Long-wavelength perturbations around homogeneous **but anisotropic** spacetimes

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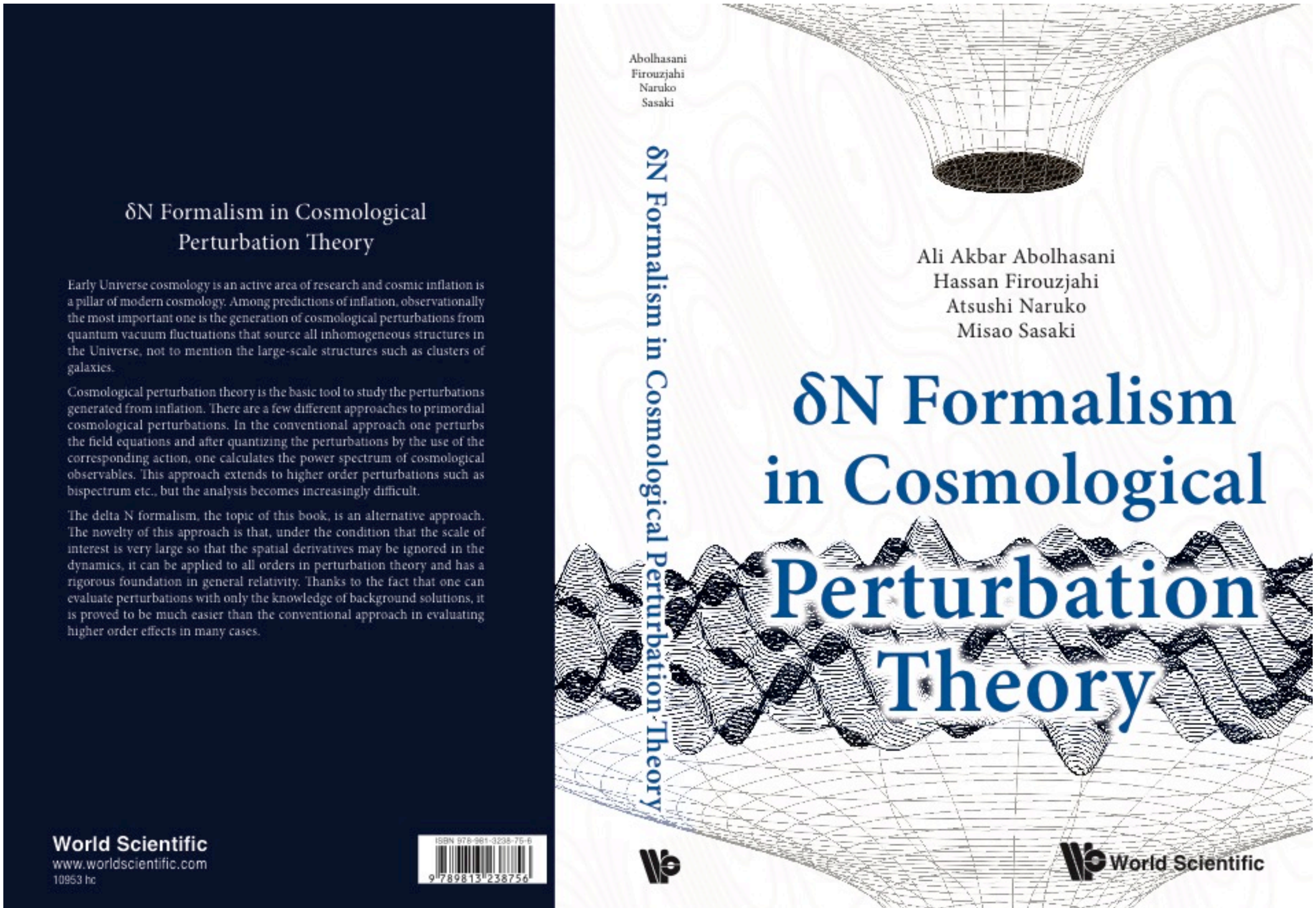
↓

