CMB probes on the correlated axion isocurvature peturbations

Kenji Kadota
IBS Center for Theoretical Physics of the Universe(CTPU),
Institute for Basic Science(IBS), S. Korea

Based on:

- "CMB probes on the correlated axion isocurvature perturbation" (arXiv:1411.3974)
  KK, Jinn-Ouk Gong (APCTP) , Kiyotomo Ichiki (Nagoya), Takahiro Matsubara (Nagoya)

- "Axion inflation with cross-correlated axion isocurvature perturbations"(arXiv:1509.04523)
  KK, Tatsuo Kobayashi (Hokkaido), Hajime Otsuka (Waseda).

- Motivations for cross correlations:

- Parameter precision

- Concrete example (Analytical formula for cross-correlation)

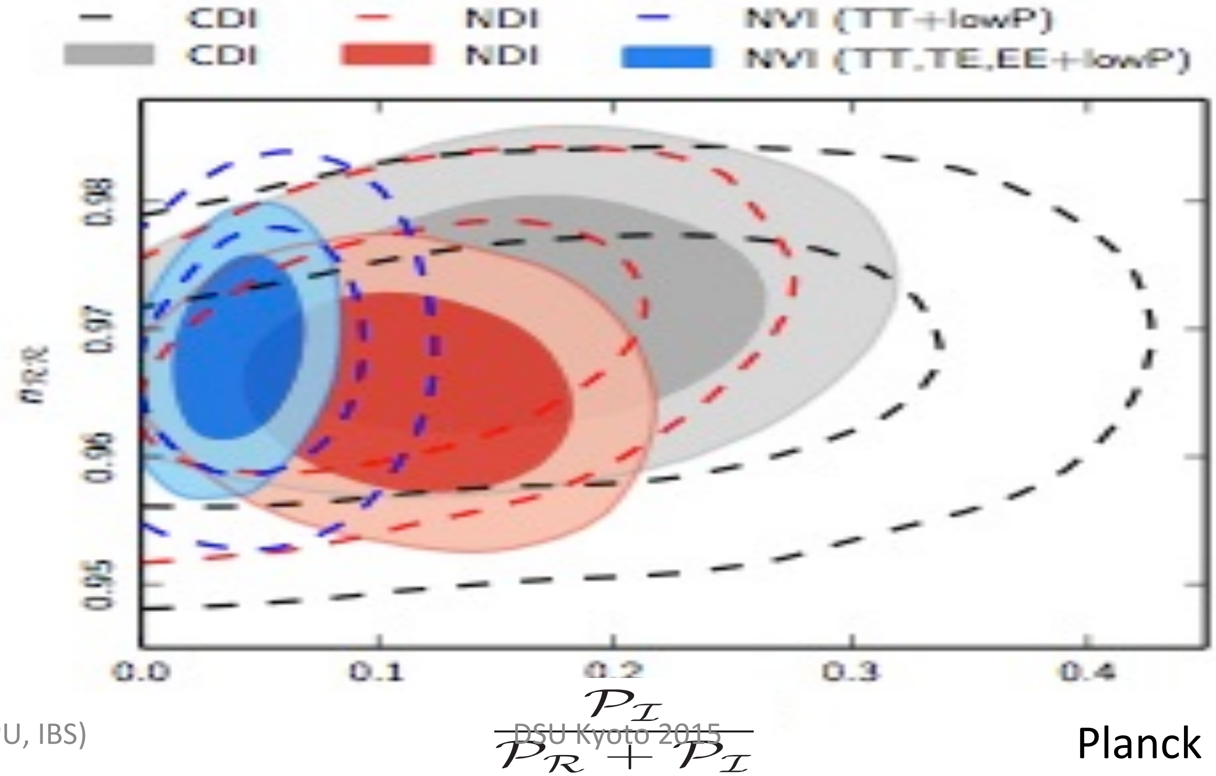
- Conclusion

$$P = P_R + P_I + P_C$$

Planck (2015) 95% CL

Uncorrelated isocurvature mode: $\dfrac{P_I}{P_R + P_I} < 0.038$

Cross-correlated isocurvature mode: $0.034 < \dfrac{P_I}{P_R + P_I} < 0.28$



Planck (2015)

Cross correlation between curvature and isocurvature perturbation

(Polarski, Starobinsky (1994), Pierpaoli, Garcia-Bellido, Borgani(1999), Enqvist, Kurki-Suonio (2000),Bucher,Noodley, Turok(2001), Amendola, Gordon, Wands, Sasaki (2002), ...)

$$P = P_R + P_I + P_C$$

$$\mathcal{P}_X = A_X(k_0)\left(\frac{k}{k_0}\right)^{n_X-1}$$

$$A_X = \begin{pmatrix} A_R & A_C \\ A_C & A_I \end{pmatrix} \qquad n_X = \begin{pmatrix} n_R & n_C \\ n_C & n_I \end{pmatrix}$$

