May 28th, 2025

Chern-Simons interaction with a non-canonical axion
-paving the way for polarized tensor modes from inflation-

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UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

RESCEU

Jun'ya Kume (University of Padova)

Collaborators: Marco Peloso, Nicola Bartolo

Based on: arXiv:2501.02890 [astro-ph.CO]

Outline

- Inflationary phenomenology with Chern-Simons term
- Production of U(1) gauge field and sourced perturbations
- Non-canonical case: suppression of scalar mode
- Summary & Discussion

- **inflation**: accelerating expansion before Hot Big-Bang (Starobinsky, Guth, Sato, ...)

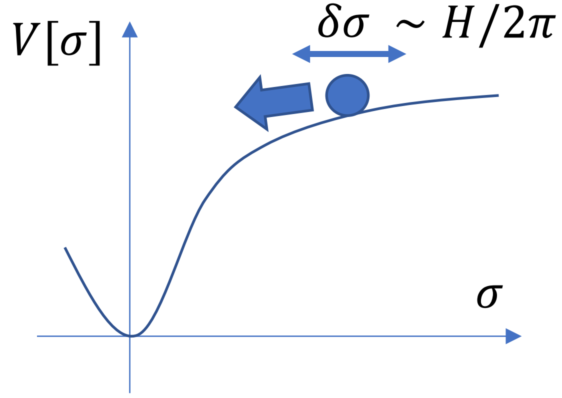
  solves classical problems in Big-Bang cosmology

  → **origin of CMB fluctuation**!

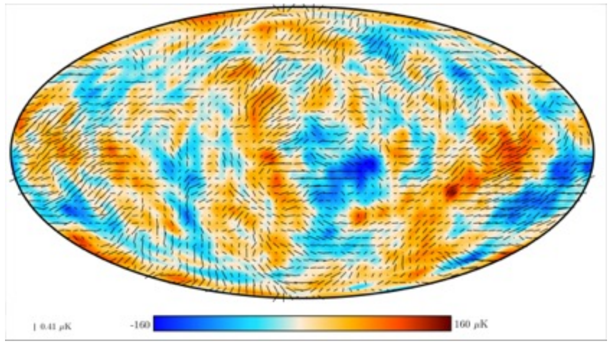
  ex.) a scalar field (inflaton) $\sigma(t,\vec{x}) = \bar{\sigma}(t) + \delta\sigma(t,\vec{x})$

  → curvature perturbation $\zeta \cong H\delta\sigma/\dot{\bar{\sigma}}$

  power spectrum & spectral index: $P_\zeta(k)$, $n_s - 1 = dlnP_\zeta/dlnk$



$\delta T/T \sim 10^{-5}$



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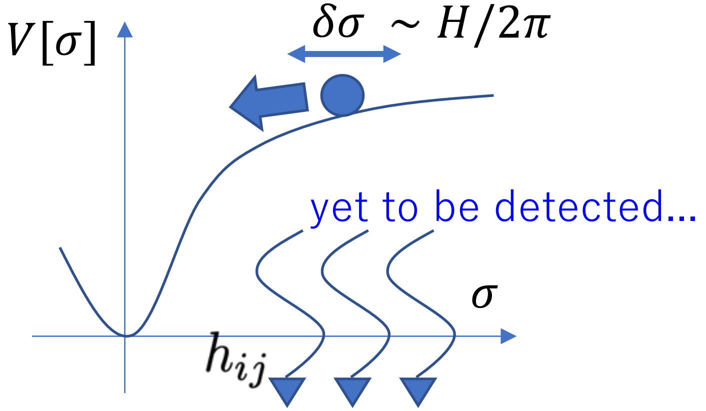


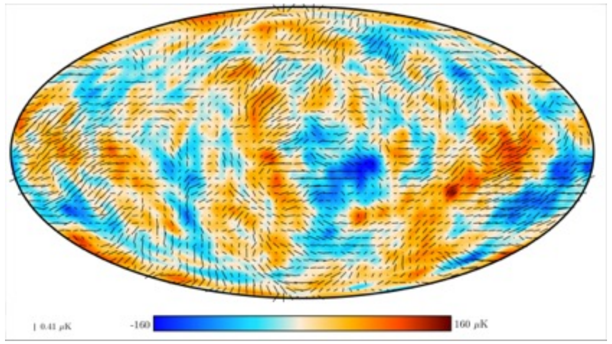
Tensor perturbation as well! → B-mode polarization

tensor-to-scalar ratio: $r \sim P_h/P_\zeta \lesssim 0.03$

vacuum fluctuation:
$P_h = (2/\pi^2)(H/M_{Pl})^2$

$H \lesssim 10^{13}$GeV…!?
not true if sourced component exists

$\delta T/T \sim 10^{-5}$



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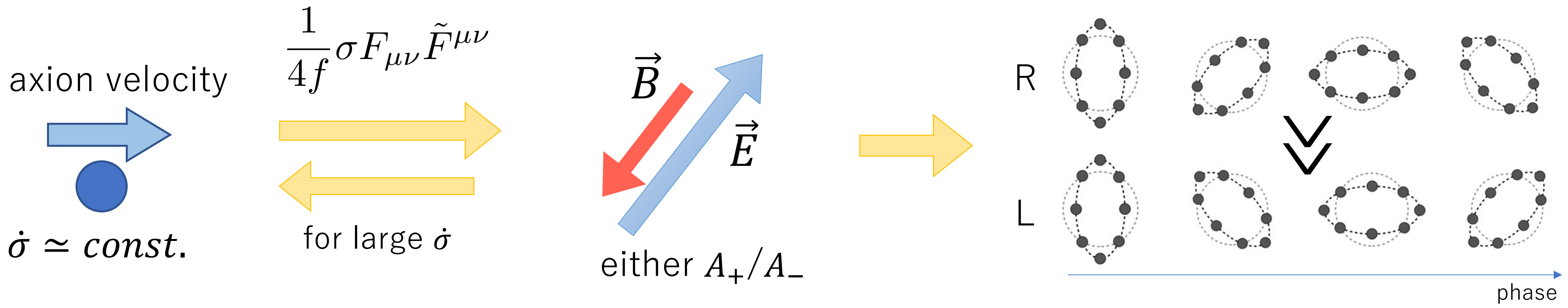
"What can we learn from the tensor signal?"

- **Polarized tensor modes** from U(1) CS term (Anber & Sorbo 2006, Sorbo 2011, …)



※fermion production: Domcke & Mukaida 2018, Gorbar+2021, Fujita, **JK**+ 2022, … also talks by Oleksandr & Richard

Circularly polarized tensor pert. → a smoking gun for identifying the inflationary model!?

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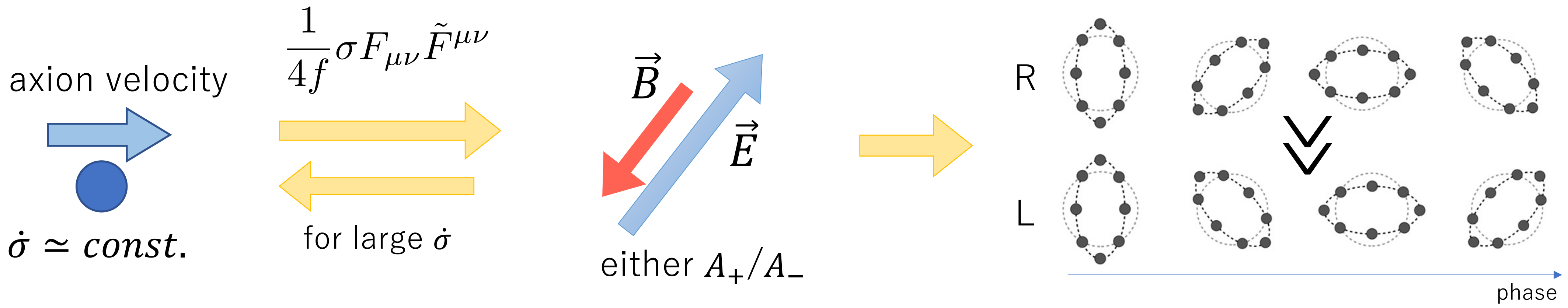

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Circularly polarized tensor pert. → a smoking gun for identifying the inflationary model!?

