June 24th, 2025

Inflationary phenomenology of a non-canonical axion with Chern-Simons interaction

@ Axions in Stockholm 2025

Jun’ya Kume (University of Padova)

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

with Marco Peloso, Nicola Bartolo

Outline

- Inflationary phenomenology with Chern-Simons term
- Production of U(1) gauge field and perturbations
- Non-canonical case: large inertia of scalar modes
- Backreaction in non-canonical case…?
- Summary

- **<u>inflation</u>**: accelerating expansion before Hot Big-Bang (Starobinsky, Guth, Sato, …)

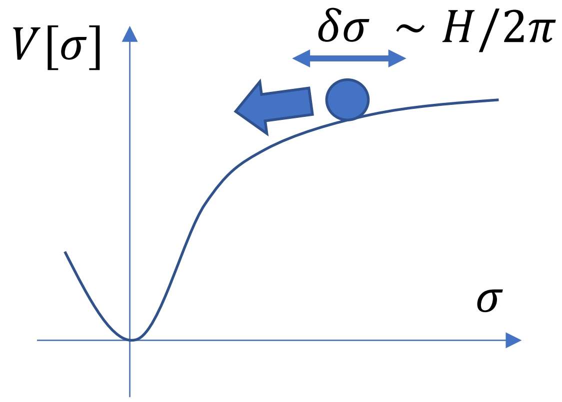
  solves classical problems in Big-Bang cosmology

  → **<u>origin of CMB fluctuation</u>**!

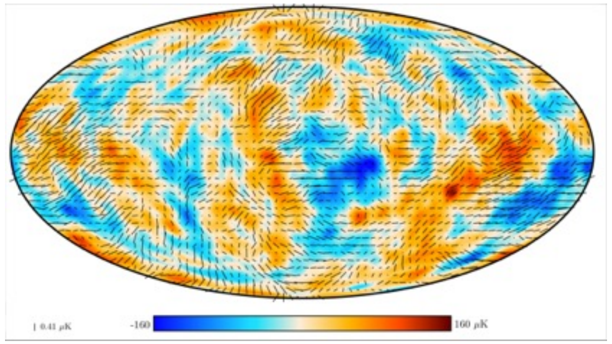
  ex.) a scalar field (inflaton) $\sigma(t,\vec{x}) = \bar{\sigma}(t) + \delta\sigma(t,\vec{x})$

  → 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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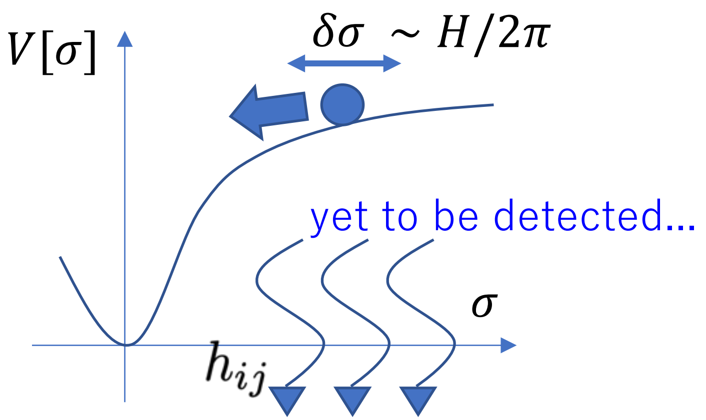

Tensor perturbation as well! → B-mode polarization

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...!?

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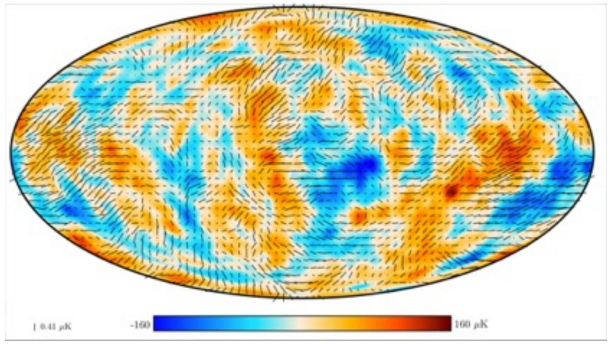

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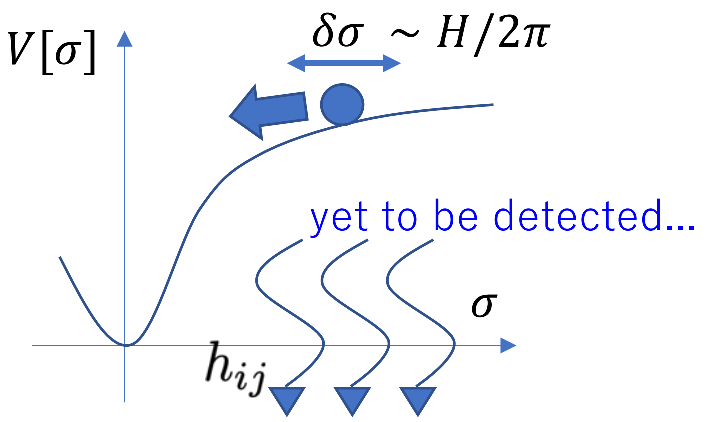

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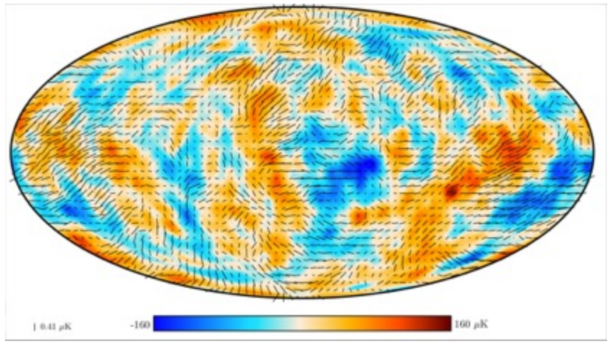
Not true if additional sourced component exists!

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



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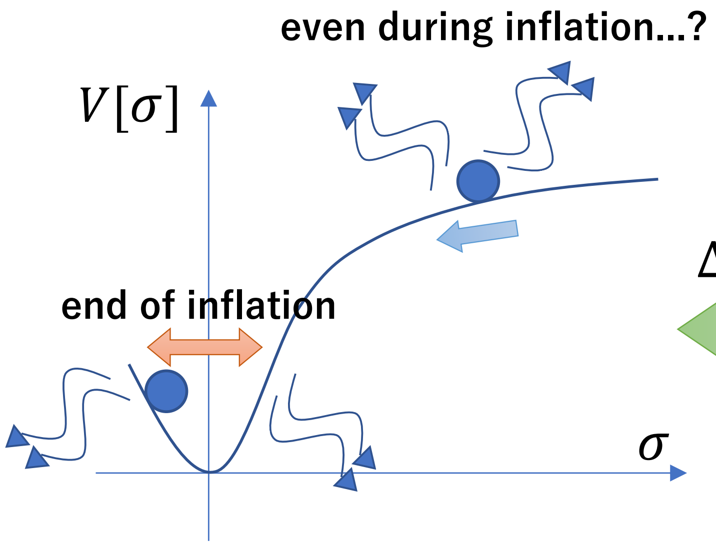
- Particle production during inflation

exit from inflation → decay into matter fields — matter coupling expected!!



$\Delta V = 0$

If inflaton is a pseudo-scalar ("**axion**-like")...

ex.)axial current, Chern-Simons (CS) term

$$\frac{\sigma}{f}\partial_\mu J_5^\mu \qquad \frac{1}{4f}\sigma F_{\mu\nu}\tilde{F}^{\mu\nu} \iff \frac{1}{2f}(\partial_\mu\sigma)\epsilon^{\mu\nu\rho\sigma}A_\nu\partial_\rho A_\sigma$$

✓ compatible with shift symmetry $\phi \to \phi + const.$

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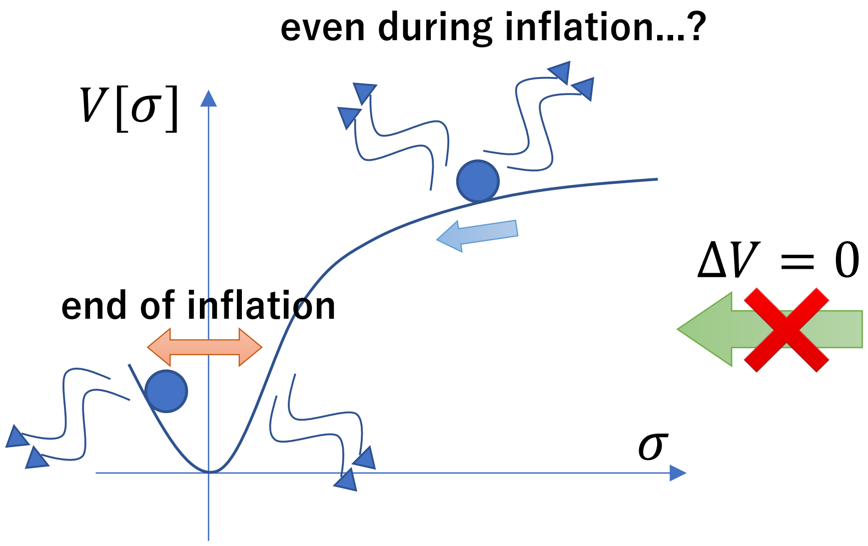

