新学術シンポジウム
March 9, 2017 KEK

EXPLORING TOPICS ON THE BORDER OF ACCELERATING UNIVERSE

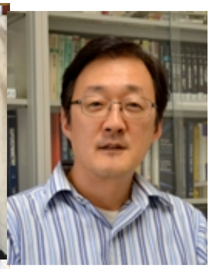
Kazuhiro Yamamoto (Hiroshima U)

Today's talk is based on the works with

Y. Ueno

N. Oshita

S. Iso



C. Hikage

Y. Nan

R. Tatsukawa

K.Ueda

Zhang

From Murayama-san’s talk

No only one way to the goal

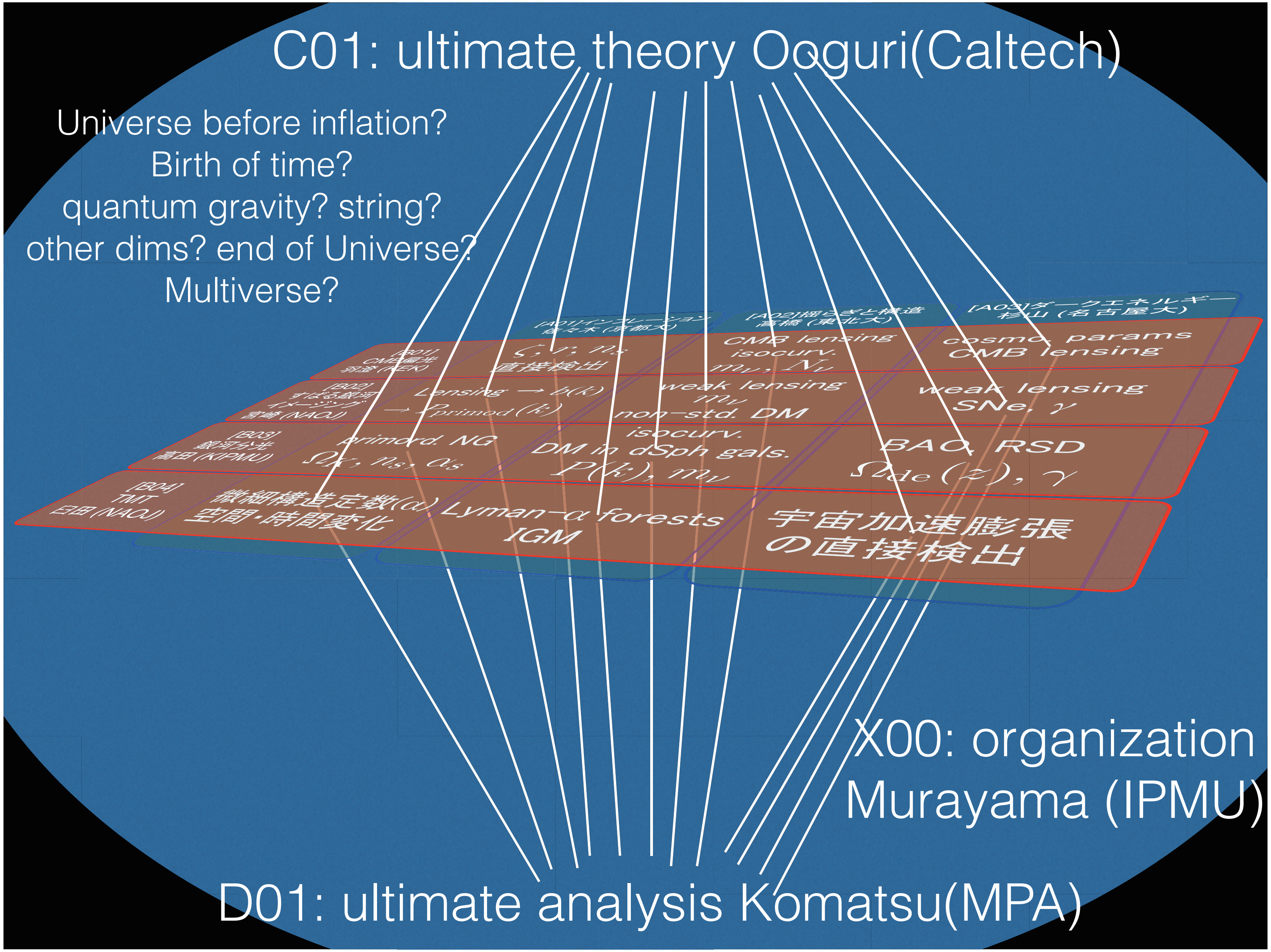
3 pillars of science (theory)