χ : inflaton

a : energetically subdominant field (e.g. axion)

$$C_R \sim \int d^3k T_\chi(k) T_\chi(k) \langle \delta\chi(k)\delta\chi(k)\rangle$$

$$C_I \sim \int d^3k T_a(k) T_a(k) \langle \delta a(k)\delta a(k)\rangle$$

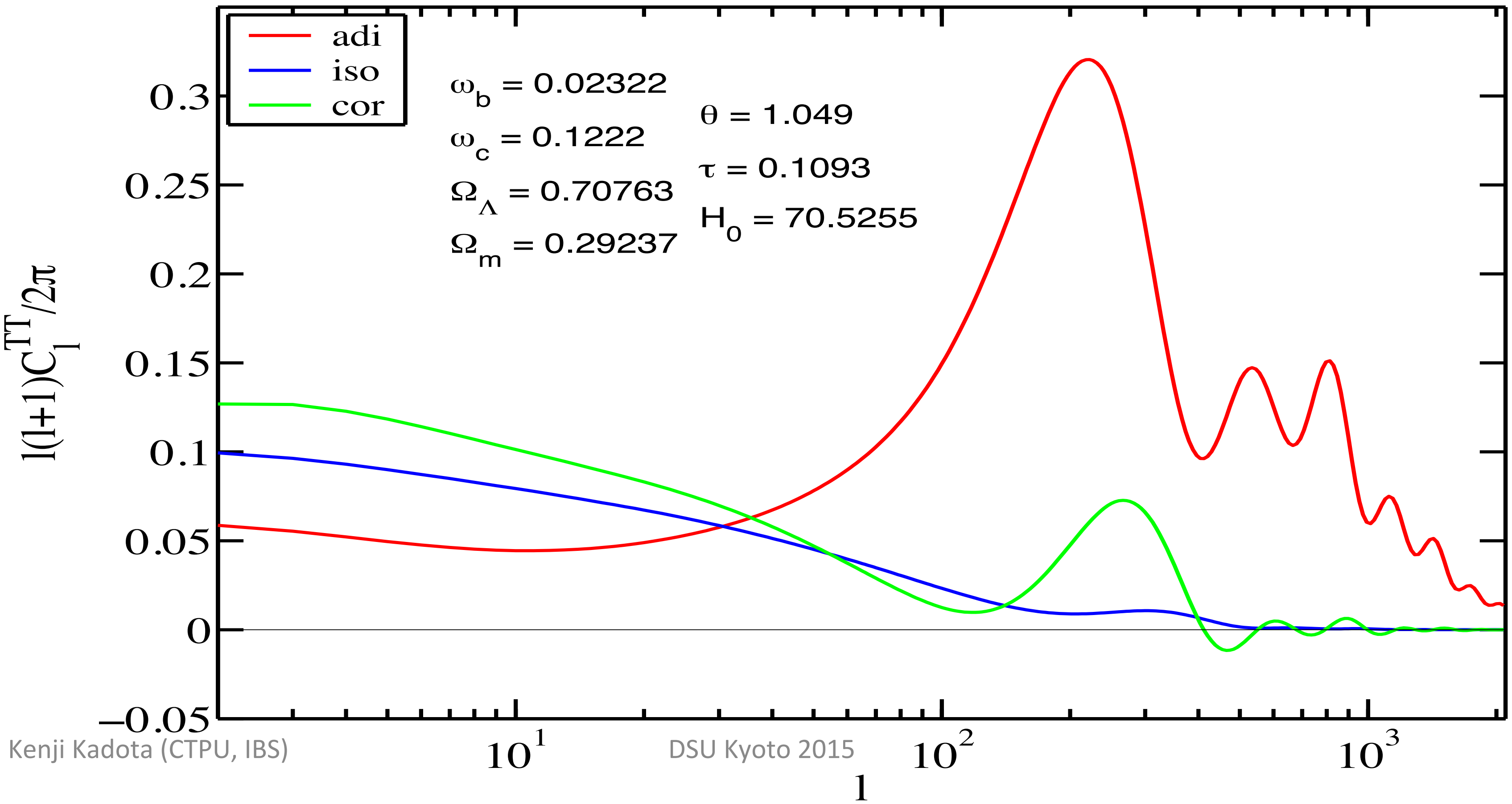
$$C_C \sim \int d^3k T_\chi(k) T_a(k) \langle \delta\chi(k)\delta a(k)\rangle$$