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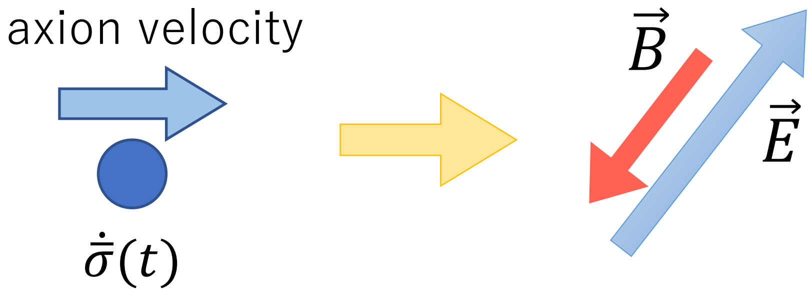


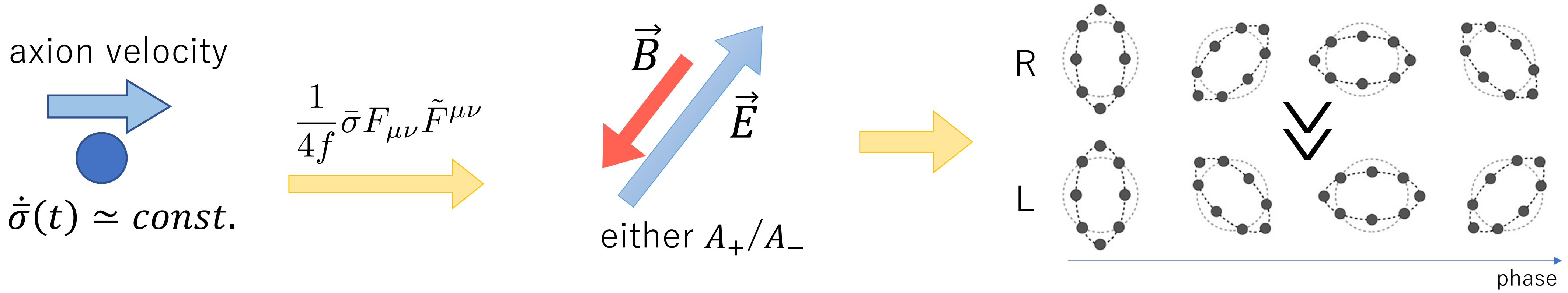
✓ **violent amplification**

enrich/complicates the primordial perturbations!!

→ we consider sterile U(1) in our study

※fermion production: Domcke & Mukaida 2018, Gorbar+2021, Fujita, **JK**+ 2022, …

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



Q1: Visible tensor signal in CMB? – **No!** in the vanilla scenario (Barnaby & Peloso 2010, ...)

- $A + A \to \delta\sigma$: too efficient & highly non-Gaussian $\to r_{\rm tot} \searrow$ & $\dot{\bar\sigma}$ cannot be large.

axion as spectator → indirect sourcing of ζ (Ferreira & Sloth 2014, Namba+ 2015)

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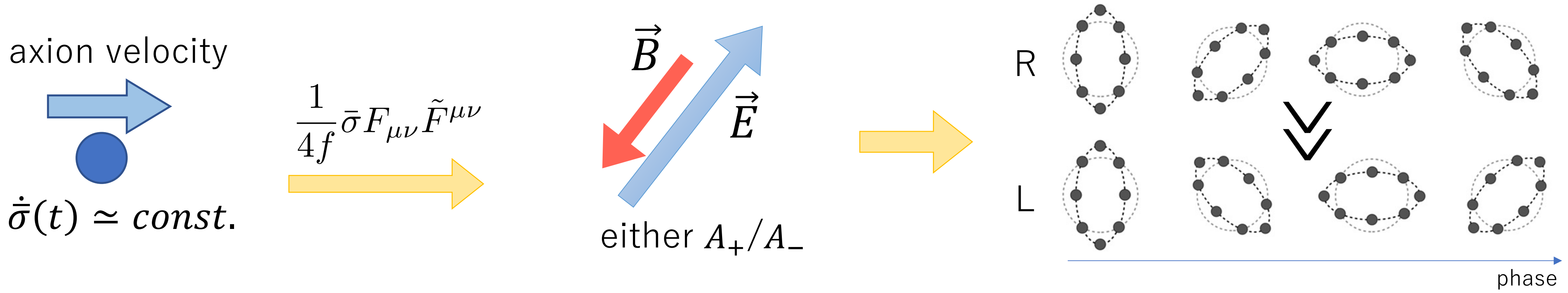

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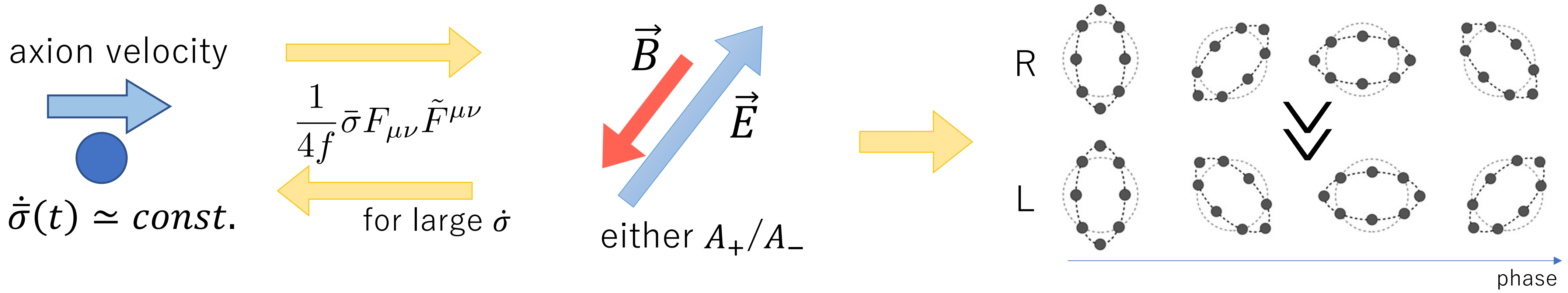

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A new solution to Q1! (in 2501.02890) (→ work in progress: What about backreaction?)

Q2: GWs at interferometer scales? – $\dot{\bar{\sigma}}$ accelerated & **backreaction becomes relevant**!

- memory: $\bar{\sigma}(t' < t) \to A_+(t)$ ⇒ **oscillatory behavior?** (Cheng+ 2015, Notari 2016, ...)

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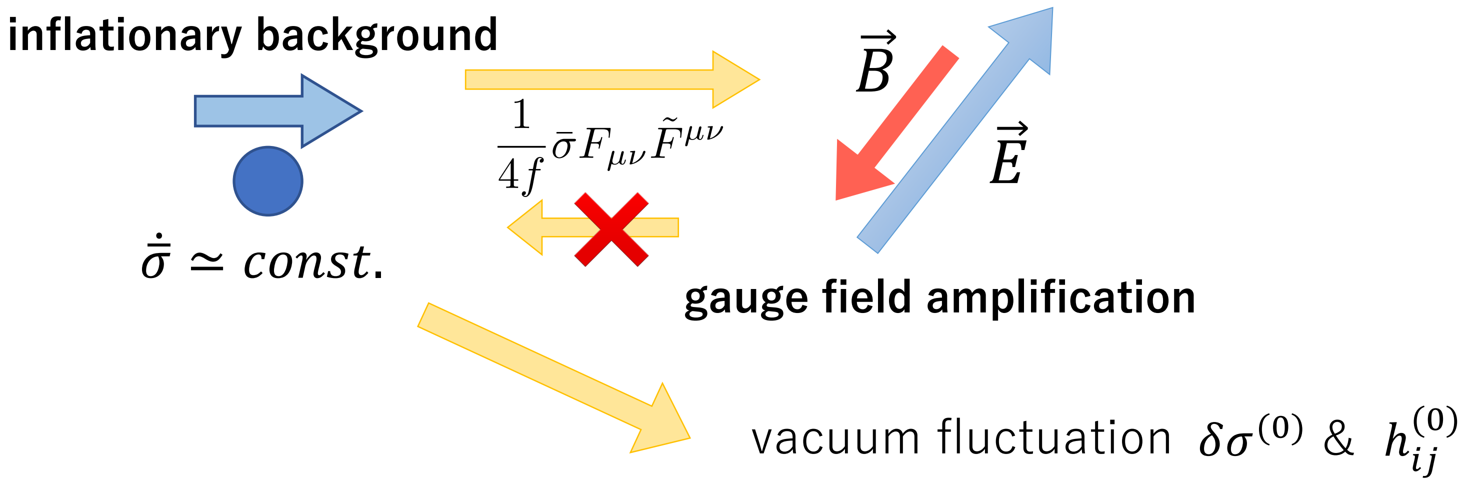
- Linear & perturbative analysis for CMB signals



$$a \propto e^{Ht}$$
$$H^2 \simeq V/3M_{Pl}^2$$
$$3H\dot{\bar{\sigma}} \simeq -\partial V/\partial\sigma$$

$$\left[\partial_\tau^2 + k^2 \pm 2k\frac{\xi}{\tau}\right]\mathscr{A}_\pm(\tau,k) = 0$$