4 approaches (expt, obs)	[A01] Inflation Sasaki (Kyoto)	[A02] fluent. & struct. Takahashi (Tohoku)	[A03] Dark Energy Sugiyama (Nagoya)
[B01] CMB polariz. Hazumi (KEK)	ζ, r, n_s direct evidence	CMB lensing isocurv. m_ν, N_ν	cosmo. params CMB lensing
[B02] Subaru galaxy imaging Miyazaki(NAOJ)	Lensing → $b(k)$ $\rightarrow P_{\rm primod}(k)$	weak lensing m_ν non-std. DM	weak lensing SNe, γ
[B03] galaxy spectroscopy Takada(KIPMU)	primord. NG Ω_K, n_s, α_s	isocurv. DM in dSph gals. $P(k), m_\nu$	BAO, RSD $\Omega_{\rm de}(z), \gamma$
[B04] TMT Usuda (NAOJ)	QED coupling (α) space time var.	Lyman-α forests IGM	direct detection of acceleration

important observables at each intersection

From Murayama-san’s talk

from view point of fundamental theory



Middle results published on the journals

- S. Iso, N. Oshita, R. Tatsukawa, K. Yamamoto, S. Zhang, *Quantum radiation produced by the entanglement of quantum fields,* Phys. Rev. D **95** 023512 1-6 (2017)
- K. Yamamoto, Y. Nan, C. Hikage, *An analytic halo approach to the bispectrum of galaxies in redshift space,* Phys. Rev. D **95**, 043528 1-17 (2017)
- R. Kimura, T. Tanaka, K. Yamamoto, Y. Yamashita, *Constraint on ghost-free bigravity from gravitational Cherenkov radiation,* Phys. Rev. D **94** 064059 (2016)
- Y. Ueno, K. Yamamoto, *Constraints on alpha-attractor inflation and reheating,* Phys. Rev. D **93** 0835241 (2016)
- K. Yamamoto, V. Marra, V. Mukhanov, M. Sasaki, *Perturbed Newtonian description of the Lemaître model with non-negligible pressure,* JCAP 03(2016)030
- N. Oshita, K. Yamamoto, S. Zhang, *Unruh radiation produced by a uniformly accelerating charged particle in thermal random motions,* Phys. Rev. D **93** 085016 (2016)
- S. Kiyota, K. Yamamoto, *Constraint on modified dispersion relations for gravitational waves from gravitational Cherenkov radiation,* Phys. Rev. D **92** 104036 (2015)
- N. Oshita, K. Yamamoto, S. Zhang, *Quantum radiation from a particle in an accelerated motion coupled to vacuum fluctuations,* Phys. Rev. D **92** 045027 (2015)
- C. Hikage, K. Yamamoto, *Finger-of-God effect of infalling satellite galaxies,* MNRAS **455** L77 (2015)
- A. Terukina, K. Yamamoto, N. Okabe, K. Matsuhita, T. Sasaki, *Testing a generalized cubic Galileon gravity model with the Coma Cluster,* JCAP 10(2015)064
- Y. Takushima, A. Terukina, K. Yamamoto, *Third order solutions of the cosmological density perturbations in the Horndeski's most general scalar-tensor theory with the Vainshtein mechanism*, Phys. Rev. D. **92** 104033 (2015)

I thank the PI Ooguri-san and Murayama-san,
everyone involved in the project, and the collaborators.

Topics and summary of results

- 1. Inflation

    constraint on the parameter n_s from CMB
    → constraint on reheating process

- 2. Quantum vacuum physics - the cosmological constant problem ?

    Unruh effect, a theoretical prediction on quantum field theory, can be seen in radiation from a uniformly accelerated d.o.f.
    The signal reflects the nonlocal correlation of the vacuum, which has its origin in the entanglement of the quantum field.