- also sourcing scalar mode: total tensor-to-scalar not increased…
- $A + A \rightarrow \delta\sigma$: **highly non-Gaussian** → $\dot{\sigma}$ cannot be large… (Barnaby & Peloso 2010, …)

axion as spectator: CS term → axion pert. → curvature pert. (indirect sourcing)

- CMB non-Gaussianity bound → axion can roll only a few e-folds

  (Ferreira & Sloth 2014, Namba+ 2015)

- Any other possibilities?

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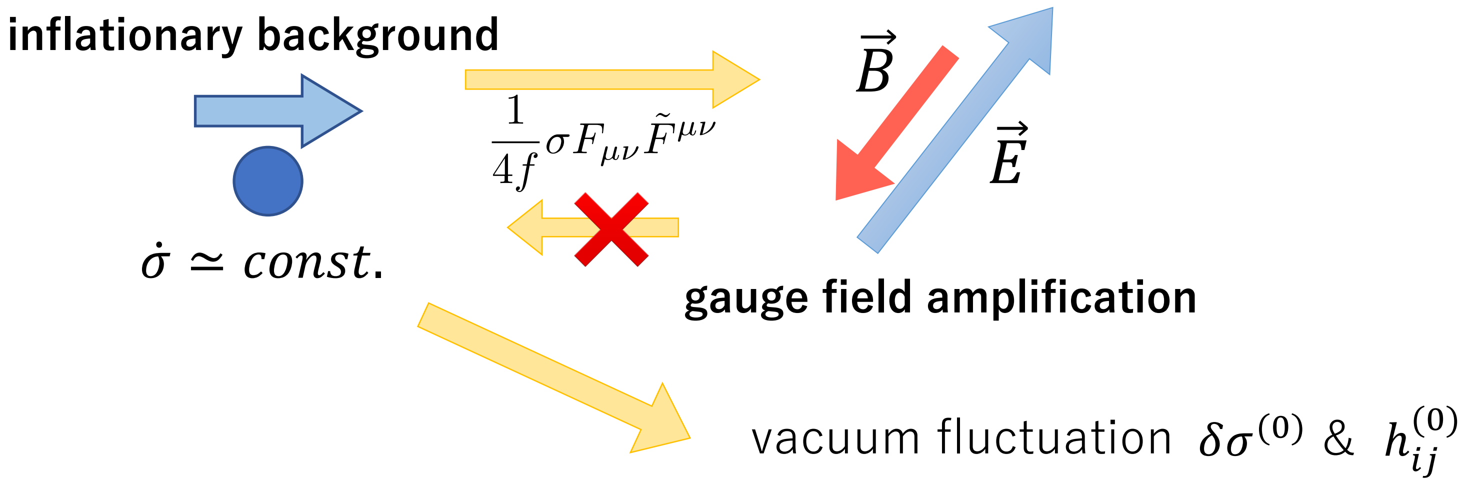
- The system & working assumption



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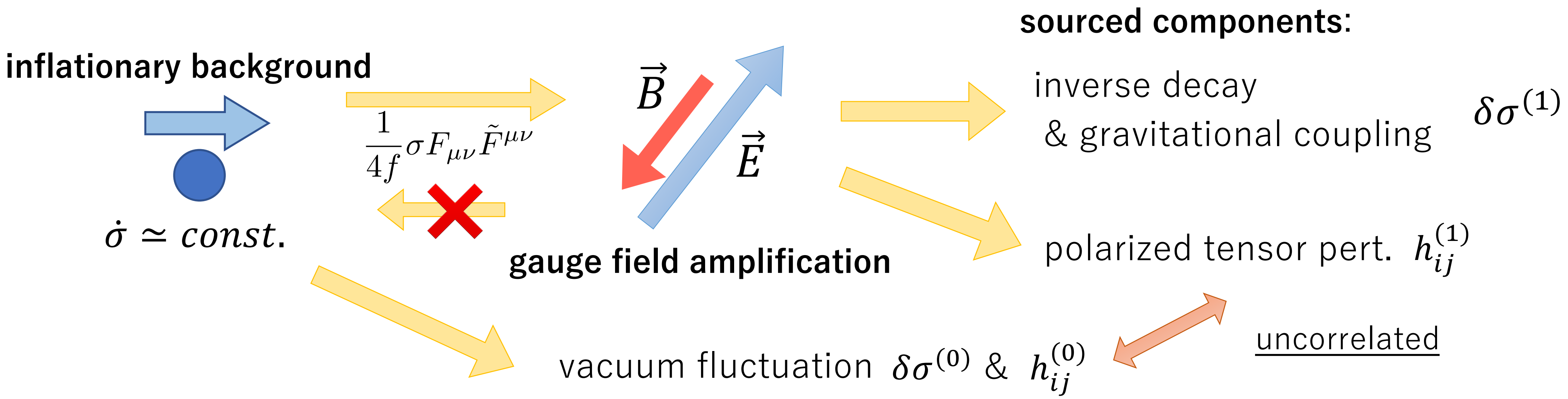

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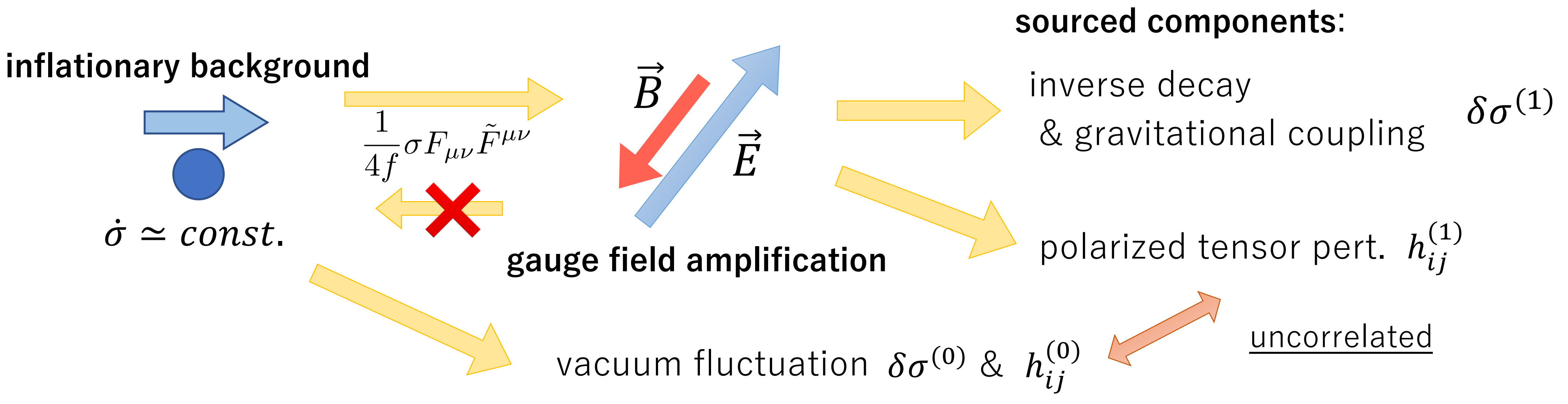


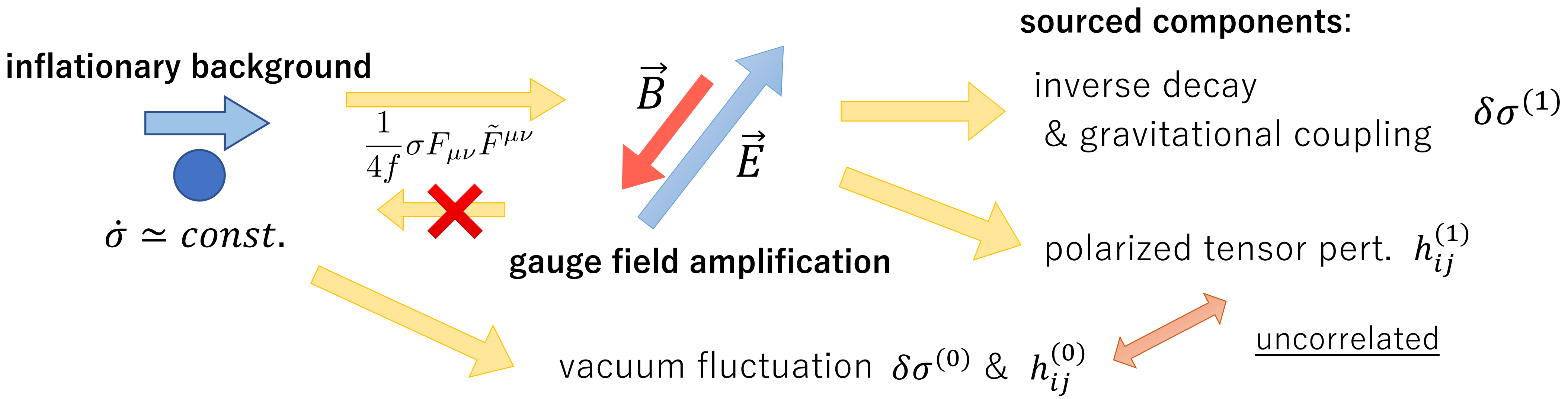
observables of our interest:

$$P_\zeta(k) = P_\zeta^{(0)}(k) + P_\zeta^{(1)}(k)$$ with vacuum pert.: $8\pi^2\epsilon_I P_\zeta^{(0)} = H^2/M_{Pl}^2$

$$f_{\rm NL} = \frac{10}{9(2\pi)^{5/2}} \frac{k^6}{P_\zeta^2} F\Big|_{|\vec{k}_1|=|\vec{k}_2|=|\vec{k}_3|=k}$$ $$\left\langle \hat{\zeta}\left(0^-, \vec{k}_1\right) \hat{\zeta}\left(0^-, \vec{k}_2\right) \hat{\zeta}\left(0^-, \vec{k}_3\right) \right\rangle \equiv \delta^{(3)}\left(\vec{k}_1 + \vec{k}_2 + \vec{k}_3\right) F\left(\vec{k}_1, \vec{k}_2, \vec{k}_3\right)$$

$$r = (P_+ + P_-)/P_\zeta$$ $P_\pm$: tensor power spectrum for +/- polarization

- The system & working assumption



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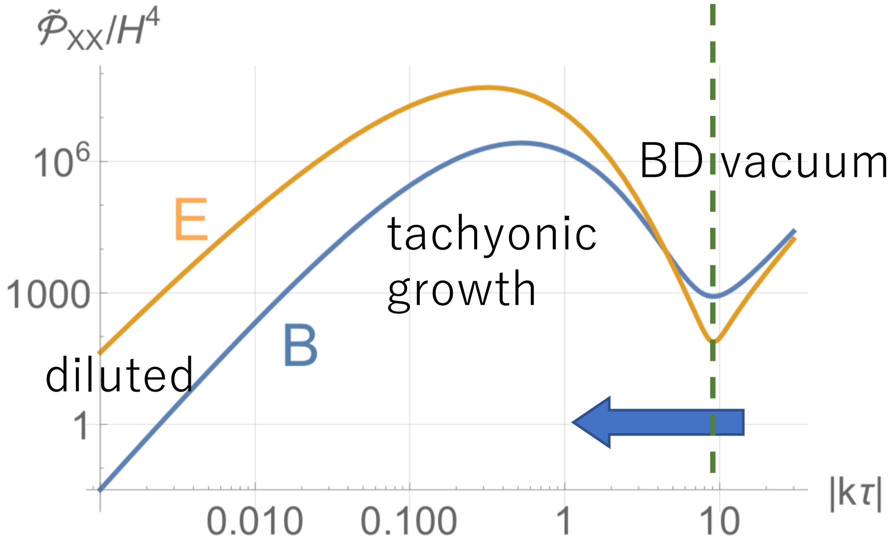
$r = (P_+ + P_-)/P_\zeta$ $\qquad$ $P_\pm$: tensor power spectrum for +/- polarization

※σ can be a spectator $\rightarrow$ $I = \{\phi, \sigma\}$, $\varphi_I = \{\phi, \sigma\}$, $\epsilon_I, \eta_I \ll 1$.

- Amplification of U(1) gauge field

$$\mathscr{L} \supset \frac{1}{4f}\sigma F_{\mu\nu}\tilde{F}^{\mu\nu} \rightarrow \underline{\text{circular pol.}}: A_+/A_-$$

dimless power spectrum: $\xi = 5$



Quantization: $\hat{A}_\lambda(\tau,\boldsymbol{k}) = \hat{a}^{(\lambda)}_{\boldsymbol{k}}\mathscr{A}_\lambda(\tau,k) + \hat{a}^{(\lambda)\dagger}_{-\boldsymbol{k}}\mathscr{A}^*_\lambda(\tau,k)$

$$\left[\partial_\tau^2 + k^2 \underline{\underline{\pm 2k\frac{\xi}{\tau}}}\right]\mathscr{A}_\pm(\tau,k) = 0 \quad \text{with} \quad \xi \equiv \frac{\dot{\sigma}}{2fH}$$

Only $\underline{+\text{ mode}}$ experiences **<u>exponential growth</u>**! ($\xi \lesssim 5$ for negligible backreaction)

Imposing Bunch-Davies condition:

$$\mathscr{A}_+(\tau,k) = \frac{1}{\sqrt{2k}}e^{\pi\xi/2}W_{-i\xi,1/2}(2ik\tau) \cong \frac{1}{\sqrt{2k}}\left(\frac{k}{2\xi aH}\right)^{1/4} e^{\pi\xi - 2\sqrt{2\xi k/(aH)}}$$

← around the peak

Electromagnetic variables: $\hat{E}_i \equiv -\frac{1}{a^2}\hat{A}'_i \;,\; \hat{B}_i \equiv \frac{1}{a^2}\epsilon_{ijk}\partial_j\hat{A}_k$

- Sourced perturbation

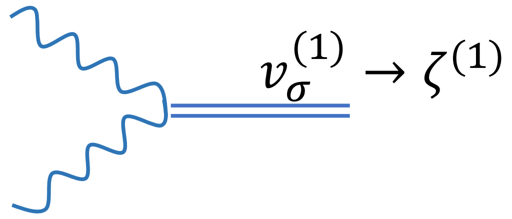
direct coupling — **inverse decay**

$$\Delta\mathcal{S}_{sAA} = \frac{1}{2}\int d\tau d^3k\left[-\frac{\dot{\varphi}_I}{2M_p^2 H}\frac{1}{a}\left(\underline{\underline{a^4 Q_1 - \frac{ik_k}{k^2}(a^4 Q_{2,k})'}}\right)v_I^\dagger + \underline{\underline{a^3\frac{Q_3}{f}}}v_\sigma^\dagger + \mathrm{h.c.}\right]$$

v_I: canonical variables
$I = \{\phi, \sigma\}$

with $Q_1(x) \equiv \frac{1}{2}\left(\hat{E}_i\hat{E}_i + \hat{B}_i\hat{B}_i\right)$ $Q_{2,k}(x) \equiv \epsilon_{ijk}\hat{E}_i\hat{B}_j \ll Q_3(x) \equiv \hat{E}_i\hat{B}_i$

- single field case: $\{I, \varphi_I\} \to \sigma$



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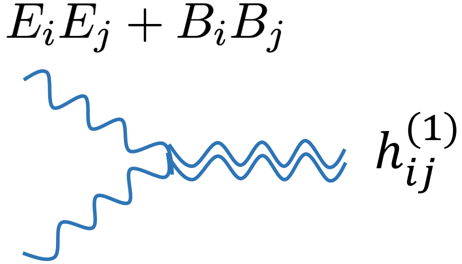
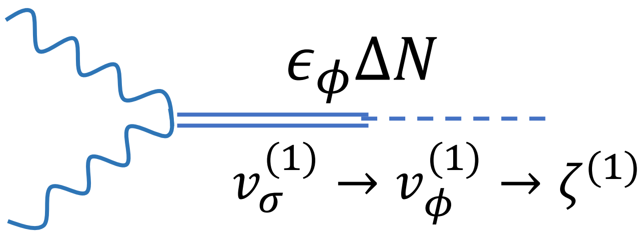


- two-field case:

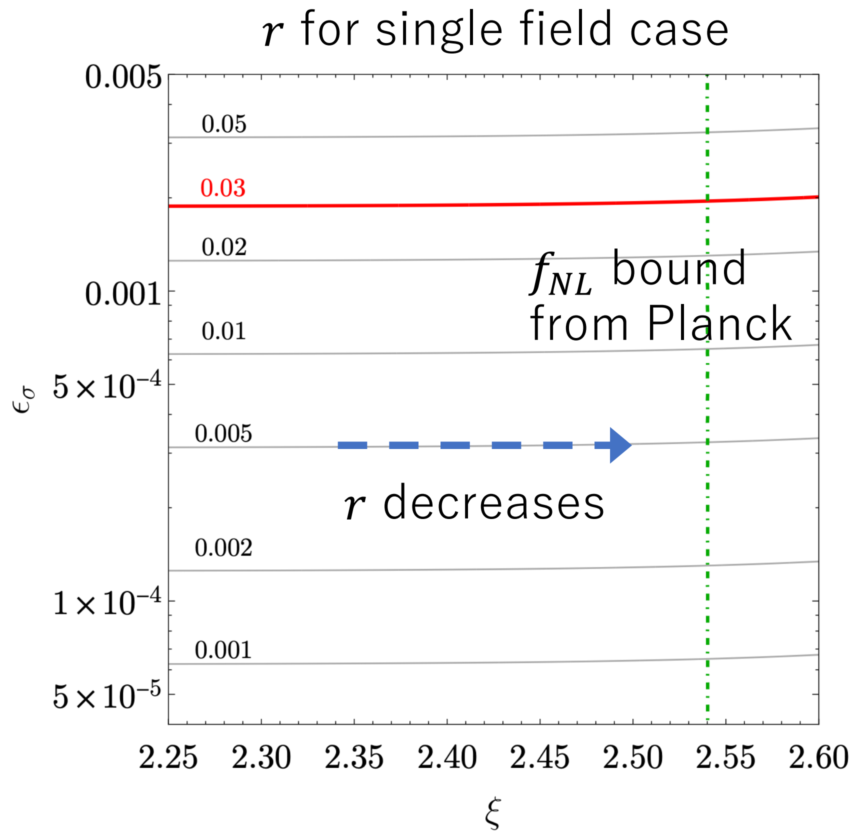


σ decays $\Delta N \lesssim 5$ e-folds

after the CMB mode crossing

$\to$ visible sourced tensor

(Ferreira & Sloth 2014, Namba+ 2015)



Outline

- ➢Axion inflation with Chern-Simons term
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- Non-canonical scalar and perturbation

$$\mathcal{L} = K_\phi(X) - V(\hat{\phi}) \qquad X \equiv -\frac{1}{2} g^{\mu\nu}\partial_\mu\hat{\phi}\partial_\nu\hat{\phi}$$

Scalar field (b.g. & pert.) acquires large inertia:

$$\underline{\left(K_{\phi,1} + \dot{\phi}^2 K_{\phi,2}\right)} \ddot{\phi} + 3K_{\phi,1}\frac{\dot{a}}{a}\dot{\phi} + \frac{\partial V}{\partial \phi} = 0 \qquad K_{\phi,n} \equiv (\partial/\partial X)^n K_\phi$$

・examples, but not for a pseudo-scalar...

k-inflation:

Armendariz-Picon 1999, Garriga & Mukhanov 1999

DBI-model: Silverstein & Tong 2003, Alishahiha+ 2004

$$\boxed{\textbf{sound speed}:\ c_{s,I}^2 \equiv \frac{K_{I,1}}{K_{I,1} + \dot{\varphi}_I^2 K_{I,2}}}$$

⇒ parametrical changes $\hat{\zeta} \simeq \dfrac{c_{s,I} H\tau}{\sqrt{2\epsilon_I} M_{\rm Pl}} v_I$

・power spectrum

$$\mathcal{P}_\zeta^{(0)} = \frac{H^2}{8\pi^2 c_{s,I}\epsilon_I M_{\rm Pl}^2} \rightarrow r = 16\epsilon_I c_{s,I}$$

・non-Gaussianity

$$f_{\rm NL} = \frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle^2} \propto \frac{1}{c_s^2}$$

→ CMB bound on single field EFT: $c_s < 0.02$

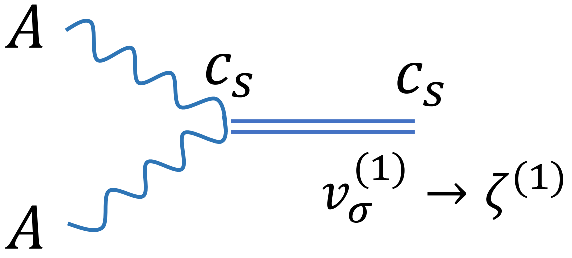
※standard scenario recovered by taking $c_s \rightarrow 1$

※smaller c_s ↔ larger inertia → persistence of the vacuum mode, enhancing the non-linearity(?)

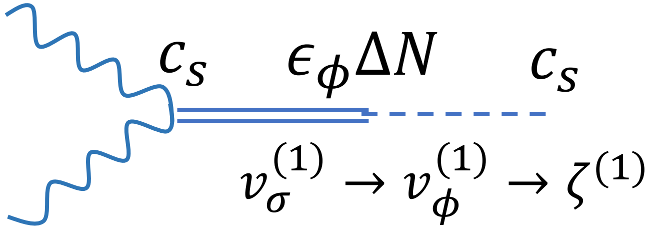
- Suppressing the interaction with gauge field

$$\hat{\zeta} \simeq \frac{c_{s,I} H\tau}{\sqrt{2\epsilon_I} M_{\rm Pl}} v_I \quad \& \quad \frac{1}{2}\int d\tau d^3k \left[-\frac{\sqrt{K_{I,1}}\dot{\varphi}_I}{2M_p^2 H}\frac{1}{a c_{s,I}}\left(c_{s,I}^2 a^4 Q_1 - \frac{i k_k}{k^2}(a^4 Q_{2,k})' \right) v_I^\dagger + \underline{\underline{\frac{c_{s,\sigma}}{\sqrt{K_{\sigma,1}}} a^3 \frac{Q_3}{f} v_\sigma^\dagger}} + \text{h.c.} \right]$$

parametric dependence:



or



single field case: $$\hat{\zeta}^{(1)}\left(0^-, \vec{k}\right) \simeq \frac{H^2}{M_p^2}\int_{-\infty}^{0^-} d\tau' \, k \left(-\frac{k^3 \tau'^3}{3} \right) \left[\underbrace{\frac{1}{2} J_{1,2}\left(\tau', \vec{k}\right)}_{\sim Q_1 + Q_2} - \underbrace{\underline{\underline{\frac{c_{s,\sigma}^2 \xi}{\epsilon_\sigma}}} J_3\left(\tau', \vec{k}\right)}_{\sim Q_3} \right]$$

※Q_2 not suppressed by c_s → must be included for smaller c_s

- Suppressing the interaction with gauge field

$$\hat{\zeta} \simeq \frac{c_{s,I} H \tau}{\sqrt{2\epsilon_I} M_{\rm Pl}} v_I \quad \& \quad \frac{1}{2}\int d\tau d^3k \left[-\frac{\sqrt{K_{I,1}}\dot{\varphi}_I}{2M_p^2 H}\frac{1}{a c_{s,I}}\left(c_{s,I}^2 a^4 Q_1 - \frac{i k_k}{k^2}(a^4 Q_{2,k})' \right) v_I^\dagger + \frac{c_{s,\sigma}}{\sqrt{K_{\sigma,1}}} a^3 \frac{Q_3}{f} v_\sigma^\dagger + \text{h.c.} \right]$$

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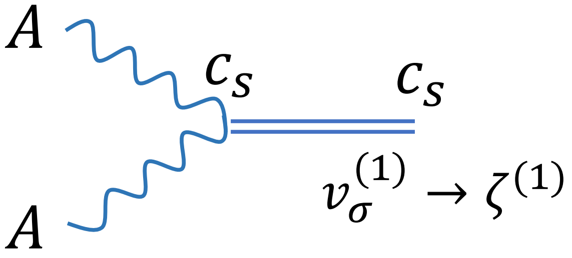

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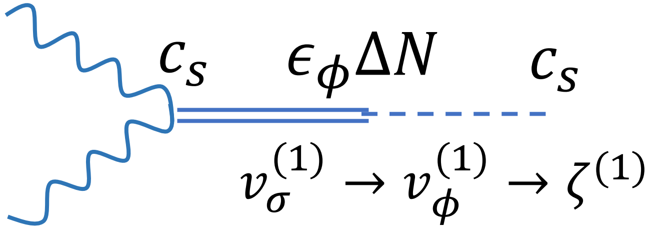