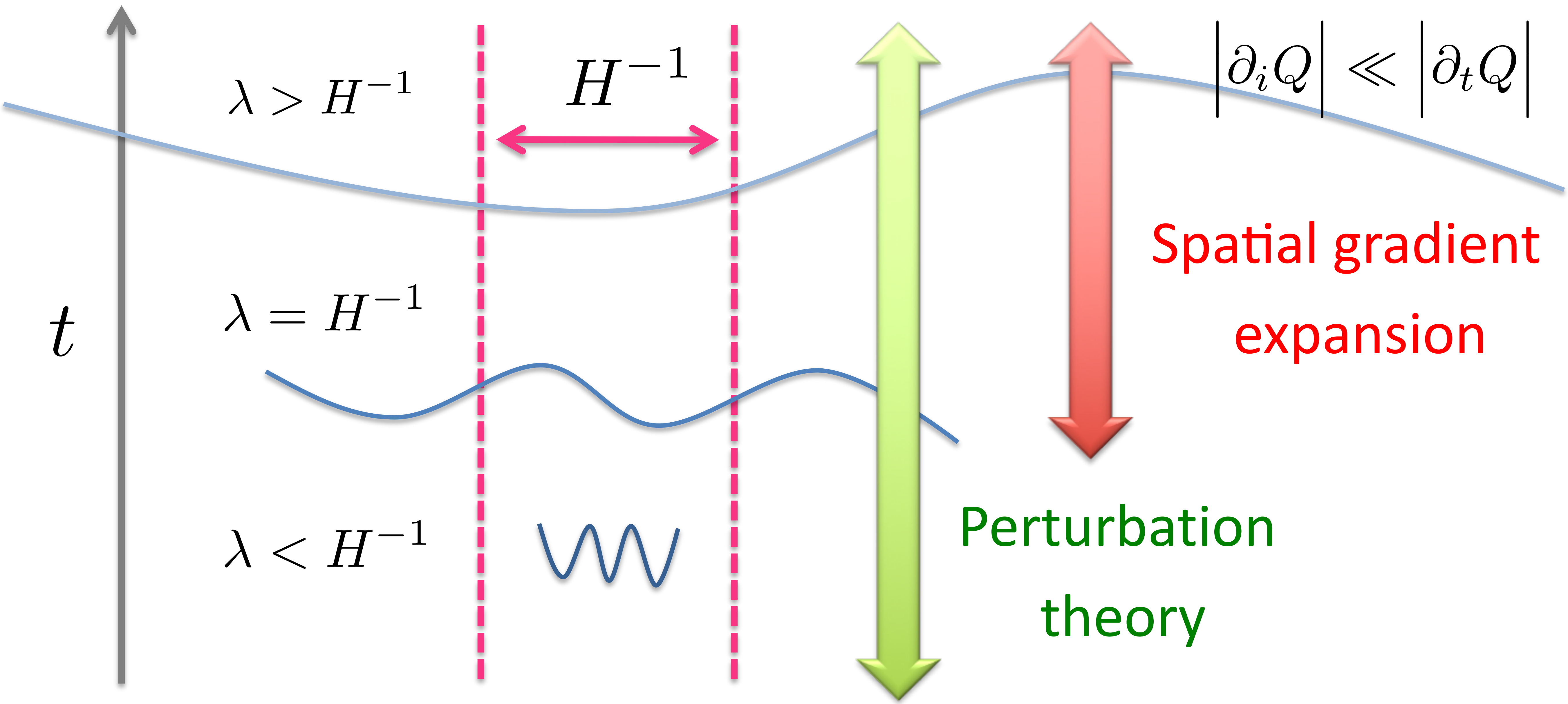
Going beyond δN

text book for δN



What is δN ??

✓ evolution of fluctuations during inflation



δN and the next ??

✓ based on the ***leading order*** approximation of GE method

✓ a way to evaluate **the (conserved) curvature perturbation** around ***homogeneous & isotropic*** universe
just by solving BG eqs. not (involved ?) perturbation eqs.

$$\mathcal{R}_c\Big|_{\rm final} = \delta N$$

1. the *next order* in gradient expansion ??