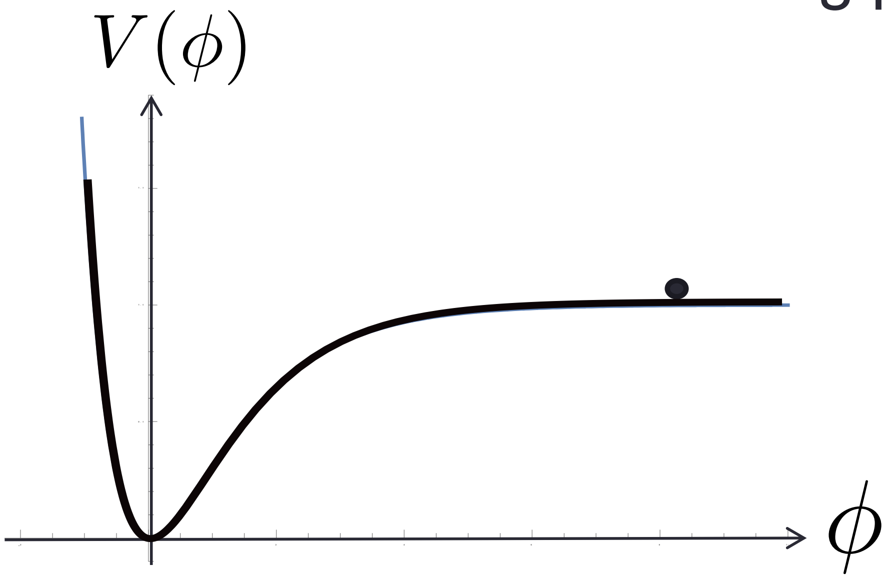
- 3. Large scale structure of galaxies

    development of analytic theoretical model for galaxy bispectrum in redshift space

1. Inflation

constraint on inflation parameter
→ reheating process

Y. Ueno



$$n_s - 1 = -3M_{pl}^2 \left(\frac{V'}{V}\right)^2 + 2M_{pl}^2 \left(\frac{V''}{V}\right)$$

$$r = 8M_{pl}^2 \left(\frac{V'}{V}\right)^2$$

Planck Collaboration (2016)

(TT, TE, EE+lowP+lensing+ext)

$$n_s = 0.9967 \pm 0.0040$$

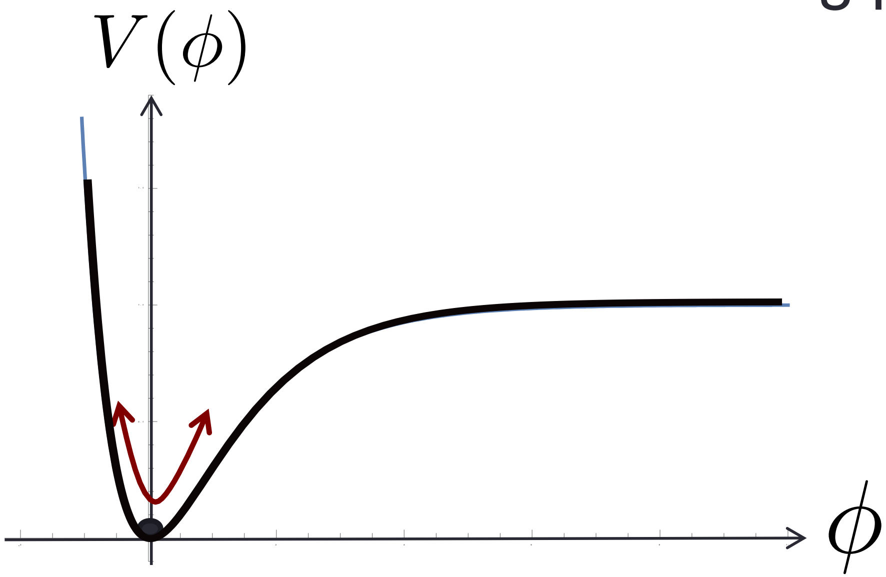
$$r < 0.11$$

1. Inflation

constraint on inflation parameter

→ reheating process

Y. Ueno



oscillation of inflaton field

lighter particles

big-bang universe

Planck Collaboration (2016)