Two independent solutions for the acoustic wave equation

Adiabatic initial condition $$\frac{\Delta T}{T} \sim \cos(k c_s \eta_{dec})$$

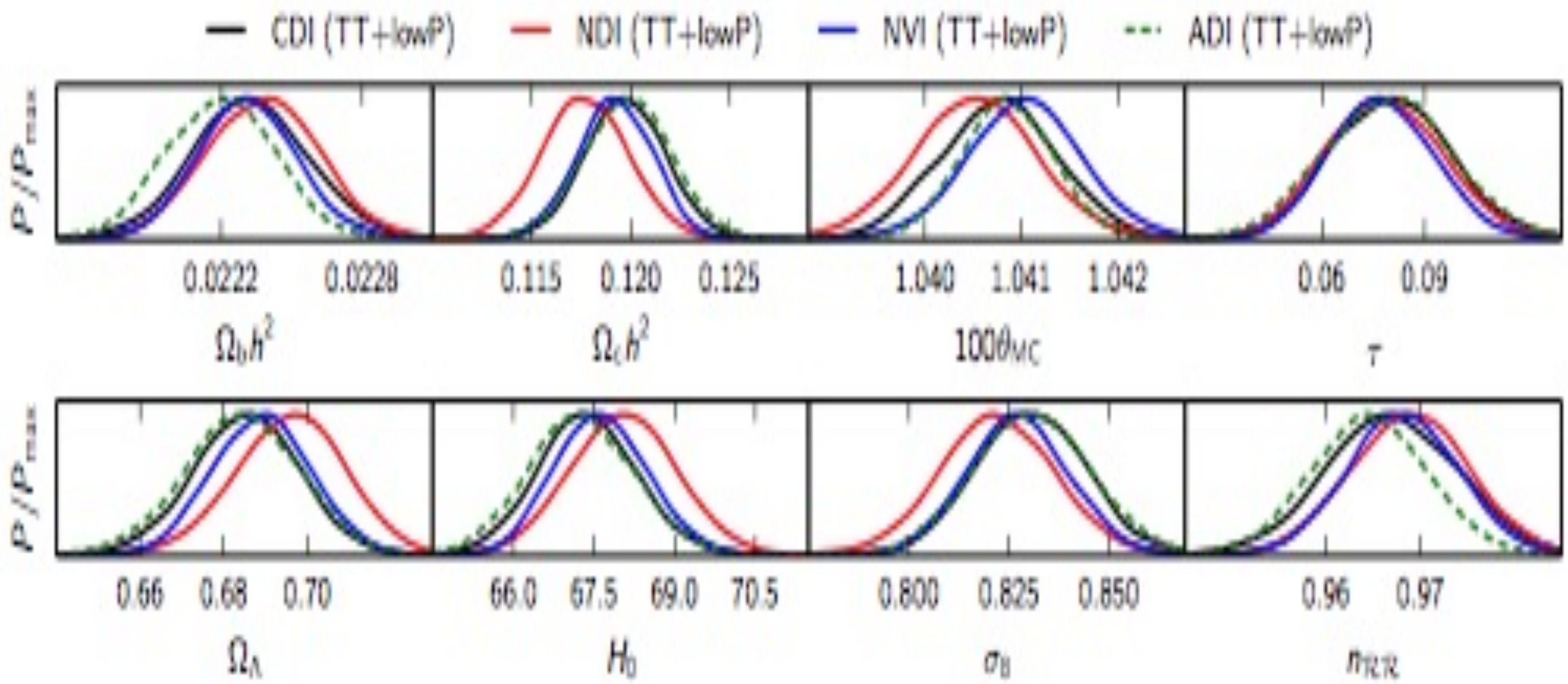
Isocurvature initial condition $$\frac{\Delta T}{T} \sim \sin(k c_s \eta_{dec})$$

Kurki-Suonio et al (2004)



Robustness of the base ΛCDM model against different assumptions on initial conditions

Planck (2015)



- Motivations for cross correlations:

- Parameter precision

- Concrete example: Axion (analytical formula for cross-correlation)

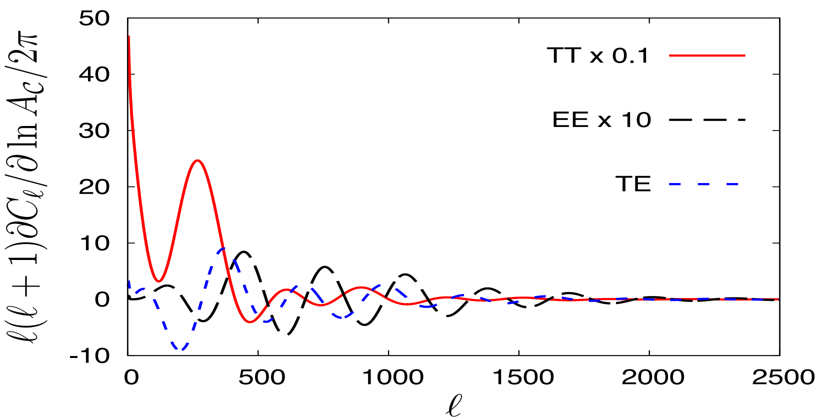
- Conclusion

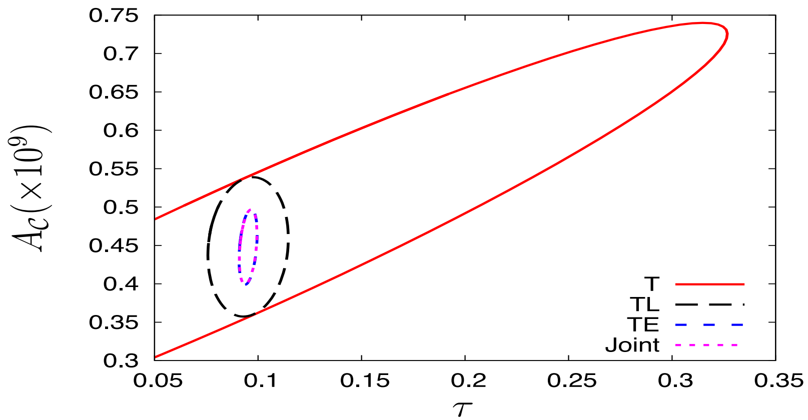
$$\beta_{\mathcal{C}} \equiv \frac{P_{\mathcal{C}}}{\sqrt{P_{\mathcal{R}} P_{\mathcal{I}}}}$$