$$\left[\partial_\tau^2 + k^2 - \frac{z''}{z}\right] v_k^{(0)} = 0$$

$$v^{(0)} \to z_\sigma \delta\sigma^{(0)}, z_h h^{(0)}$$

- Linear & perturbative analysis for CMB signals

inflationary background

$\dot{\bar{\sigma}} \simeq const.$

$\frac{1}{4f}\bar{\sigma}F_{\mu\nu}\tilde{F}^{\mu\nu}$

$\vec{B}$ $\vec{E}$

gauge field amplification

sourced components:

inverse decay

& gravitational coupling $\delta\sigma^{(1)}$

polarized tensor pert. $h_{ij}^{(1)}$

uncorrelated

vacuum fluctuation $\delta\sigma^{(0)}$ & $h_{ij}^{(0)}$

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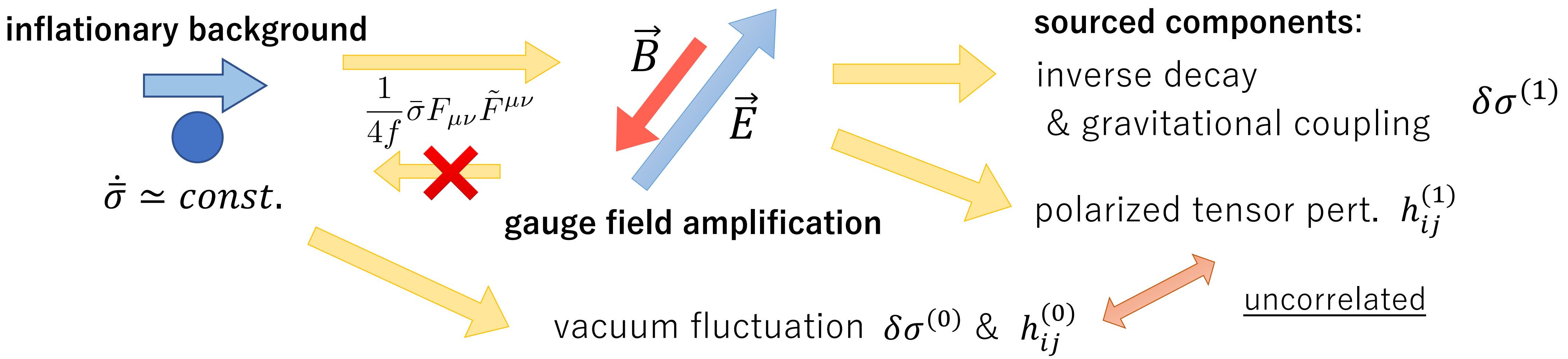
$$\left[\partial_\tau^2 + k^2 - \frac{z''}{z}\right]v_k^{(1)} = \underline{\underline{Q\left[\mathcal{A}_+(\tau,k)\right]}}$$

- Linear & perturbative analysis for CMB signals



<u>observables of our interest</u>:

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

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

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

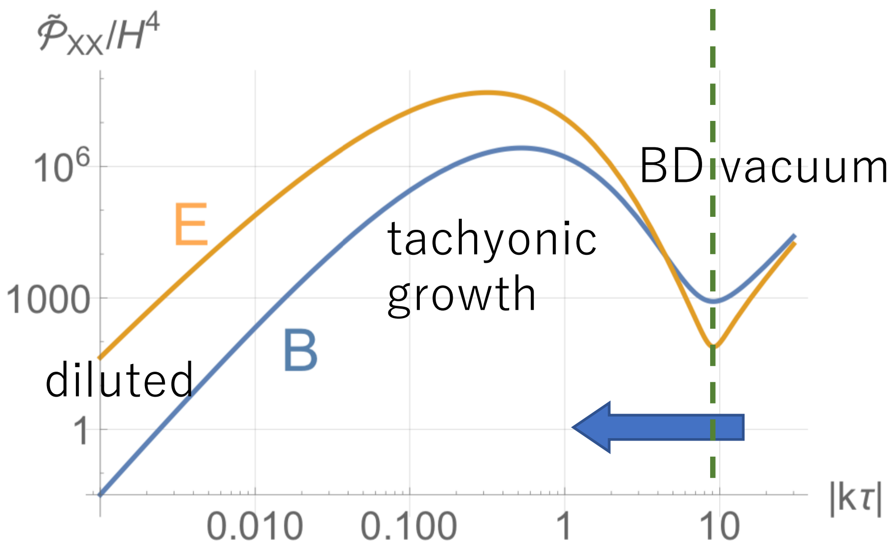
※σ can be a spectator $\rightarrow \varphi_I = \{\phi, \sigma\}$ $\quad$ ($\epsilon_I, \eta_I = const. \ll 1.$ assumed in our study)

- Amplification of U(1) gauge field

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

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 perturbations

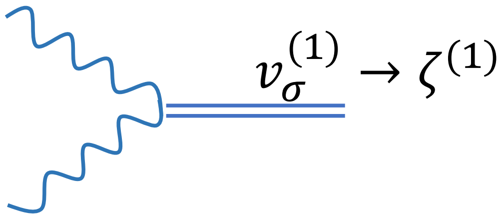
gravitational coupling　　inverse decay

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

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

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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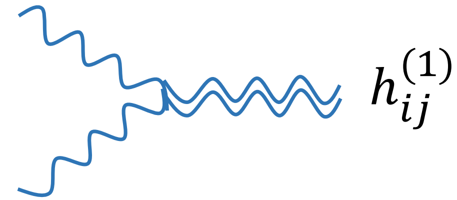
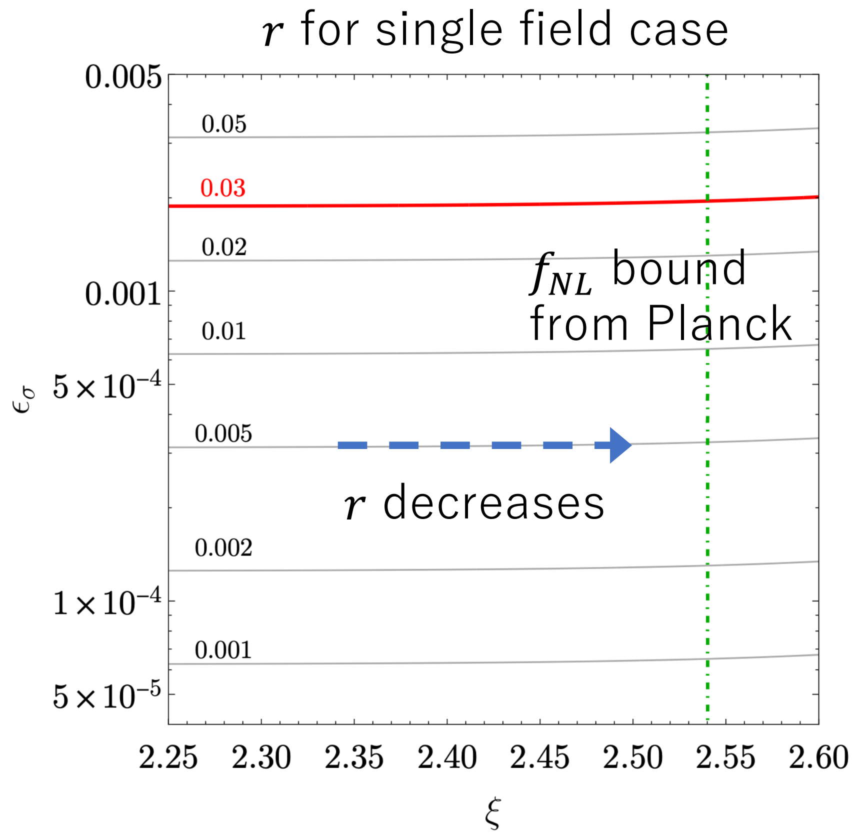
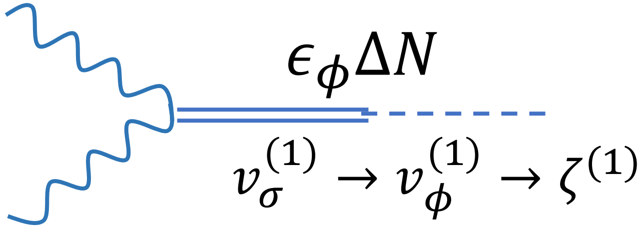




- two-field case:



σ decays $\Delta N \lesssim 5$ e-folds
after the CMB mode crossing
$\to$ visible sourced tensor
(Ferreira & Sloth 2014, Namba+ 2015)

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

・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: $c_s < 0.02$

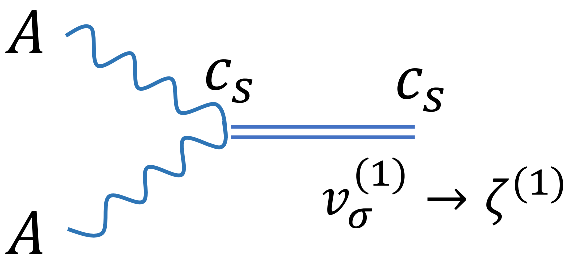
※standard scenario recovered by taking $c_s \rightarrow 1$

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

- Suppressing the scalar sourcing by 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:



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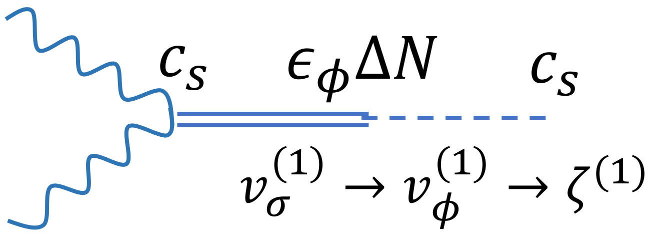

single field case:

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

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

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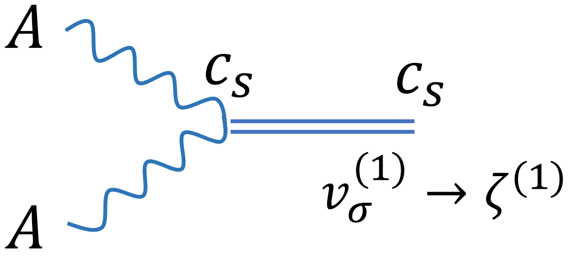

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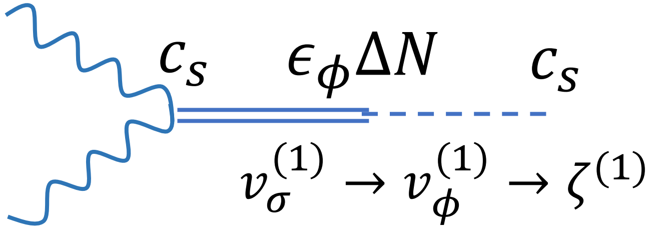

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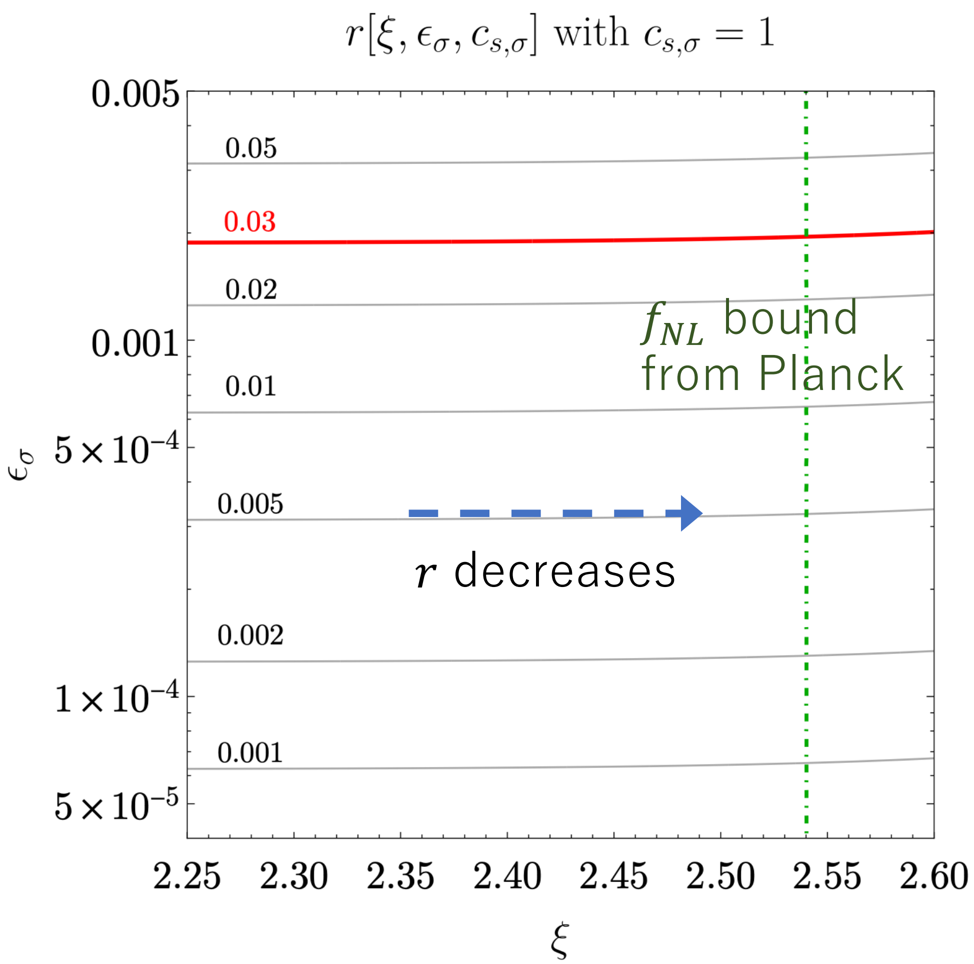
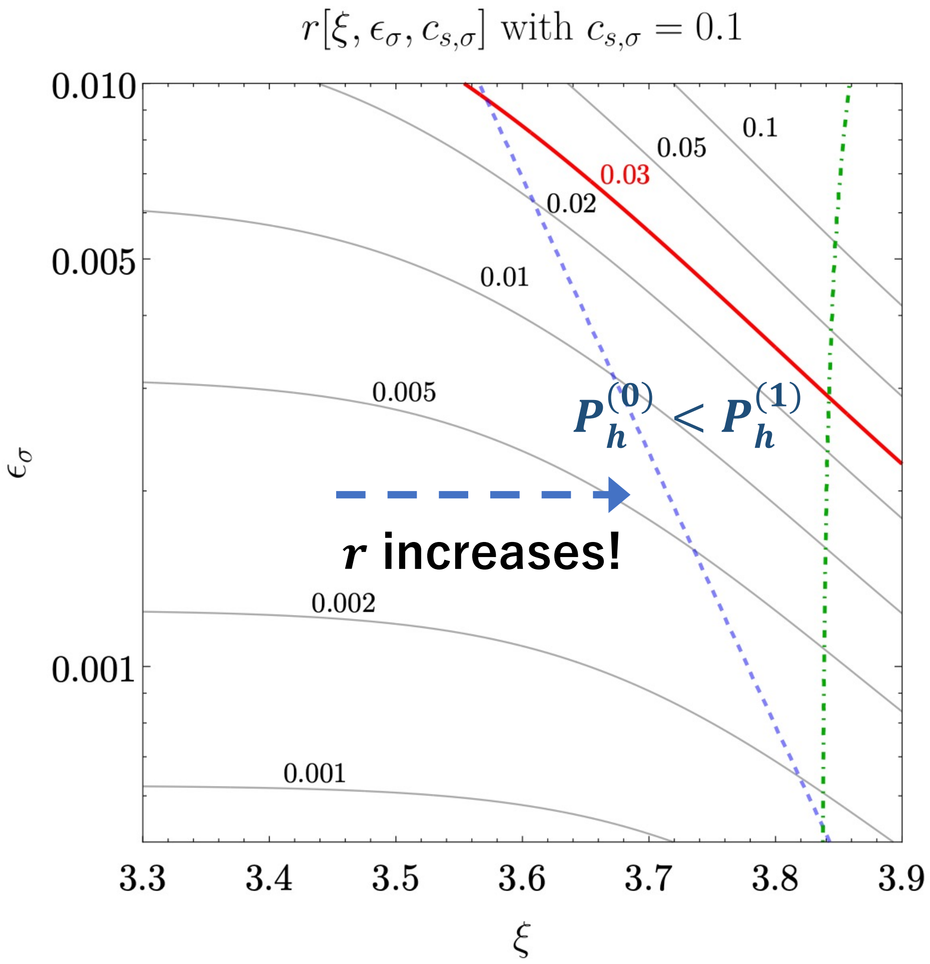
From the standard case, we get the suppression as $P_\zeta^{(1)} \propto c_s^4$ and $f_{NL} \propto c_s^6$!!

※※ Tensor sector not modified!

- Single field case (σ: inflaton, $\dot{\sigma}, \epsilon_\sigma, c_{s,\sigma} = const.$ assumed for simplicity)