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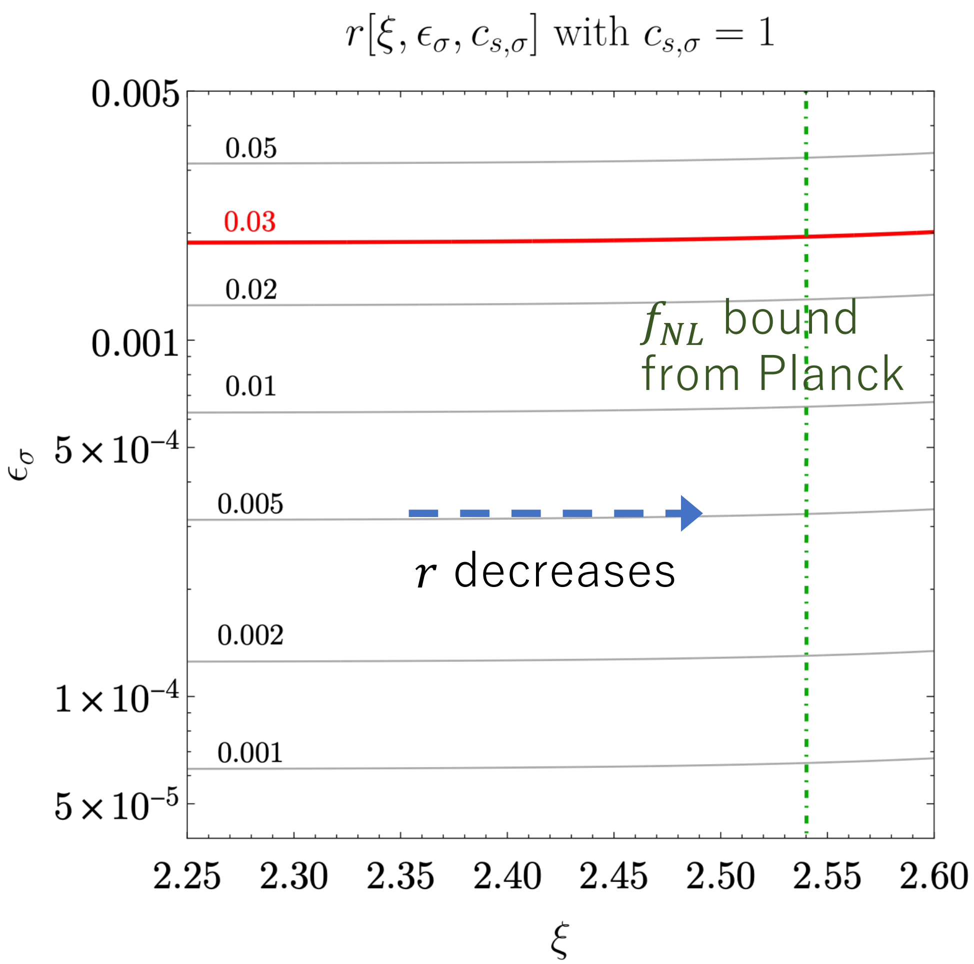
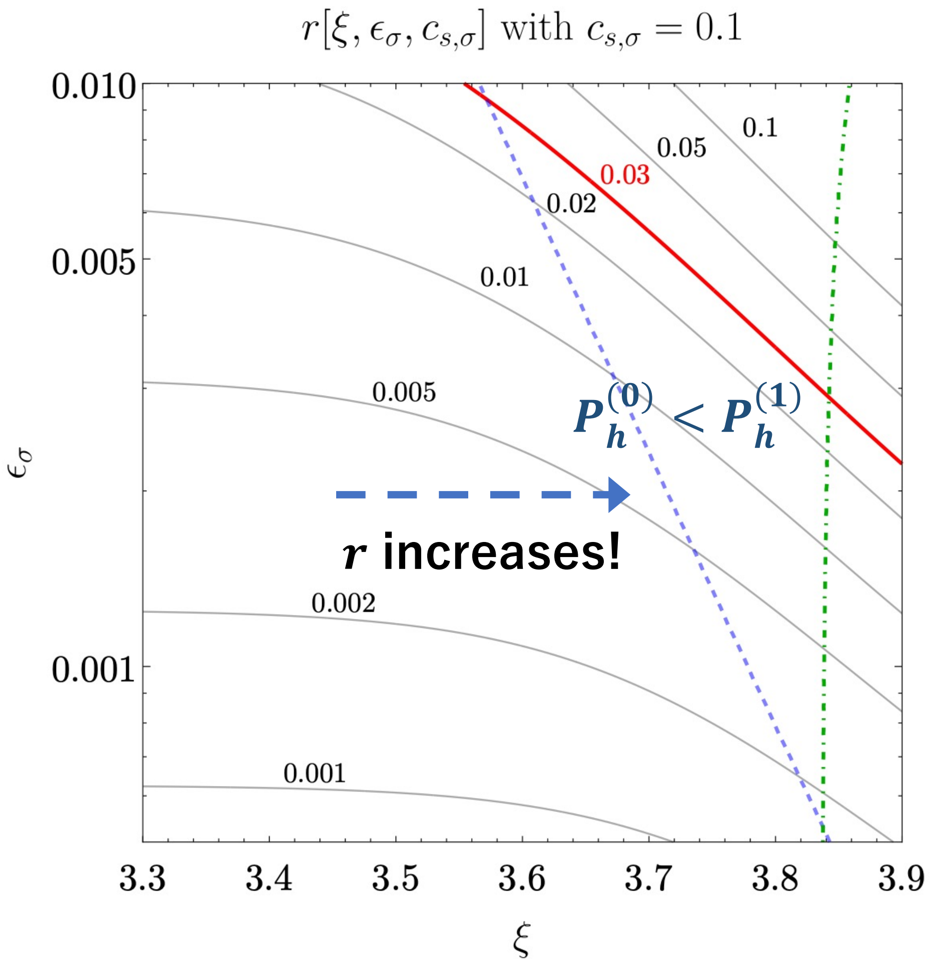
※Q_2 not suppressed by c_s → must be included for smaller c_s

From the standard case, we get the suppression as $P_\zeta^{(1)} \propto c_s^4$ and $f_{NL} \propto c_s^6$!!

※※ Tensor sector not modified!

- Single field case (σ: inflaton)