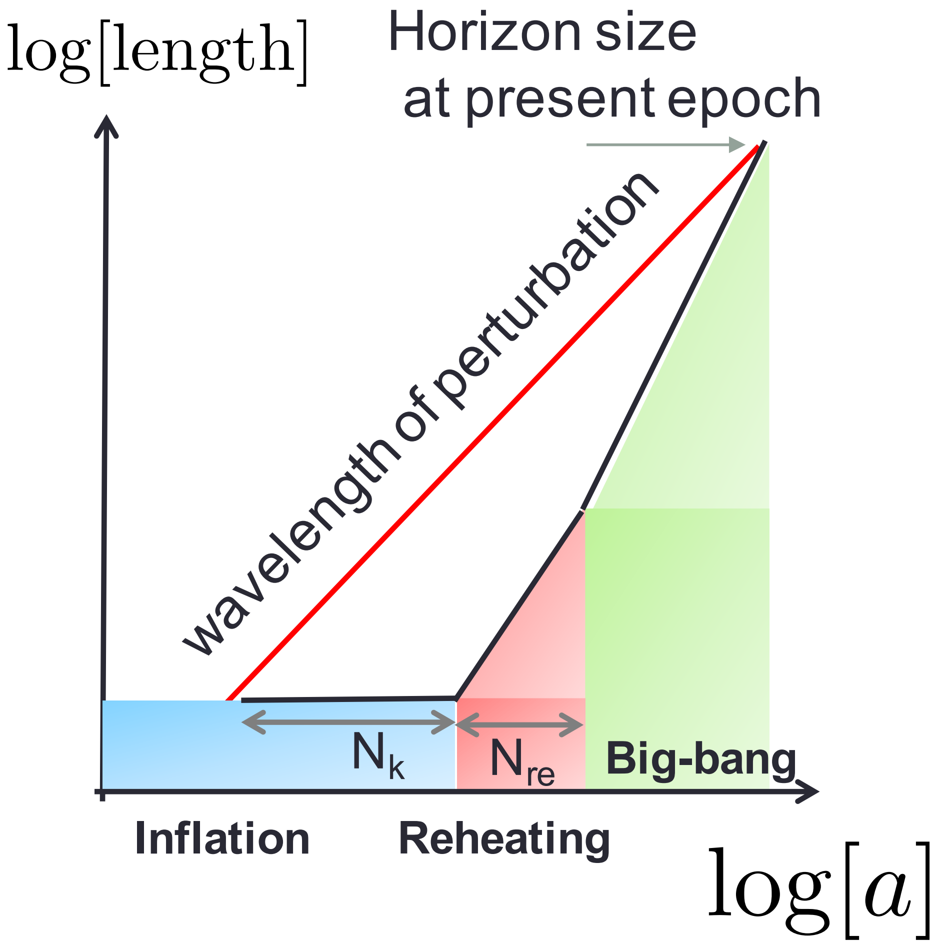
(TT, TE, EE+lowP+lensing+ext)

$$n_s = 0.9967 \pm 0.0040$$

$$r < 0.11$$

$$n_s - 1 = -3M_{pl}^2\left(\frac{V'}{V}\right)^2 + 2M_{pl}^2\left(\frac{V''}{V}\right)$$

$$r = 8M_{pl}^2\left(\frac{V'}{V}\right)^2$$



The pivot scale of n_s
$\rightarrow$ the horizon scale.

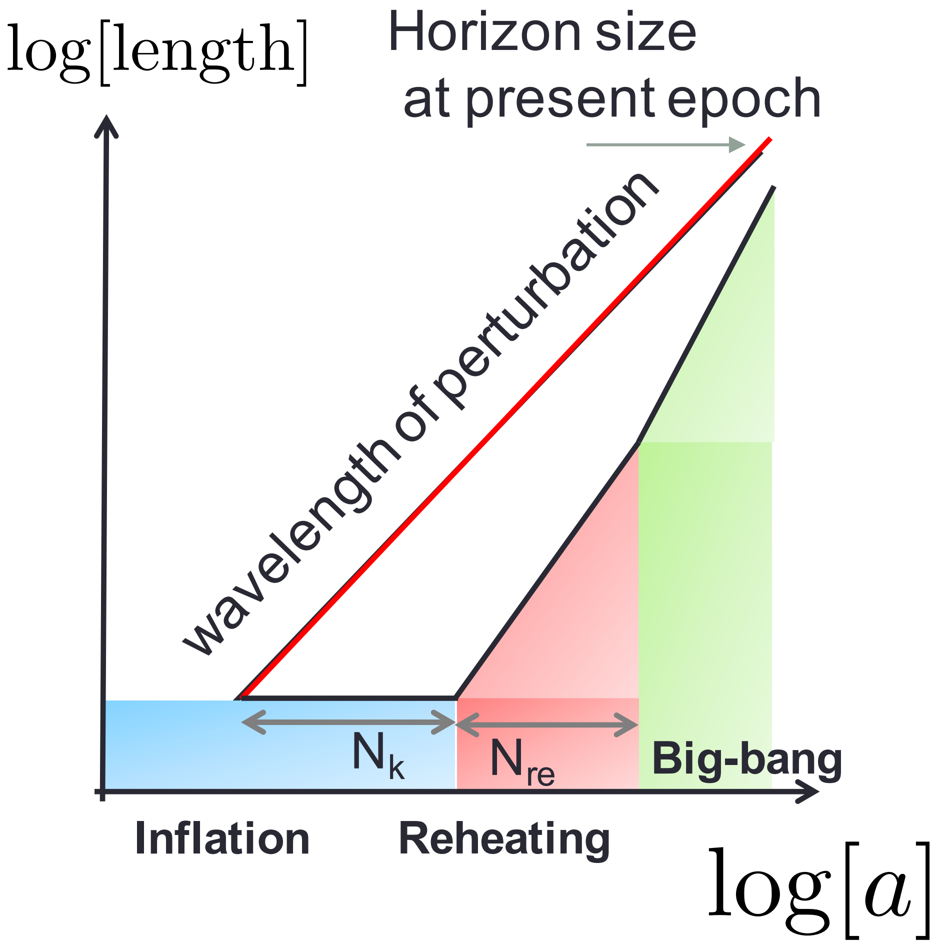
The pivot scale perturbation is generated when the wavelength of perturbation crosses the horizon.