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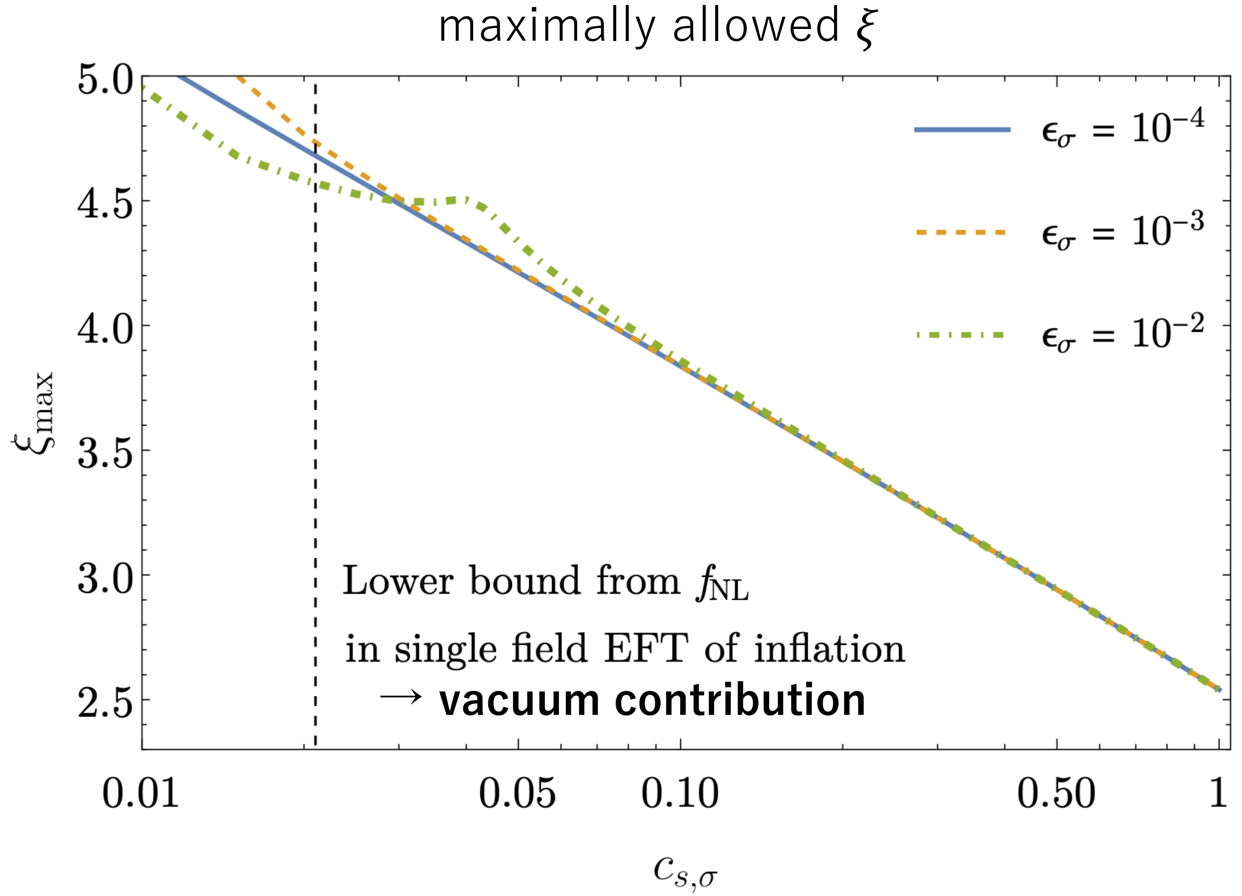
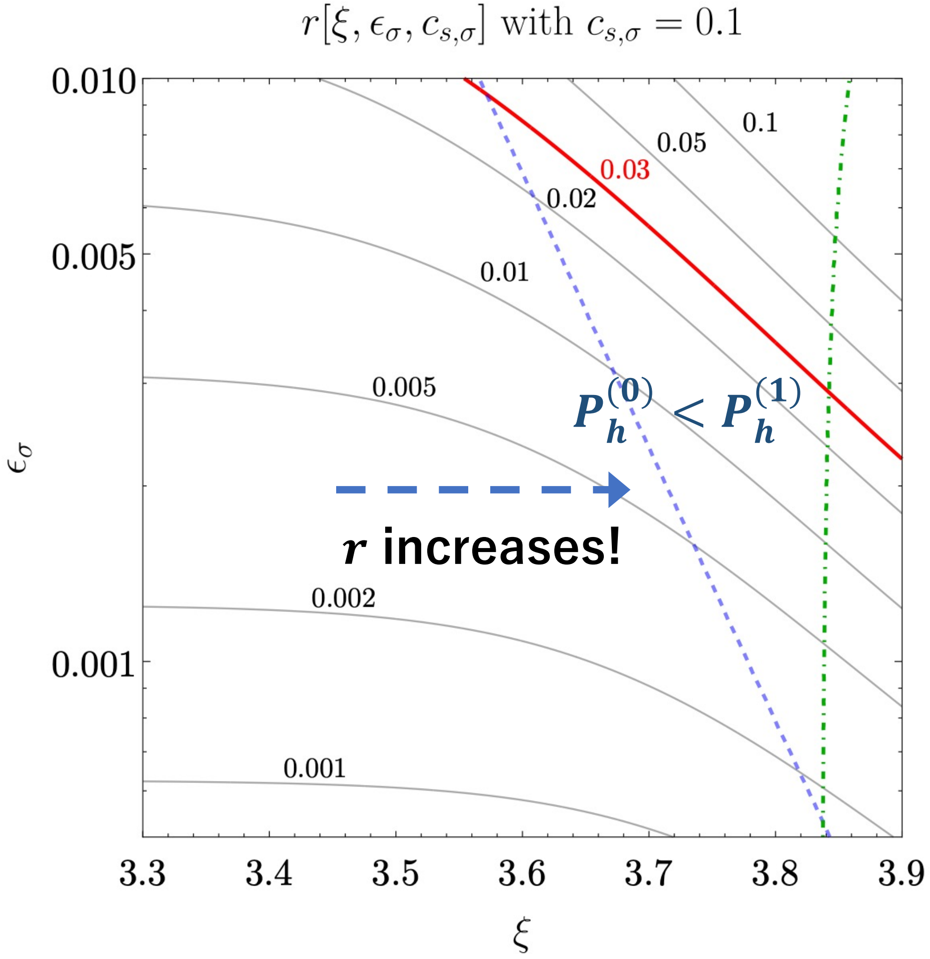
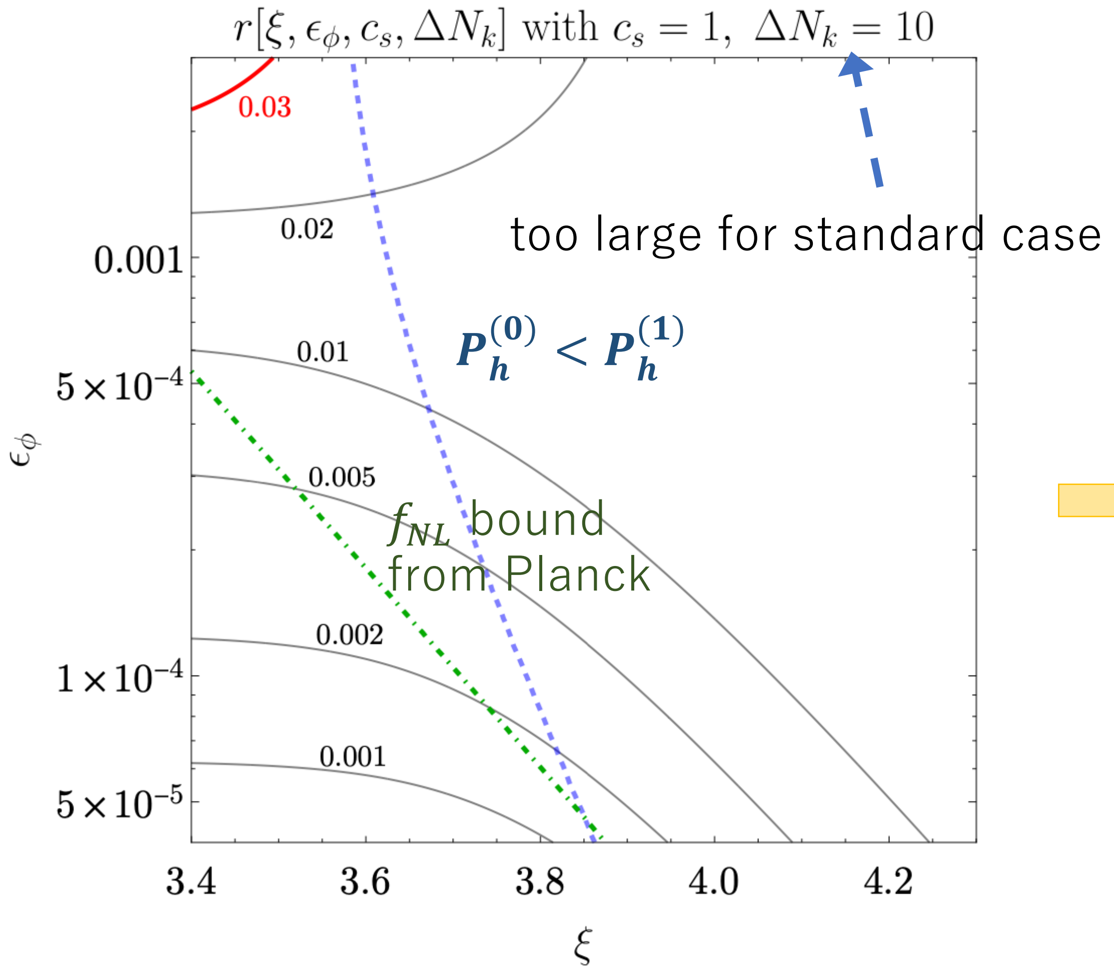
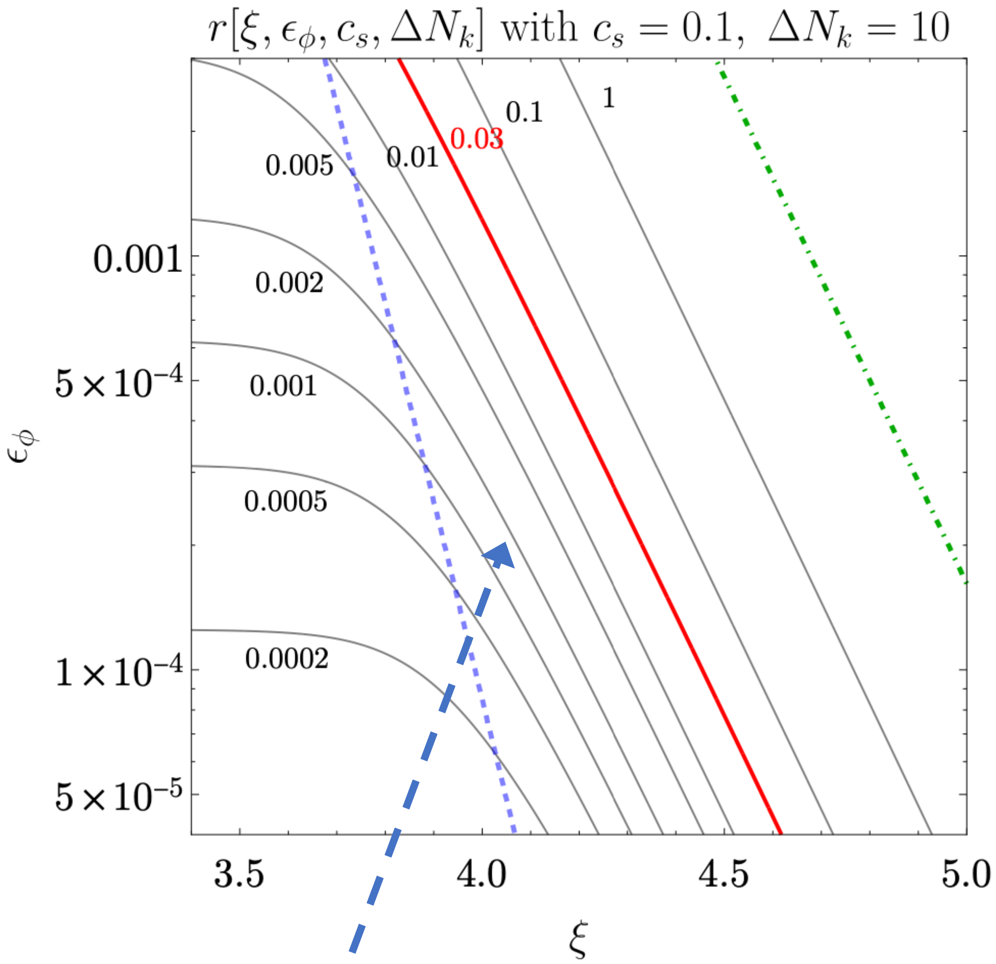