How large does βc have to be, for the isocurvature parameters to be determined precisely by Planck?
βc ≥0.1

	T	TE	TL	Joint
$\beta_{\mathcal{C}} = 1$				
$\sigma(n_{\mathcal{I}})/n_{\mathcal{I}}$	33	13	21	12
$\sigma(A_{\mathcal{I}})/A_{\mathcal{I}}$	240	81	220	80
$\sigma(A_{\mathcal{C}})/A_{\mathcal{C}}$	65	11	20	11
$\beta_{\mathcal{C}} = 0.1$				
$\sigma(n_{\mathcal{I}})/n_{\mathcal{I}}$	110	39	65	38
$\sigma(A_{\mathcal{I}})/A_{\mathcal{I}}$	260	100	260	100
$\sigma(A_{\mathcal{C}})/A_{\mathcal{C}}$	230	76	170	74

Polarization Important!





KK, Gong, Ichiki and Matsubara (2014)

How much does βc affect the ΛCDM parameter estimations?
10% or more.

	Ω_Λ	$\Omega_m h^2$	$\Omega_b h^2$	$n_{\mathcal{R}}$	$A_{\mathcal{R}}$	τ
$\beta_{\mathcal{C}} = 1$	1.1	1.1	1.0	1.4	0.97	0.94
$\beta_{\mathcal{C}} = 0.1$	1.1	1.1	1.0	1.4	1.1	1.1
No correlation	1.0	1.0	1.0	1.1	1.1	1.1

Normalized error $\sigma/\sigma_{\text{no iso}}$

ΛCDM + isocurvature

ΛCDM

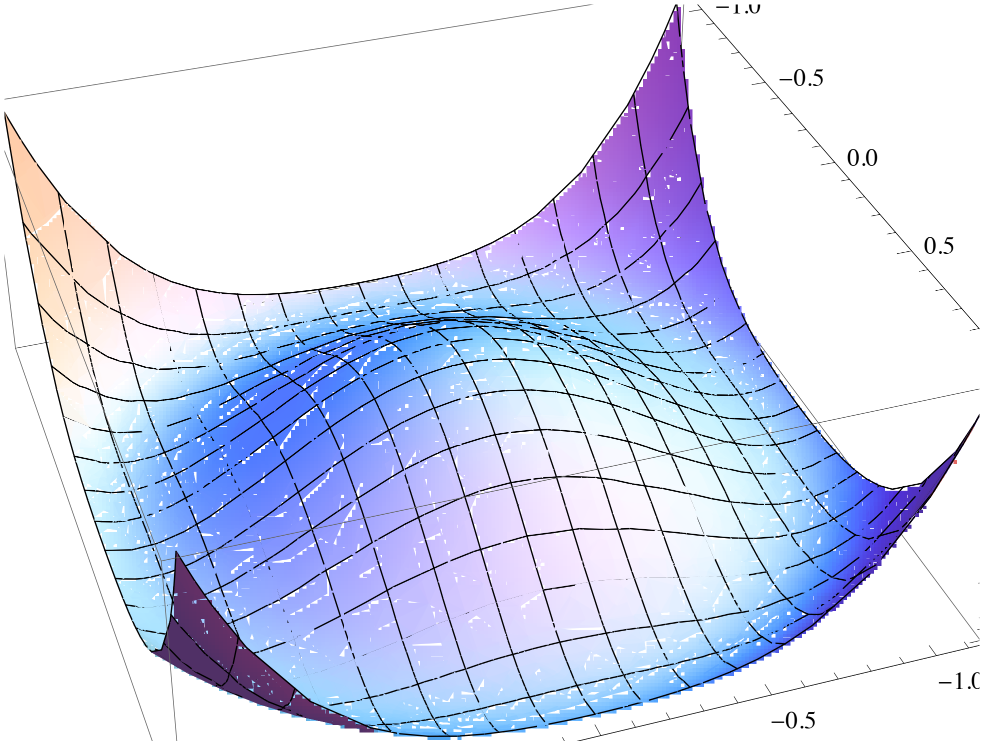
- Motivations for cross correlations:

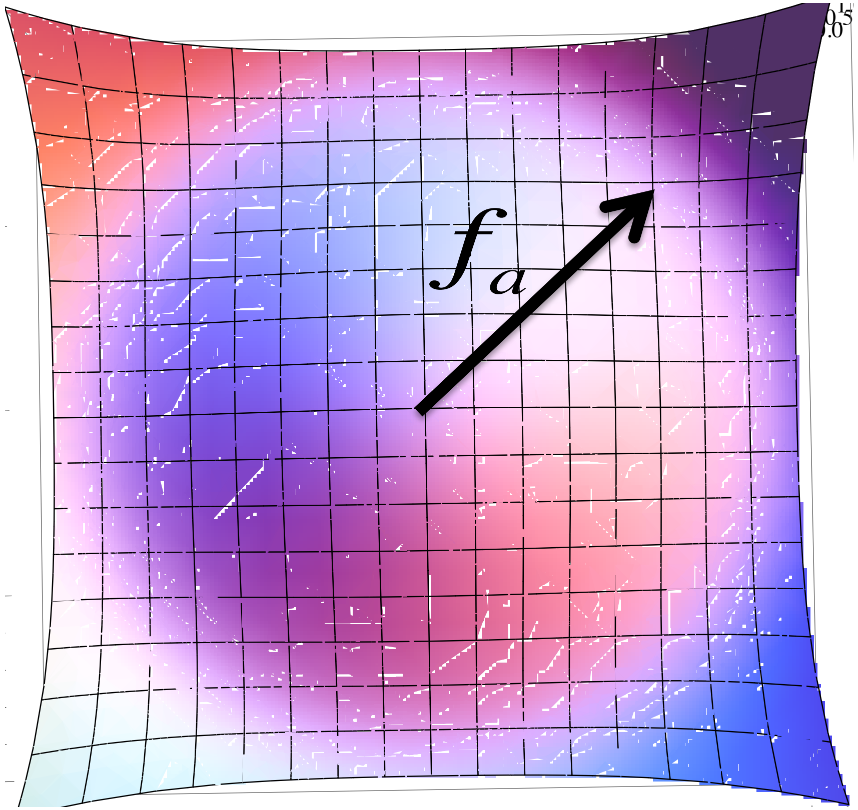
- Parameter precision

- Concrete example: Axion (analytical formula for cross-correlation)

- Conclusion

Example: Nambu-Goldstone boson





$$\phi = \frac{re^{i\theta}}{\sqrt{2}}, a = f_a\theta$$

Analytical Formula for βc in terms of axion parameters

1) Upper bound on βc in terms of axion parameters. Bc ~0.1 possible.

2) Implications: Spontaneous Symmetry breaking scale ~ Mp is desired

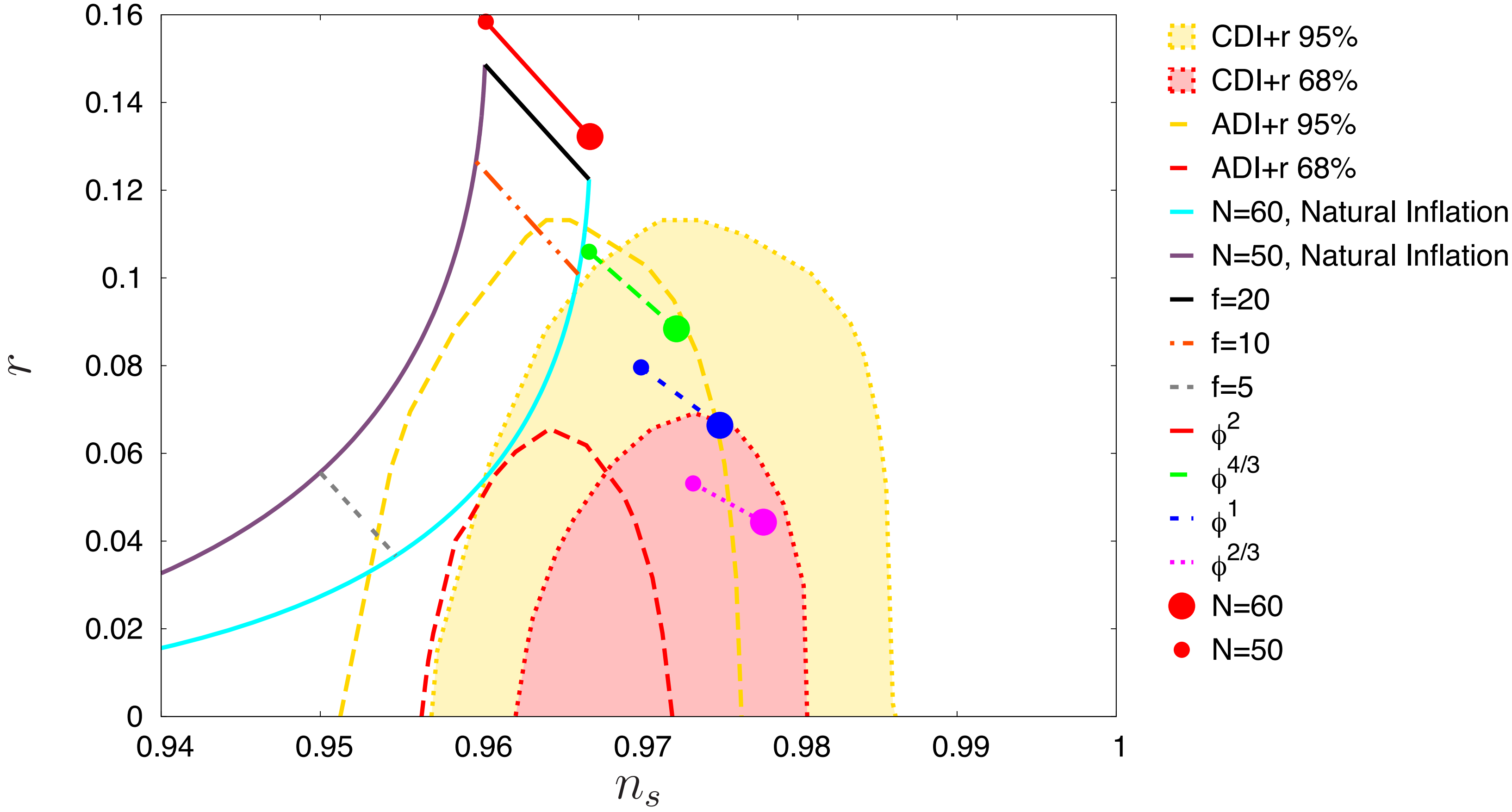
$$e.g.\ \mathrm{I}:\quad V \sim g\frac{\chi\phi^4}{m_{pl}} \qquad\qquad \frac{n_R+n_I}{2}=n_C$$