2. breaking homogeneity ??

3. breaking isotropy ??

① next order in GE

✓ We have already investigated **the next order** in GE.

PTEP 2013 (2013)
arXiv:1210.6525

Beyond δN formalism

Atsushi Naruko[1,*], Yu-ichi Takamizu[2], and Misao Sasaki[2]

- gauge choice : **uniform N (e-folding)** gauge (slicing)

  Sasaki & Tanaka [1998]

- non-linear gauge transformation :

  sol. in the **N gauge** -> sol. in the **comoving gauge**

- proper definition of non-linear curvature perturbation :

  R = [perturbation of “a”] + **[perturbation of GW]**

② breaking homogeneity

✓ maybe interesting… analysis involved ? any application ?

③ breaking isotropy

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motivation -why anisotropic BG-

Gibbons & Hawking 1977, Wald 1983

✓ **cosmic no-hair** theorem/conjecture for inflationary universe

-- Λ (c.c.) **+** (homogeneous) matter with energy conditions

→ universe will be **isotropized** & evolve towards **de Sitter**

= **anisotropy will disappear** (even if exist initially)

✓ **symmetry during inflation**

-- **time-translation symmetry** in de Sitter ↔ **scale inv. Ps**

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + e^{2Ht}\,\mathrm{d}\vec{x}^2 \qquad [\ t \to t+\lambda \ \ \&\ \ x \to e^{-H\lambda}x\ ]$$

→ ns -1 = O(ε) implies the **breaking** of time-tr. symmetry !!

→ what about **spatial rotational symmetry** ?? **O(ε)** ???

anisotropic inflation

✓ *inflation with anisotropic hair* Watanabe, Kanno, Soda [2009]

$$\mathcal{L} = R + \mathcal{L}^{\phi} + f(\phi)\, F_{\mu\nu}^2 \quad \mathbf{+} \quad \vec{A}_{BG}$$

-- **f (ϕ)** breaks **conformal inv.** & **no instability** in pert.

-- predict **(statistically) anisotropic** power spectrum

$$P(\vec{k}) = P(k)\left[1 + g_*\,(\vec{k}\cdot\vec{v_P})\right]$$

vP : preferred direction

$$\rightarrow \quad g_* = 0.002\,^{+0.016}_{-0.016}$$

Kim & Komatsu [2013]

✓ *implication for **symmetry** during inflation* **AN +** [2015]

→ breaking of rotational sym. = **10^{-8} O(ε)** ↔ **O(ε)** for time-sym.

GE in anisotropic BG

✓ let us focus on **linear perturbations** in a simple setup !!

Bianchi I : $\mathrm{d}s^2 = -\mathrm{d}t^2 + e^{2\alpha(t)}\left[e^{-4\beta(t)}\,\mathrm{d}x^2 + e^{2\beta(t)}\,(\mathrm{d}y^2 + \mathrm{d}z^2)\right]$

$$\delta g_{\mu\nu}\,\mathrm{d}x^\mu \mathrm{d}x^\nu = -2A\,\mathrm{d}x^2 + (B_x\,\mathrm{d}x + B_{,a}\mathrm{d}x^a)\mathrm{d}t$$
$$+(\mathrm{d}x\ \mathrm{d}x^a)\begin{pmatrix} 2C - 4D & E_{,a} \\ E_{,a} & (2C + 2D)\delta_{ab} + F_{,ab} \end{pmatrix}\begin{pmatrix} \mathrm{d}x \\ \mathrm{d}x^a \end{pmatrix}$$

δ (BG eqs) $\overset{\text{only}}{=}$ pert. eqs

almost all

in the N gauge

[C = const. & B=0]

summary

- ✓ We have considered possible extensions of δN formalism.
- ✓ First, we have investigated the next leading order in gradient expansion method around isotopic case.
- ✓ Next, we have investigated gradient expansion method around homogeneous but anisotropic background.
- ✓ By carefully studying linear perturbations on that background, we confirm that the nature of perturbations on large scales can be completely captured by the background physics while there would be seemingly non-trivial one.

Thank you
for your attention !!