\psi\psi(x)|in\rangle-\langle WKB,vac,t_x|\bar\psi\psi(x)|WKB,vac,t_x\rangle\end{aligned}$$

δZ_5 + $\delta Z_7 R(x)$ +  = finite related to particle production

δZ_8 $\sigma(x)=c$ is equivalent to a shift in fermion mass; Taylor expand

$$\begin{aligned}\lambda\partial_m n_\psi(x) &= -i\lambda\int_{CTP}(dy)\sum_{N,M}\langle in|P\{\bar\psi_M(x)\psi_N(x)\bar\psi_N(y)\psi_M(y)\}|in\rangle_{conn}\\ &\quad +\delta Z_4+\delta Z_8 R(x),\end{aligned}$$

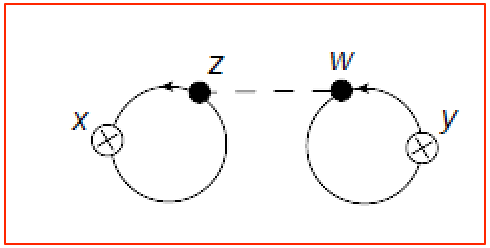
$\delta Z_4+\delta Z_8 R(x)$ +  = finite related to particle production

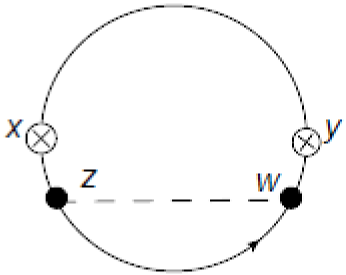
Yukawa Induced Two-Point Function

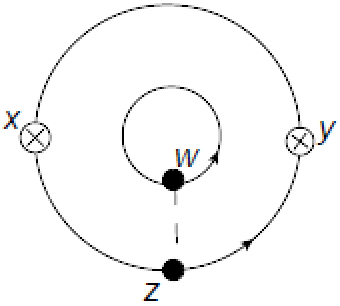
$$\langle (\bar{\psi}\psi)_{x,r} (\bar{\psi}\psi)_{y,r} \rangle$$

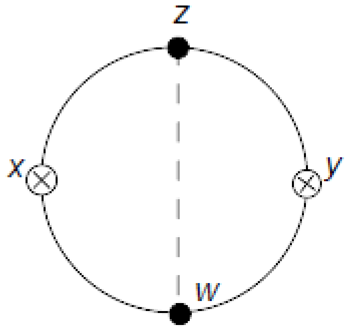
$$(\bar{\psi}\psi)_{x,r} = (\bar{\psi}_x)_r (\psi_x)_r (1 + \delta Z_1) + \delta Z_2 (\sigma_{x,r})^3 + \delta Z_3 (\sigma_{x,r})^2$$
$$+ \delta Z_4 \sigma_{x,r} + \delta Z_5 + \delta Z_6 \Box \sigma_{x,r} + \delta Z_7 R + \delta Z_8 R \sigma_{x,r}$$

dominates









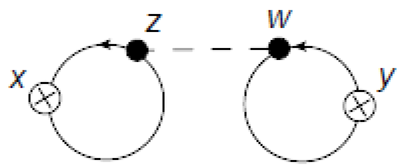
Isocurvature 2-point function

$$\delta_S^{(C)} \approx \omega_\psi \frac{\rho_\psi - \langle \rho_\psi \rangle}{\langle \rho_\psi \rangle} = \omega_\psi \frac{\bar{\psi}\psi - \langle \bar{\psi}\psi \rangle}{\langle \bar{\psi}\psi \rangle}$$

$$\boxed{\langle (\delta_S)_{r,x} (\delta_S)_{r,y} \rangle_{NLO} \approx \omega_\psi^2 \lambda^2 [\partial_m \ln n_\psi|_x][\partial_m \ln n_\psi|_y] \langle \sigma_{\{(\vec{x},t_*)} \sigma_{(\vec{y},t_*)\}} \rangle}$$

intuition: light scalar's quantum fluctuation modulate the fermion mass

renormalization condition of shift in fermion mass is important



$$\boxed{\Delta_{\delta_S}^2(k) \approx \omega_\psi^2 \lambda^2 \left(\frac{\partial_m n_\psi(m_\psi)}{n_\psi} \right)^2 \frac{H^2(t_k)}{4\pi^2}}$$

$$H(t_k) = H(t_1) \left(\frac{k}{a(t_1)H(t_1)} \right)^{-\epsilon}$$

$$\omega_\psi \equiv \bar{\rho}_\psi / \left(\bar{\rho}_\psi + \bar{\rho}_m \right)$$