$$\beta_C \equiv \frac{P_C}{\sqrt{P_R P_I}} \sim g\sin(4\theta_0)\left(\frac{f_a}{m_{pl}}\right)^3\left(\frac{m_{pl}}{H}\right)^2$$

$$e.g.\ \mathrm{II}:\quad V_{\mathrm{int}} \sim g\frac{\chi^m\phi^n}{m_{pl}^{m+n-4}}$$

$$\beta_C \equiv \frac{P_C}{\sqrt{P_R P_I}} \sim g\sin(n\theta_0)\left(\frac{\chi_0}{m_{pl}}\right)^{m-1}\left(\frac{f_a}{m_{pl}}\right)^{n-1}\left(\frac{m_{pl}}{H}\right)^2$$

Model discrimination



Planck (2015), KK, Kobayashi, Otsuka(2015)

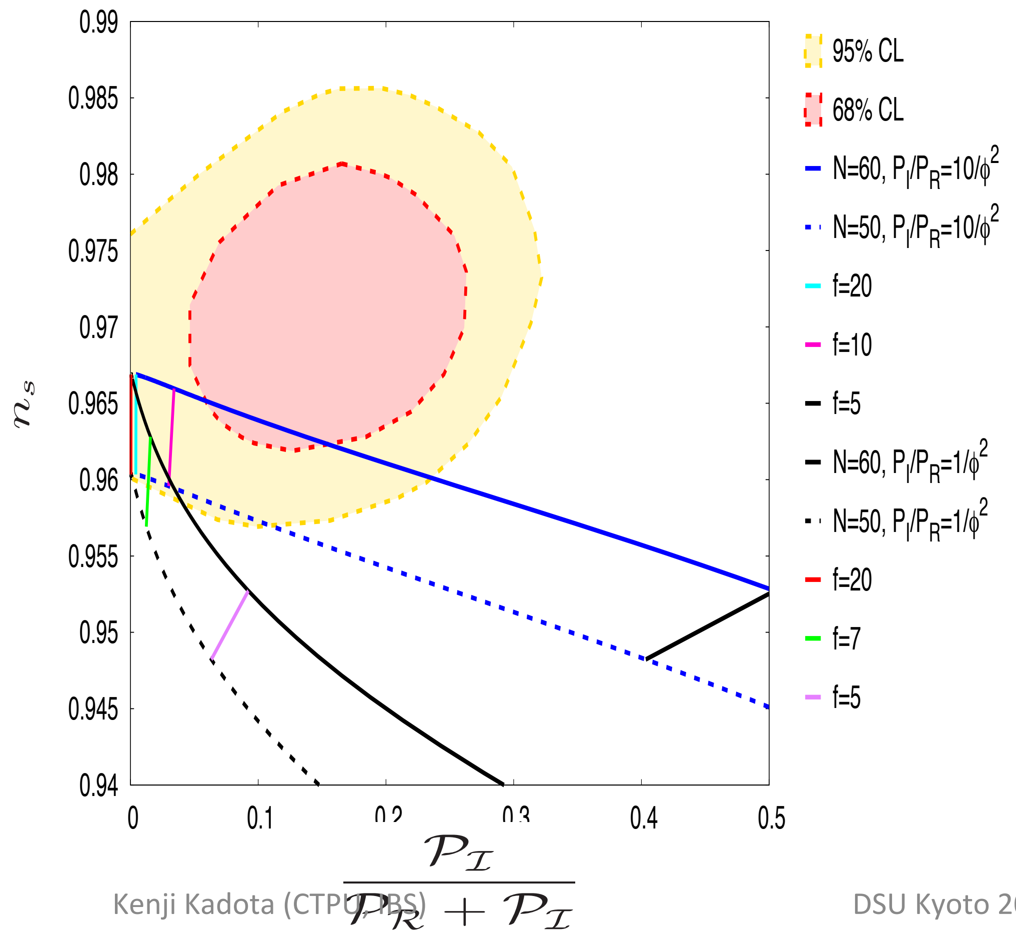
Concrete Example: Natural inflation (Freese, Frieman, Olinto (1990))