exponential dependence on ξ → sourcing effect can be significantly large!

- two-field case (ϕ: inflaton, σ: spectator, $c_{s,\phi} = c_{s,\sigma} = c_s$)





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

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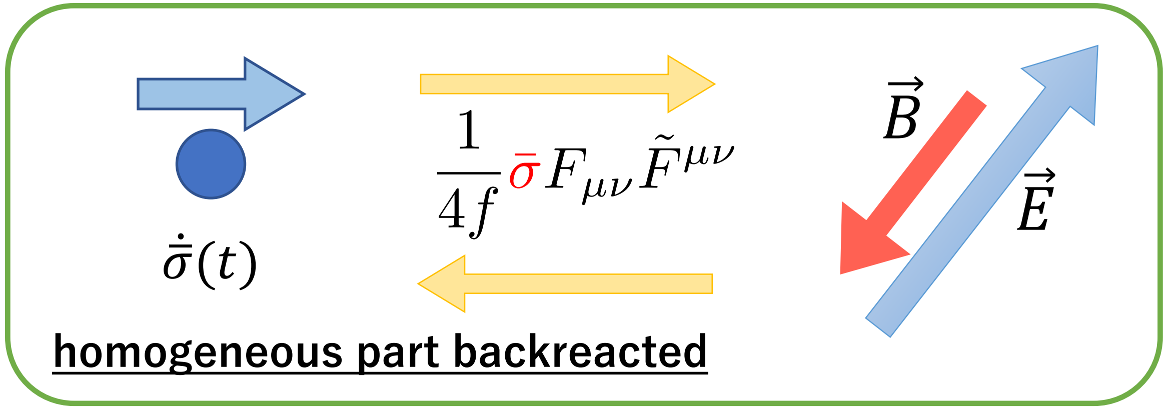
- GWs at interferometer scales

$\delta\sigma$ loosely bounded on small scales → larger $\dot{\bar{\sigma}}(t)$ & subjected to the **backreaction**

・ integro-differential system $(\bar{\sigma}(t)\ /\ A_+(t,k))$ (Cheng+ 2015, Notari 2016, Dall'Agata+ 2019, Domcke+ 2020)



→ **polarized tensor pert**. $h_{ij}^{(1)}$

→ scalar pert. $\delta\sigma^{(1)}$ → PBHs…?

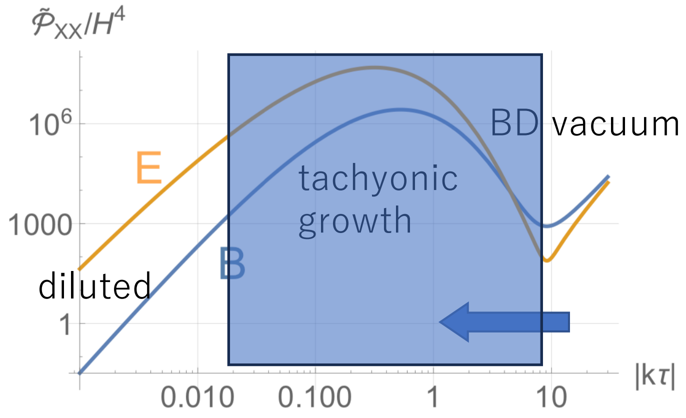
(Linde+ 2012, García-Bellido+ 2017)

→ Mathematica code recently developed in García-Bellido+ 2023

$$\ddot{\bar{\sigma}} + 3H\dot{\bar{\sigma}} + \frac{\partial V}{\partial \sigma} = \frac{1}{f}\underline{\underline{\vec{E}\cdot\vec{B}}}$$ ← adding relevant modes

$$\left\langle \vec{E}\cdot\vec{B}\right\rangle_{\mathrm{symm}} = -\frac{V_0^2}{8\pi^2 M_p^4}\frac{\tilde{H}}{\mathrm{e}^{3N}}\int d\tilde{k}\,\tilde{k}^2 \sum_\lambda \lambda \frac{d}{dN}\left|\bar{A}_\lambda\right|^2$$

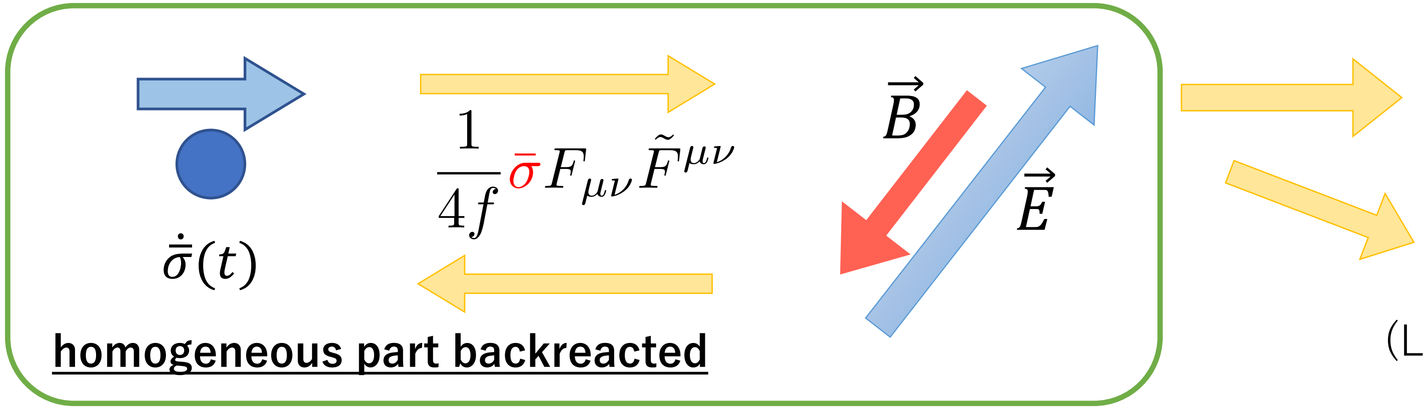
$\bar{\sigma}$ and EB spectrum with backreaction → $h_{ij}^{(1)}$



- GWs at interferometer scales

$\delta\sigma$ loosely bounded on small scales → larger $\dot{\bar{\sigma}}(t)$ & subjected to the **backreaction**

・integro-differential system ($\bar{\sigma}(t)$ / $A_+(t,k)$) (Cheng+ 2015, Notari 2016, Dall'Agata+ 2019, Domcke+ 2020)



polarized tensor pert. $h_{ij}^{(1)}$

scalar pert. $\delta\sigma^{(1)}$ → PBHs...?