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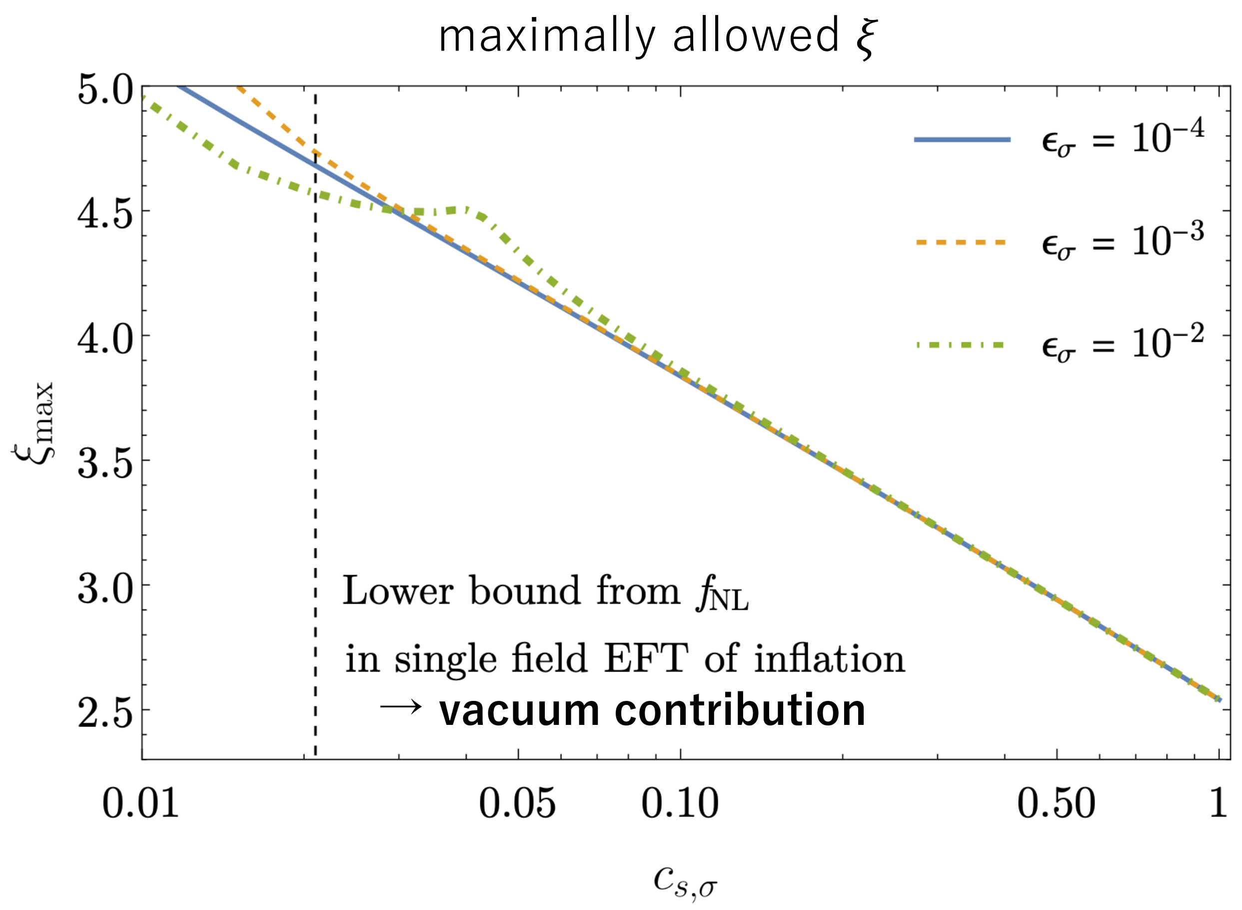
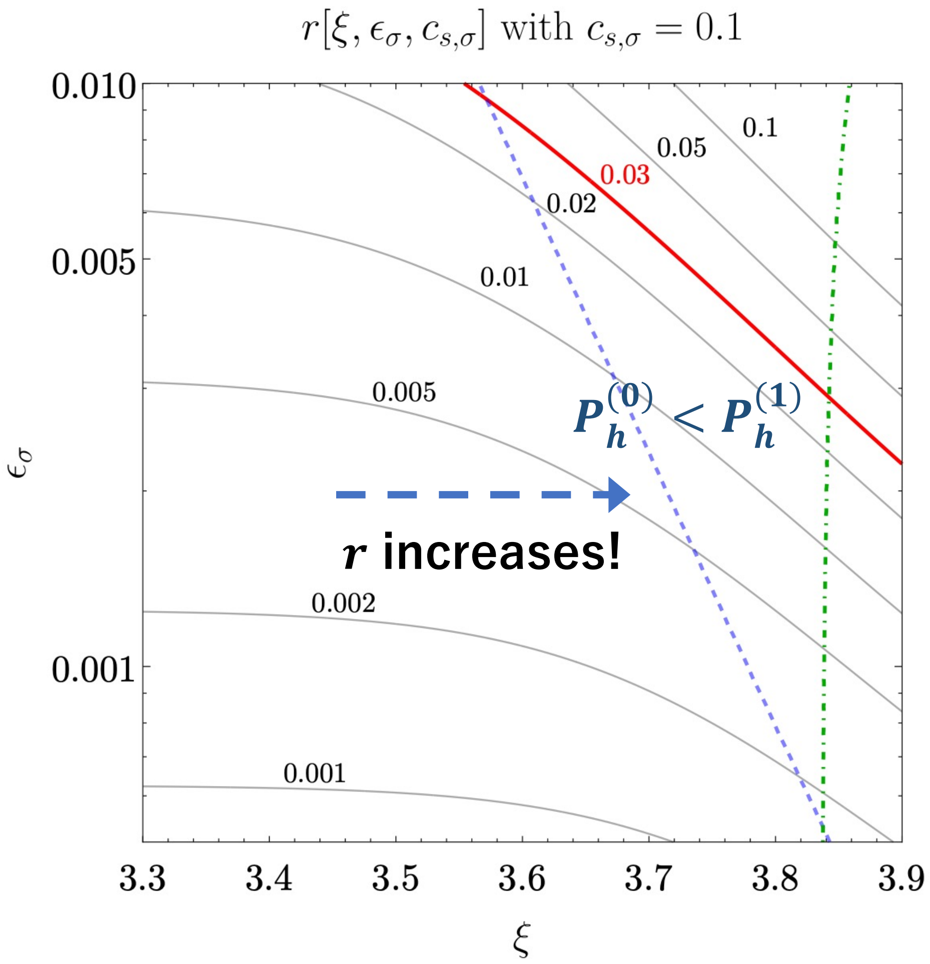
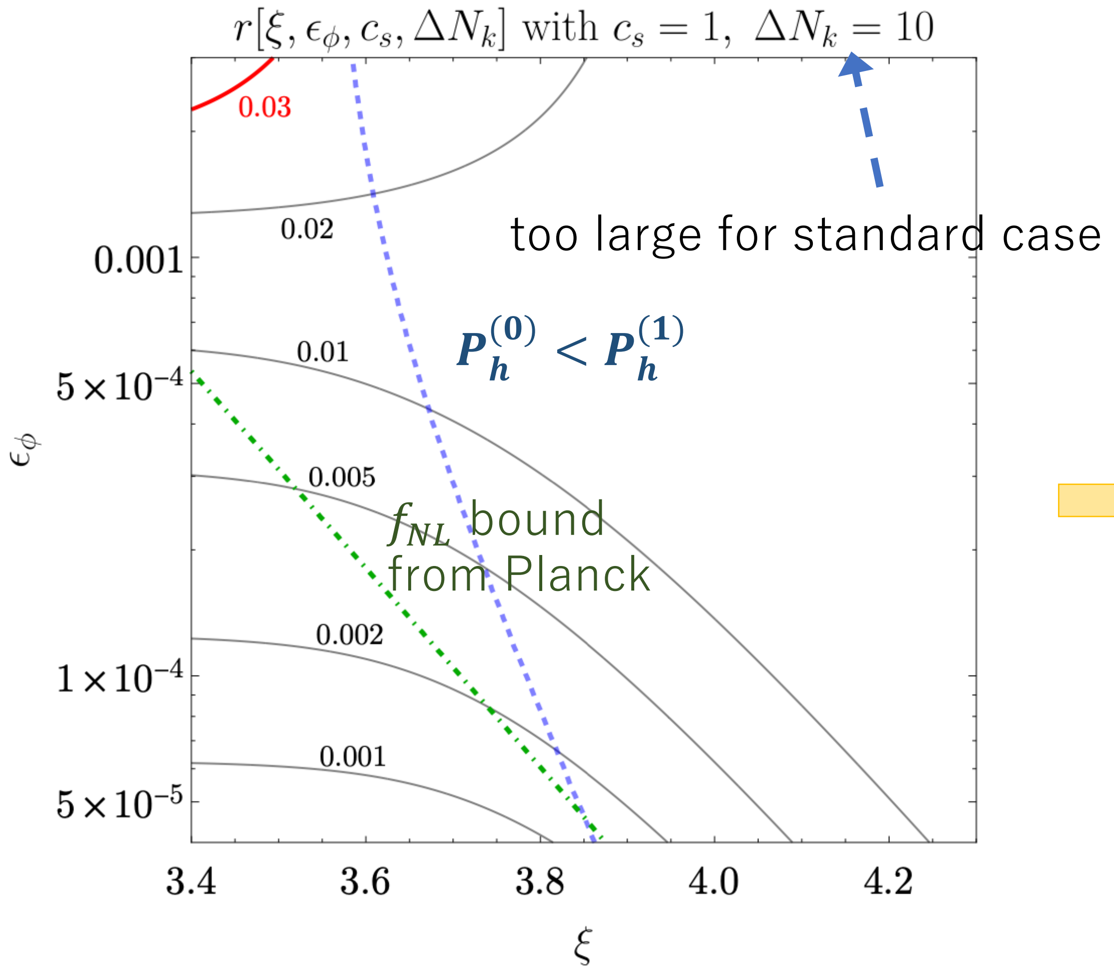
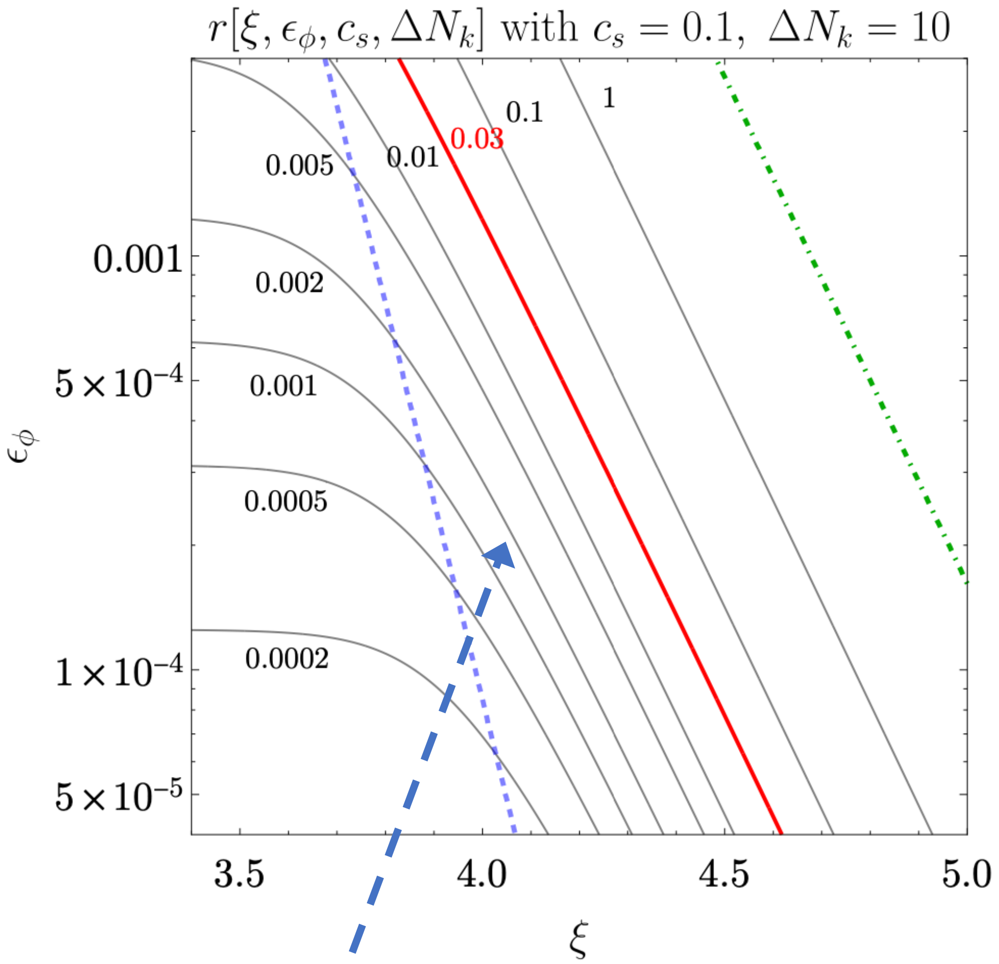