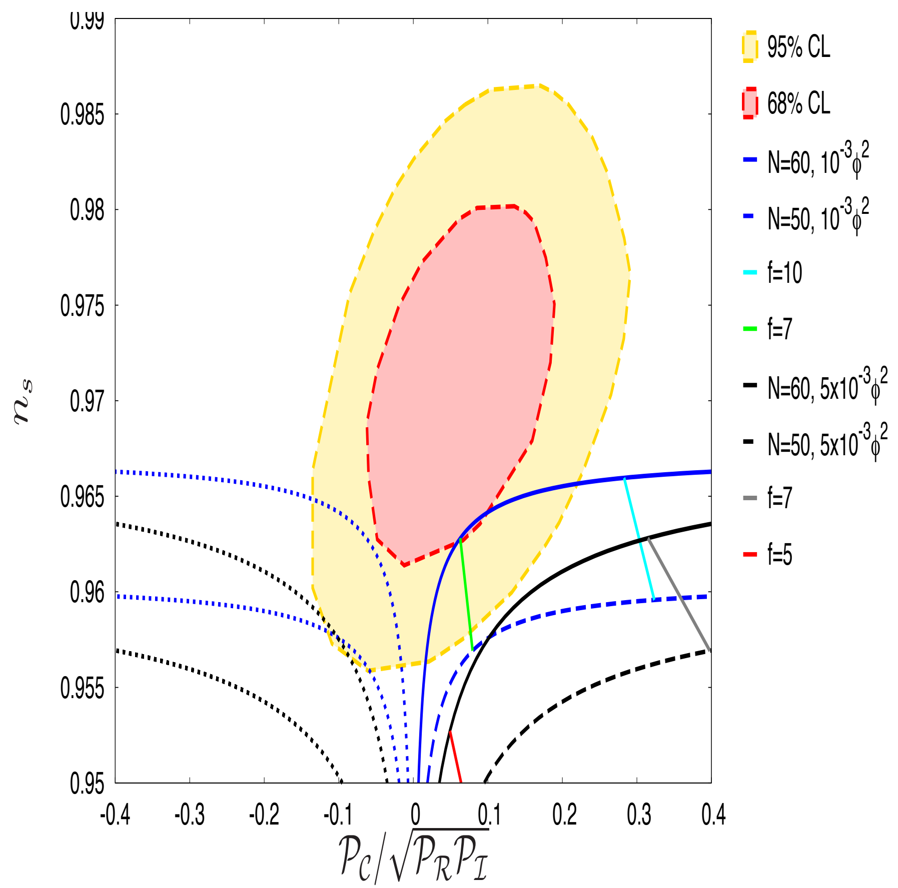
Adiabatic fluctuations:

$$V_{\rm inf} = \Lambda_1^4 \left(1 - \cos\frac{\phi}{f}\right)$$

Isocurvature fluctuations:

$$V_{\rm int} = \Lambda_2^4 \left(1 - \cos\left(\frac{\phi}{g_1} + \frac{\chi}{g_2}\right)\right)$$





KK, Kobayashi, Otsuka (2015)

Concrete Example:
Axion monodromy inflation (McAllister, Silverstein, Westphal (2008, 2010))

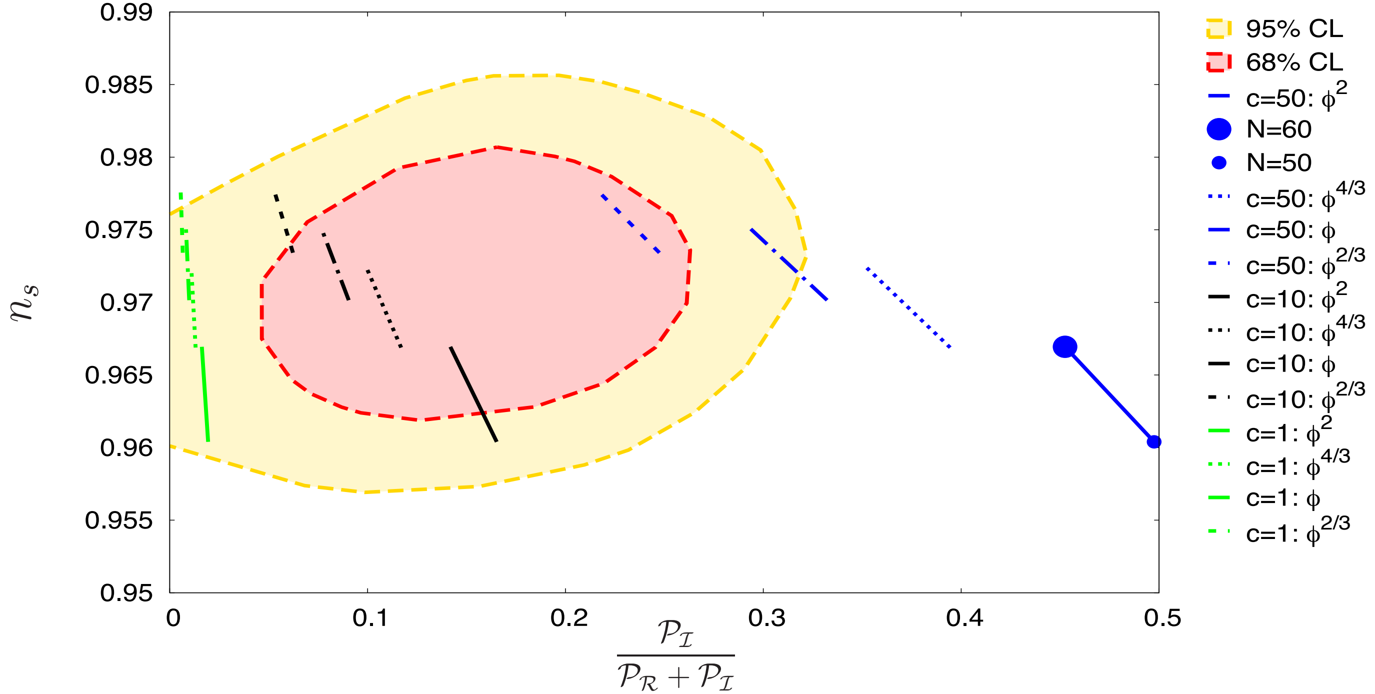
$$V = \mu_1^{4-p}\phi^p + \mu_2^4 \cos\left(\frac{\phi}{g_1} + \frac{\chi}{g_2}\right)$$