Isocurvature-curvature cross correlation

Similar story as the zeta-mediation being weak:

diffeo Ward identity: $x^i \to (1+\lambda)x^i$

$$\int_{-\infty}^{t} dt_z \int d^3z\, a^3(t_z)\langle[\bar\psi\psi_x, T_{\psi}{}^{i}{}_{i}(z)]\rangle = 0$$

$$\boxed{\left\langle \zeta_x \left(\bar\psi\psi\right)_y \right\rangle \sim O\left(\frac{a^2(t_r)}{a^2(t)}\right)}$$

i.e. uncorrelated type

Isocurvature 2-pt Comparison

	$\Delta^2_{\delta_S}$	$\Omega_X h^2 (\propto \omega_X^2)$
tunable diff from axions fermion (in the computationally simple regime) $m_\psi > \lambda H_{\rm inf}/2\pi$ [1306.1966]	$\omega_\psi^2 \frac{\lambda^2 H^2(t_1)}{4\pi^2 m_\psi^2} \left(\frac{k}{a(t_1)H(t_1)}\right)^{-2\epsilon}$	$\left(\frac{m_\psi}{10^{11}\mathrm{GeV}}\right)^2 \left(\frac{T_{RH}}{10^9\mathrm{GeV}}\right)$
axion [e.g. ph/0606107]	$\omega_a^2 \frac{H^2(t_1)}{\pi^2 f_a^2 \langle\theta^2_{QCD}\rangle} \left(\frac{k}{a(t_1)H(t_1)}\right)^{-2\epsilon}$	$7.24\, g_{*,1}^{-5/12} \langle\Theta^2_{\rm QCD}\rangle \left(\frac{200\mathrm{MeV}}{\Lambda_{\rm QCD}}\right)^{\frac{3}{4}} \left(\frac{1\mu\mathrm{eV}}{m_a}\right)^{\frac{7}{6}}$

axions are initial condition sensitive

Fermions have different parametric relationship between $\Delta^2_{\delta_S}$ and $\Omega_X h^2 (\propto \omega_X^2)$

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tunable diff from axions

axions are initial condition sensitive

Fermions have different parametric relationship between $\Delta^2_{\delta_S}$ and $\Omega_X h^2 (\propto \omega_X^2)$

In the case of axion, isocurvature bound + all relic abundance from axion + PQ broken during inflation + no symmetry restoration:

$$H(t_1) \lesssim \begin{cases} 10^7 \text{ GeV} \left(\frac{f}{10^{11} \text{ GeV}}\right)^{0.4} & f \lesssim 10^{17} \text{ GeV} \\ 10^8 \text{ GeV} \left(\frac{f}{10^{11} \text{ GeV}}\right)^{1/4} & f \gtrsim 10^{17} \text{ GeV} \end{cases}$$

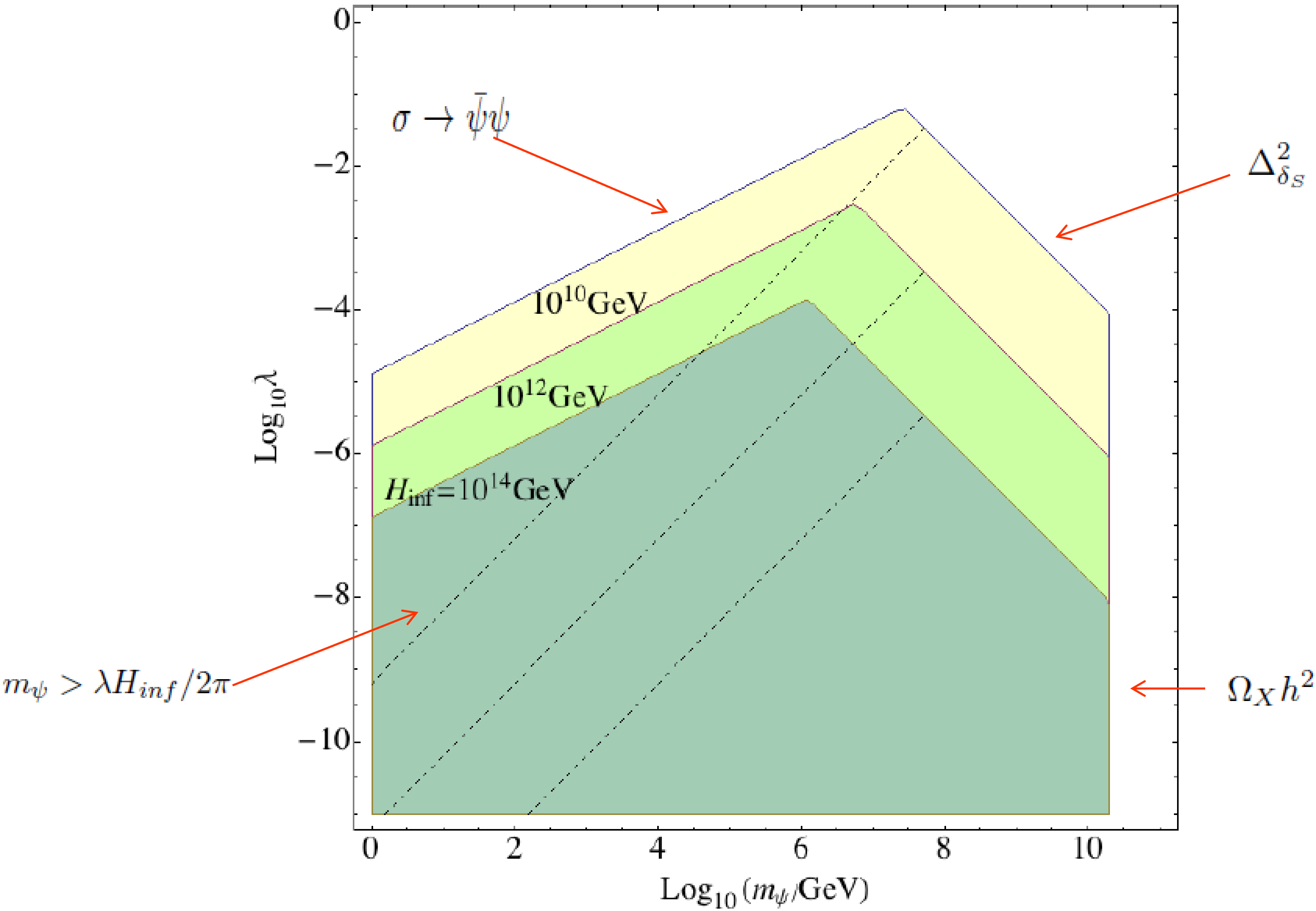
[e.g. 1303.5082, 1403.4594]