(Linde+ 2012, García-Bellido+ 2017)

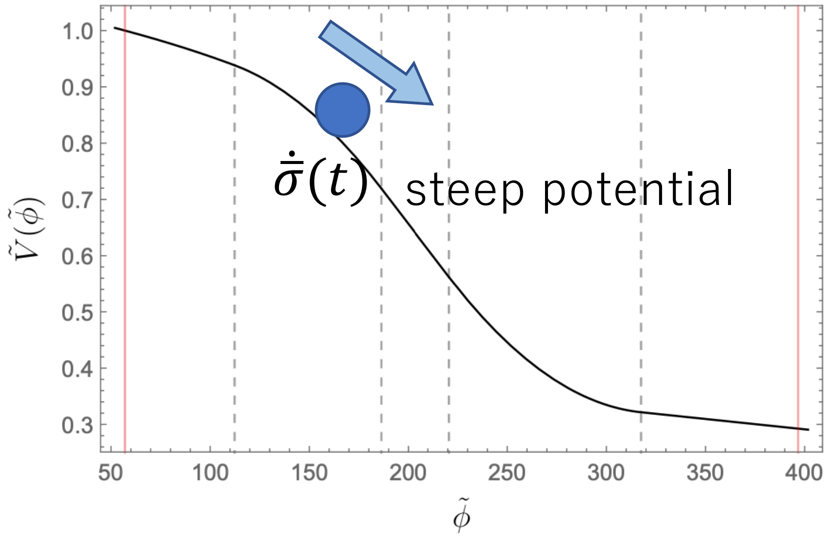
→ Mathematica code recently developed in García-Bellido+ 2023

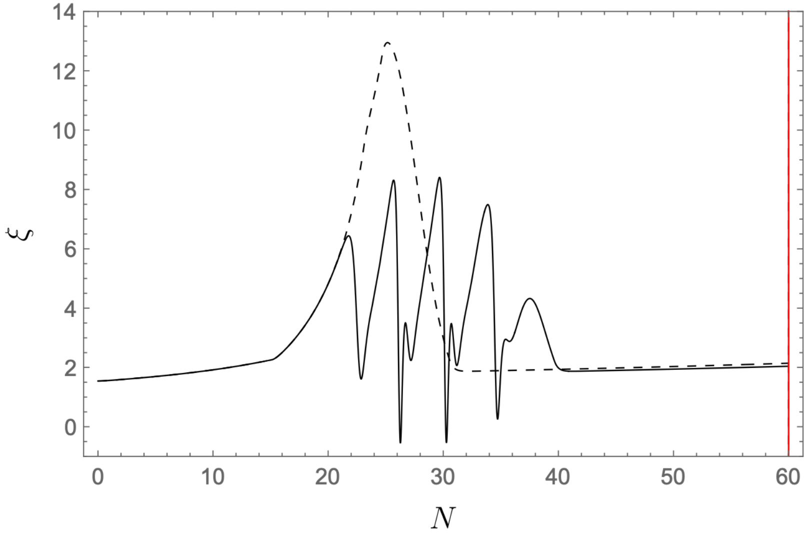
Other approaches:

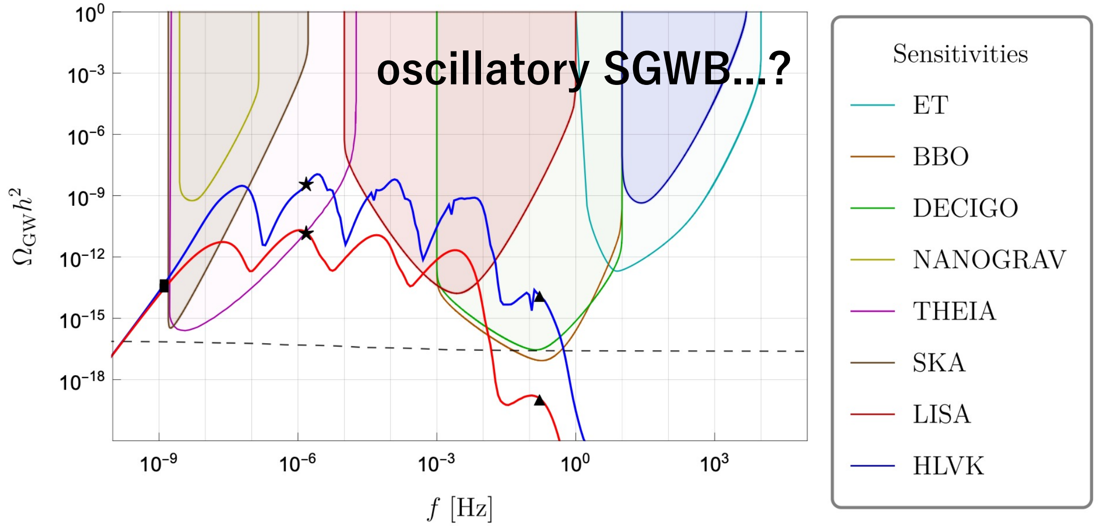
・Gradient expansion (Sobol+ 2019, ...) → incorporating $\delta\sigma(t,\vec{x})$ in Domcke+ 2023

・Lattice simulation for $\sigma(t,\vec{x})$ (Caravano+ 2022, Figueroa+ 2023, Caravano & Peloso 2024)

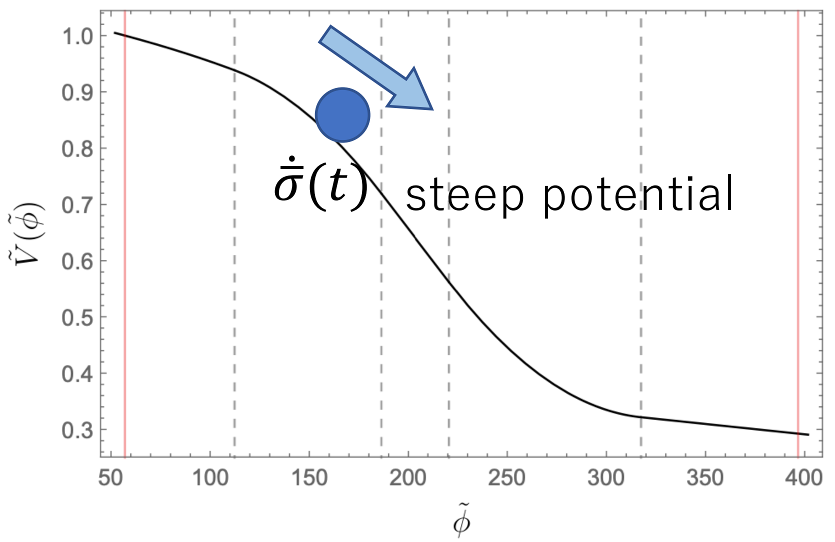
- "<u>First-step estimate</u>" with homogeneous backreaction (García-Bellido+ 2023)

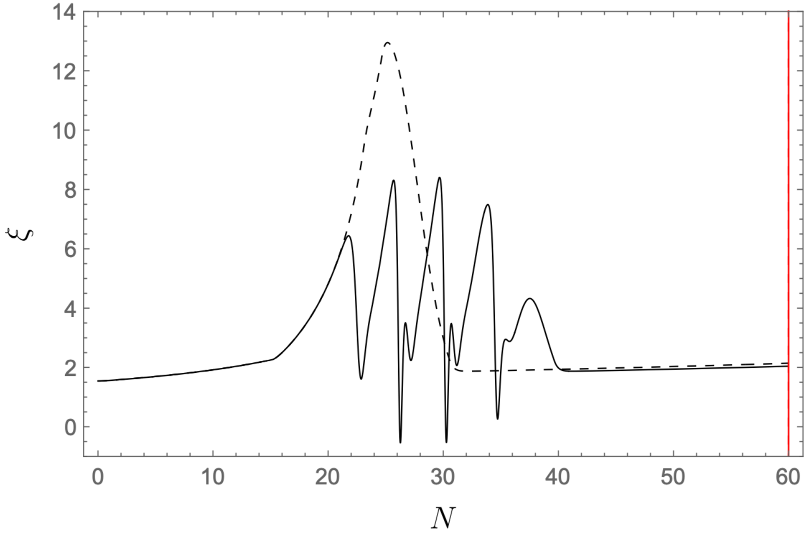


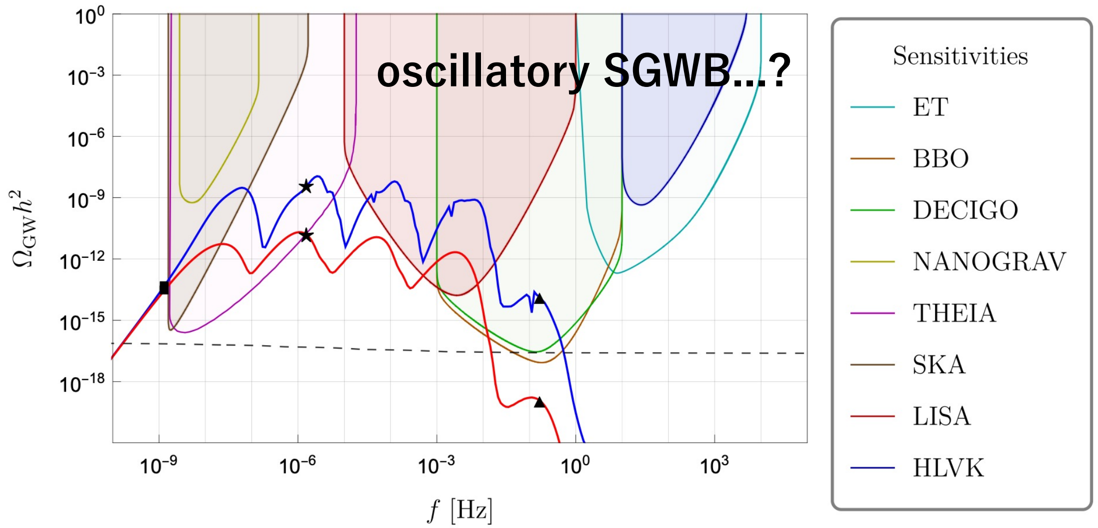




- “First-step estimate” with homogeneous backreaction (García-Bellido+ 2023)