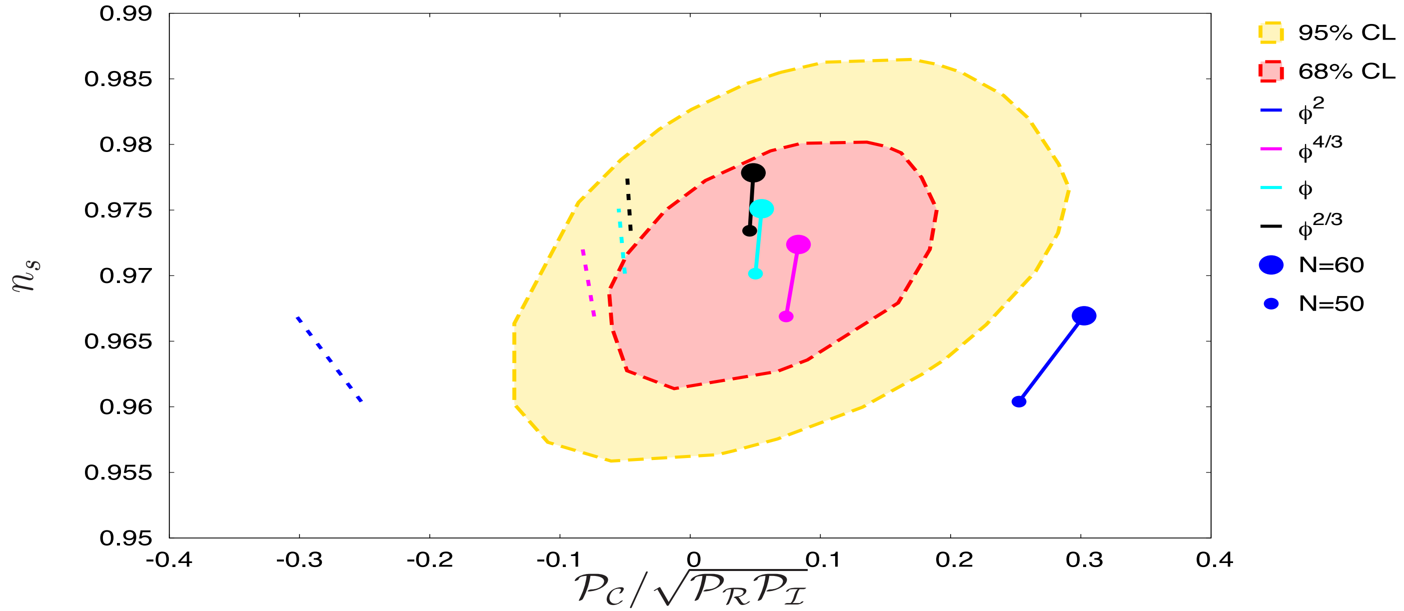
$$\frac{P_I}{P_R} \sim \left(\frac{\Omega_a}{\Omega_m}\right)^2 \left(\frac{1}{g_1\theta_0}\right)^2 \left(\frac{p}{\phi_0}\right)^2$$

$$\beta_C \sim \frac{1}{g_1 g_2}\frac{\mu_2^4}{A_S}\cos(\psi_0+\theta_0)\left(\frac{\phi_0}{p}\right)^2$$

KK, Kobayashi, Otsuka (2015)

p	N	g_1	g_2	μ_2^{4-p}/H^2	Ω_a/Ω_m	$\cos(\psi_0+\theta_0)$	θ_0	β_C	β_{iso}	n_s
2	55	10^{-2}	10^{-2}	6×10^{-7}	0.03	1/2	2	0.002	0.14	0.964
4/3	55	10^{-2}	10^{-2}	3×10^{-7}	0.03	1/2	2	0.001	0.1	0.97
1	55	10^{-2}	10^{-2}	4×10^{-7}	0.03	1/2	2	0.001	0.08	0.973
2/3	55	10^{-2}	10^{-2}	4×10^{-7}	0.03	1/2	2	0.001	0.05	0.976





KK, Kobayashi, Otsuka (2015)

Conclusion:

- CMB measurement perspectives:

Polarization is very powerful to constrain the isocurvature cross-correlation.

ΛCDM parameter estimation can be affected by 10% or more.

- Cross-correlated isocurvature modes through a concrete example: Axion

Inflation model discrimination:
preferred for the monodromy inflation, disfavored for natural inflation.