BICEP 2 (in slow-roll inflation): $H(t_1) = 6 \times 10^{14}$ GeV

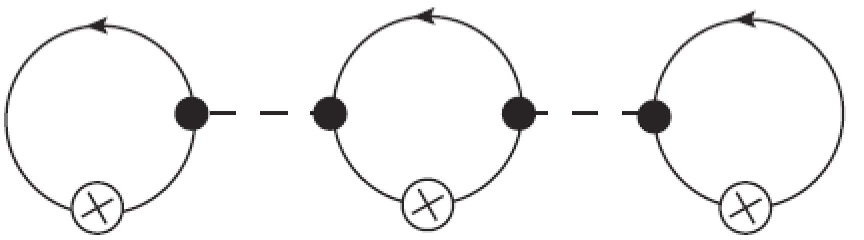
$\longrightarrow$ $f \gg M_{pl}$ minimal axions of this type looks bad [e.g. 1403.4186, 1403.4594]

Allowed Parameter Region

$T_{RH} = 10^9 GeV$



3-Point Function



$$\boxed{B_S(\vec{p}_1,\vec{p}_2,\vec{p}_3) \;=\; \lambda^4\omega_\psi^3\frac{(\partial_m n_\psi)^2\,(\partial_m^2 n_\psi)}{n_\psi^3}\left[\Delta_\sigma^2(p_1)\Delta_\sigma^2(p_2)+2\text{ perms}\right]}$$

non-gaussianities are similar to the local type

$$f_{NL}^S \sim a_1\left(\frac{\alpha_S(\lambda,m_\psi,H_e,T_{RH})}{0.02}\right)^2\left(\frac{\Omega_\psi h^2(m_\psi,T_{RH})}{10^{-7}}\right)^{-1}\left(\frac{m_\psi/H_e}{10^{-1}}\right)$$

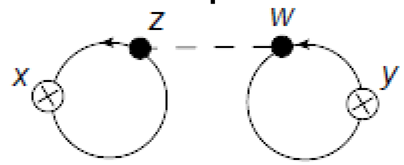
Can be observationally large in a corner of the parameter space.

Intuition for making it large: make inhomogeneity large but suppress gravitational disturbance by making the energy density small.

Summary

- A “minimal” setup for observable fermion fluctuations during inflation:
  - coupling to a non-conformal sector different from the inflaton and graviton (Ward identity plays a role in establishing this)
  - fermions are stable

- For a Yukawa coupling to a scalar mediating long range forces:
  - the isocurvature spectral shape is similar to that of the axion



  - the dark matter abundance – isocurvature spectral phenomenology is different from that of the axion
  - isocurvature – curvature cross correlation is small (Ward identity)

- Large non-Gaussianities are possible and are of the local type