exponential dependence on ξ → sourcing effect can be significantly large!

- two-field case (ϕ: inflaton, σ: spectator)





The new window exists even for $\Delta N \sim 50 - 60$!!

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Summary & Discussion

✓axion inflation + U(1) CS term → polarized tensor perturbation?

i)strong f_{NL} bound and ii)decreasing total r...

✓Extension: non-canonical kinetic term for axion (and inflaton)

→ Inverse decay contribution is suppressed by c_s!

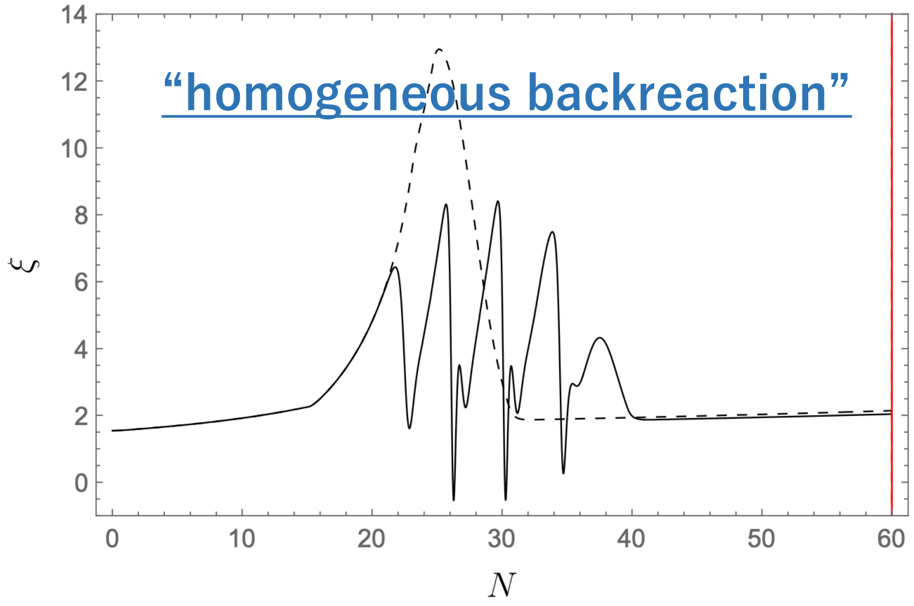
→ <u>Sourced tensor becomes dominant</u> while satisfying f_{NL} bound.

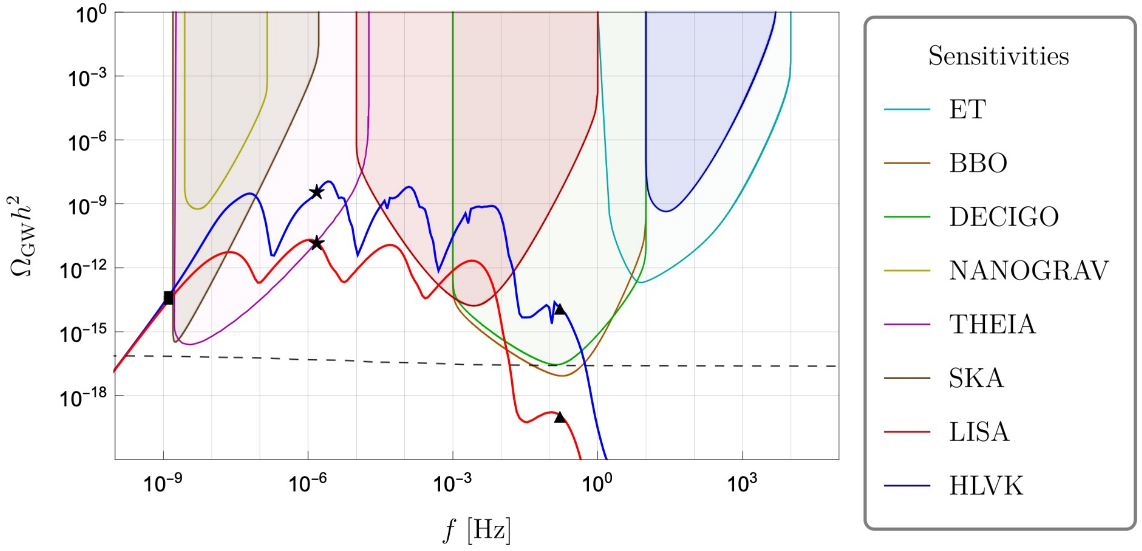
✓Physics behind: large inertia of scalar

→ <u>generally applicable</u> to other scenarios with “unwanted” scalar

For SU(2): Watanabe & Komatsu 2020, Dimastrogiovanni+ 2023, Murata & Kobayashi 2024...