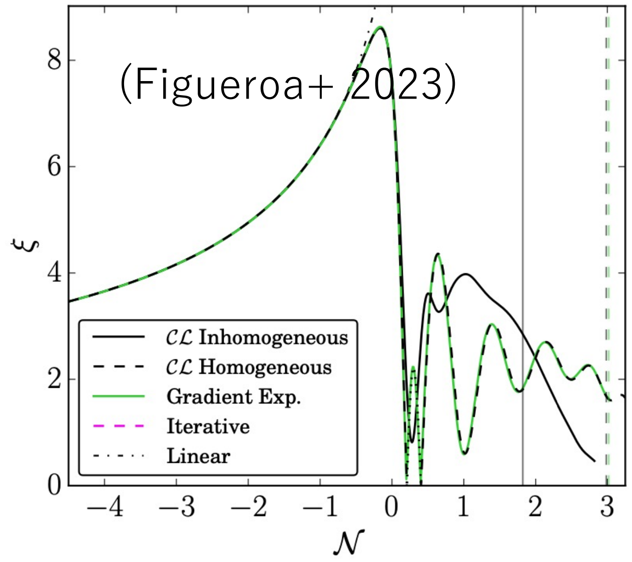


cf. **lattice simulations**

solid line for $\sigma(t,\vec{x})$

oscillation
→ smoothed out?

※at the end of inflation



- "Homogeneous backreaction" in non-canonical case (Very preliminary!!)

$$\left(K_{\sigma,1} + \dot{\sigma}^2 K_{\sigma,2}\right)\ddot{\sigma} + 3K_{\sigma,1}H\dot{\sigma} + \frac{\partial V}{\partial \sigma} = \frac{1}{f}\vec{E}\cdot\vec{B}$$

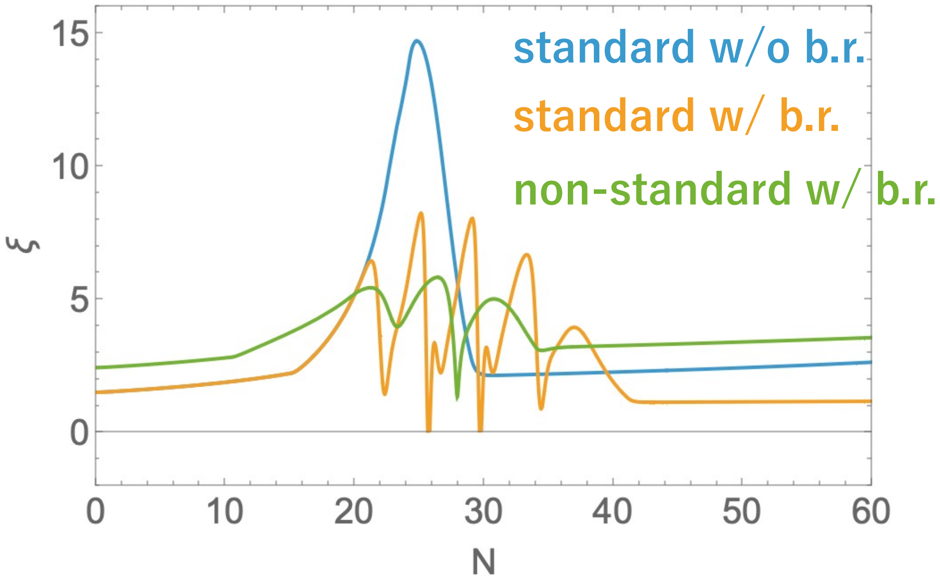
- What does the inertia bring?

suppresses acceleration by ∂V → reducing ξ / also suppresses $\vec{E}\cdot\vec{B}$ effect on $\ddot{\sigma}$

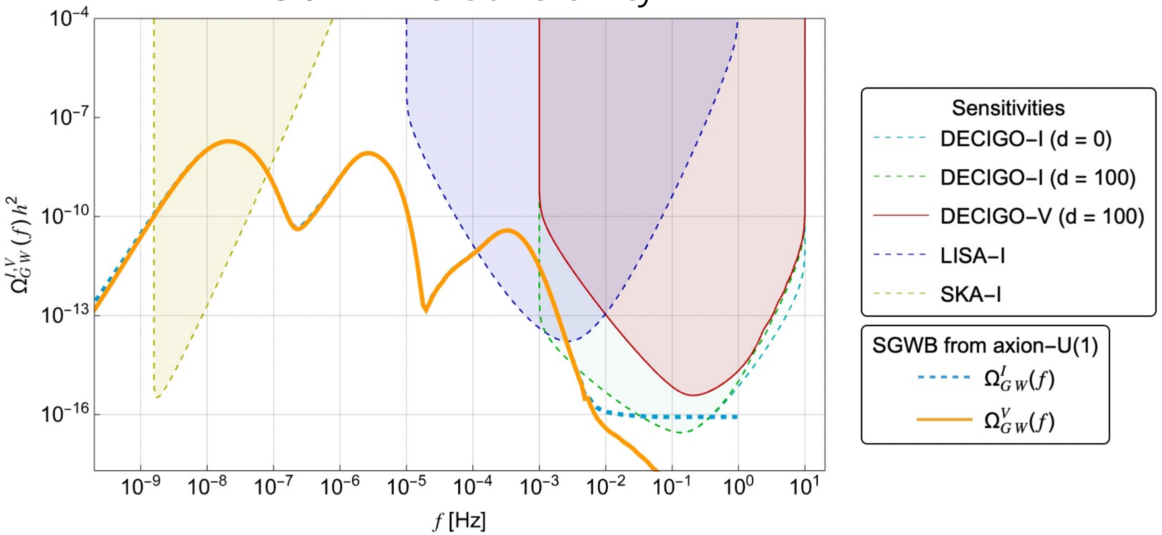
・A toy example: $K_\sigma(Y) = Y(Y/M)^{\alpha-1}$ (Unnikrishnan 2008, Li & Liddle 2012, Lola+ 2020, …)

→ $K_{\sigma,1} + \dot{\sigma}^2 K_{\sigma,2} = (2\alpha - 1)K_{\sigma,1}$ $\left(c_{s,\sigma} = 1/(2\alpha - 1)\right)$

$\alpha = 2, M/V_0 \sim 10^{-3}$



SGWB vs sensitivity



Outline

- Inflationary phenomenology with Chern-Simons term
- Production of U(1) gauge field and perturbations
- Non-canonical case: large inertia of scalar modes
- Backreaction in non-canonical case…?
- Summary

Summary

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

i)too efficient scalar sourcing and ii)backreaction

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

→ Inverse decay contribution is suppressed by c_s!

→ Sourced tensor becomes dominant at CMB while satisfying f_{NL} bound.

✓Physics behind: large inertia of scalar

→ generally applicable to other scenarios with “unwanted” scalar

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

June 24th, 2025

Inflationary phenomenology of a non-canonical axion with Chern-Simons interaction

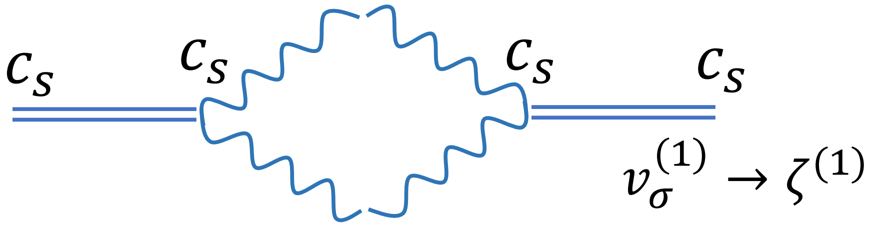
@ Axions in Stockholm 2025

Jun'ya Kume (University of Padova)

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

with Marco Peloso, Nicola Bartolo

single field



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

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

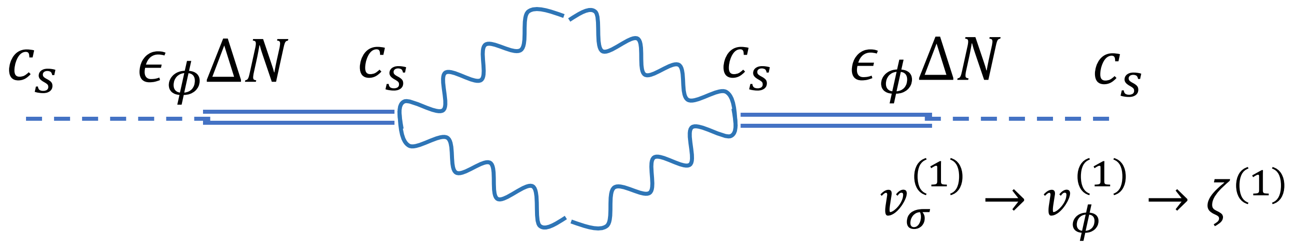
$E \cdot B$ contribution $\propto c_{s,\sigma}^6$

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

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

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

two-field



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

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

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

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

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

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

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

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

c_s does not alter scale

→ amplitude suppression