- computation including backreaction (García-Bellido+ 2023, ...) → talk by L. Sorbo

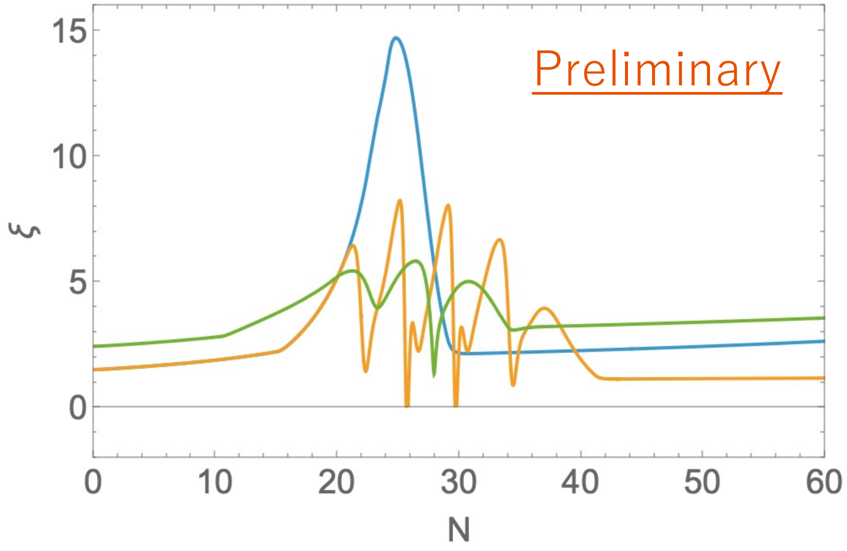




$$\left(K_{\phi,1}+\dot{\phi}^2\,K_{\phi,2}\right)\ddot{\phi}+3K_{\phi,1}\frac{\dot{a}}{a}\dot{\phi}+\frac{\partial V}{\partial \phi}=0$$

⇨ suppressing the oscillatory behavior

broadening peaks in SGWB spectrum...?



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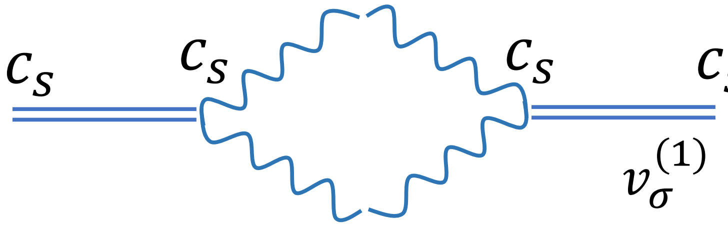
single field



$$v_\sigma^{(1)} \to \zeta^{(1)}$$

$$\mathcal{P}_\zeta^{(1)}(k) \equiv \left[\mathcal{P}_\zeta^{(0)}\right]^2 e^{4\pi\xi} f_{2,\zeta}\left[\epsilon_\sigma,\, c_{s,\sigma},\, \xi\right]$$

$c_{s,\sigma}^{-2}$

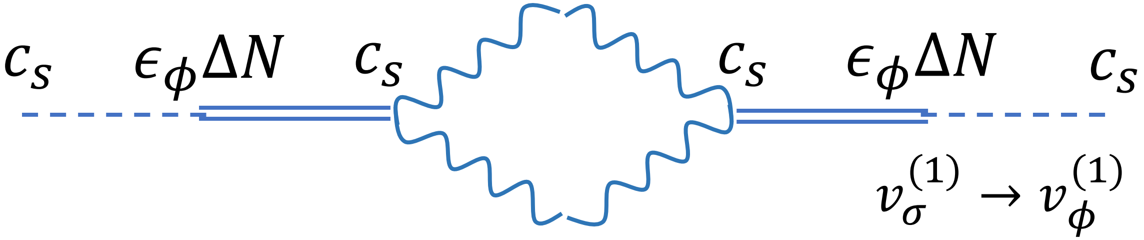
$E \cdot B$ contribution $\propto c_{s,\sigma}^6$

$$f_{2,\zeta}\left[\epsilon_\sigma,\, c_{s,\sigma},\, \xi\right] \simeq \frac{7.47\times 10^{-5}}{\xi^6} c_{s,\sigma}^6 - \frac{1.92\times 10^{-5}}{\xi^6} c_{s,\sigma}^4 \epsilon_\sigma + \frac{1.89\times 10^{-6}}{\xi^6} c_{s,\sigma}^2 \epsilon_\sigma^2 \;\cdots$$

$$F\left(\vec{k}_1,\, \vec{k}_2,\, \vec{k}_3\right) = \frac{\left[\mathcal{P}_\zeta^{(0)}\right]^3}{k_1^2 k_2^2 k_3^2} e^{6\pi\xi} f_{3,\zeta}$$

$E \cdot B$ contribution $\propto c_{s,\sigma}^9$

two-field



$$v_\sigma^{(1)} \to v_\phi^{(1)} \to \zeta^{(1)}$$

$$\mathcal{P}_\zeta^{(1)}(k) \equiv \left[\epsilon_\phi\, \mathcal{P}_\zeta^{(0)}\right]^2 e^{4\pi\xi} f_{2,\zeta}\left[c_s,\, \xi,\, \Delta N_k\right]$$

$$f_{2,\zeta} \simeq \frac{7.47\times 10^{-5}}{\xi^6} c_s^6 (1+c_s^2)^2 \Delta N_k^2 - \frac{1.92\times 10^{-5}}{\xi^6} c_s^4 (1+c_s^2) \Delta N_k \;\cdots$$

$$F\left(\vec{k}_1,\, \vec{k}_2,\, \vec{k}_3\right) = \frac{\left[\epsilon_\phi\, \mathcal{P}_\zeta^{(0)}\right]^3}{k_1^2 k_2^2 k_3^2} e^{6\pi\xi} f_{3,\zeta}$$

tensor:

$$\mathcal{P}_\lambda^{(1)}(k) \equiv \frac{2}{\pi^2} \frac{H^4}{M_p^4} \mathrm{e}^{4\pi\xi} f_{h,\lambda}(\xi) \qquad f_{h,+}(\xi) \simeq \frac{4.3\times 10^{-7}}{\xi^6}$$

・Analytic expression　　ex.) single field

$$\mathcal{P}_\zeta^{(1)}(k) = \left[\mathcal{P}_\zeta^{(0)}\right]^2 \frac{9\pi^3\xi^2 e^{4\pi\xi}}{16} \int_1^\infty dx \int_0^1 dy \frac{\left(x^2-1\right)^2}{\sqrt{x^2-y^2}} \mathcal{I}_\zeta^2 \left[\epsilon_\sigma,\, c_{s,\sigma},\, \xi,\, \sqrt{\frac{x+y}{2}},\, \sqrt{\frac{x-y}{2}}\right]$$

$$\begin{aligned}\mathcal{I}_\zeta\left[\epsilon_\sigma,\, c_{s,\sigma},\, \xi,\, \sqrt{\tilde{p}},\, \sqrt{\tilde{q}}\right] \equiv\ & c_{s,\sigma}^3 \left[\tilde{p}^{1/2}+\tilde{q}^{1/2}\right] \mathcal{T}_\zeta^{(E\cdot B)}\left[\xi,\, \sqrt{\tilde{p}}+\sqrt{\tilde{q}}\right] \\ & + \epsilon_\sigma c_{s,\sigma}\left[c_{s,\sigma}^2 - (\tilde{p}-\tilde{q})^2\right]\left\{\mathcal{T}_\zeta^{(E^2)}\left[\xi,\, \sqrt{\tilde{p}}+\sqrt{\tilde{q}}\right] + \tilde{p}^{1/2}\tilde{q}^{1/2}\,\mathcal{T}_\zeta^{(B^2)}\left[\xi,\, \sqrt{\tilde{p}}+\sqrt{\tilde{q}}\right]\right\}\end{aligned}$$

$$\begin{aligned}\mathcal{T}_\zeta^{(E^2)}[\xi,\, Q] &\equiv \frac{1}{3\pi^{3/2}\xi^{1/2}} \int_0^\infty dx \frac{-c_s x\, \cos(c_s x) + \sin(c_s x)}{c_s^3} x^{-1/2} \exp\left[-2\sqrt{2\xi x Q}\right] \\ &\simeq \frac{1}{3\pi^{3/2}\xi^{1/2}} \int_0^\infty dx \frac{x^{5/2}}{3} \exp\left[-2\sqrt{2\xi x Q}\right] = \frac{5}{32\sqrt{2}\pi^{3/2}\xi^4 Q^7}\,,\end{aligned}$$

c_s does not alter scale

→ amplitude suppression

$$\begin{aligned}\mathcal{T}_\zeta^{(E\cdot B)}[\xi,\, Q] &\equiv \frac{\sqrt{2}}{3\pi^{3/2}} \int_0^\infty dx \frac{-c_s x\, \cos(c_s x) + \sin(c_s x)}{c_s^3} \exp\left[-2\sqrt{2\xi x Q}\right] \\ &\simeq \frac{\sqrt{2}}{3\pi^{3/2}} \int_0^\infty dx \frac{x^3}{3} \exp\left[-2\sqrt{2\xi x Q}\right] = \frac{35}{64\sqrt{2}\pi^{3/2}\xi^4 Q^8}\,,\end{aligned}$$