The e-folding of inflation N_k is determined if the potential is known.

We assume the equation of state w_{re} and the e-folding N_{re} of reheating.

After the reheating, the universe becomes the big-bang universe.

Tetragon is closed



The pivot scale of n_s
$\rightarrow$ the horizon scale.

The pivot scale perturbation is generated when the wave-length of perturbation crosses the horizon.

The e-folding of inflation N_k is determined if the potential is known.

We assume the equation of state w_{re} and the e-folding N_{re} of reheating.

After the reheating, the universe becomes the big-bang universe.

Tetragon is closed

constraint on
N_{re} (e-folding for reheating)

Alpha-attractor model

Galante, Kallosh, Linde (2015)
Carrasco, Kallosh, Linde (2015)

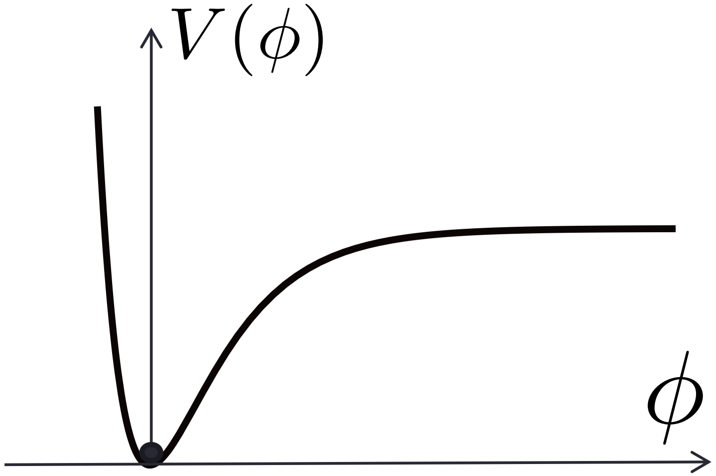
E-model

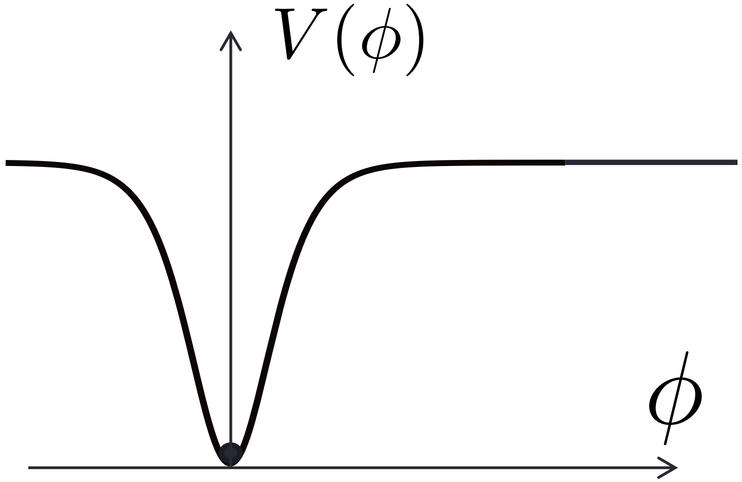
$$V = \Lambda^4 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\phi/M_{\rm pl}}\right)^{2n}$$

T-model

$$V = \Lambda^4 \tanh^{2n}\left(\frac{\phi}{\sqrt{6\alpha}\mathrm{M_{pl}}}\right),$$

$\alpha,\ n$ (parameter)



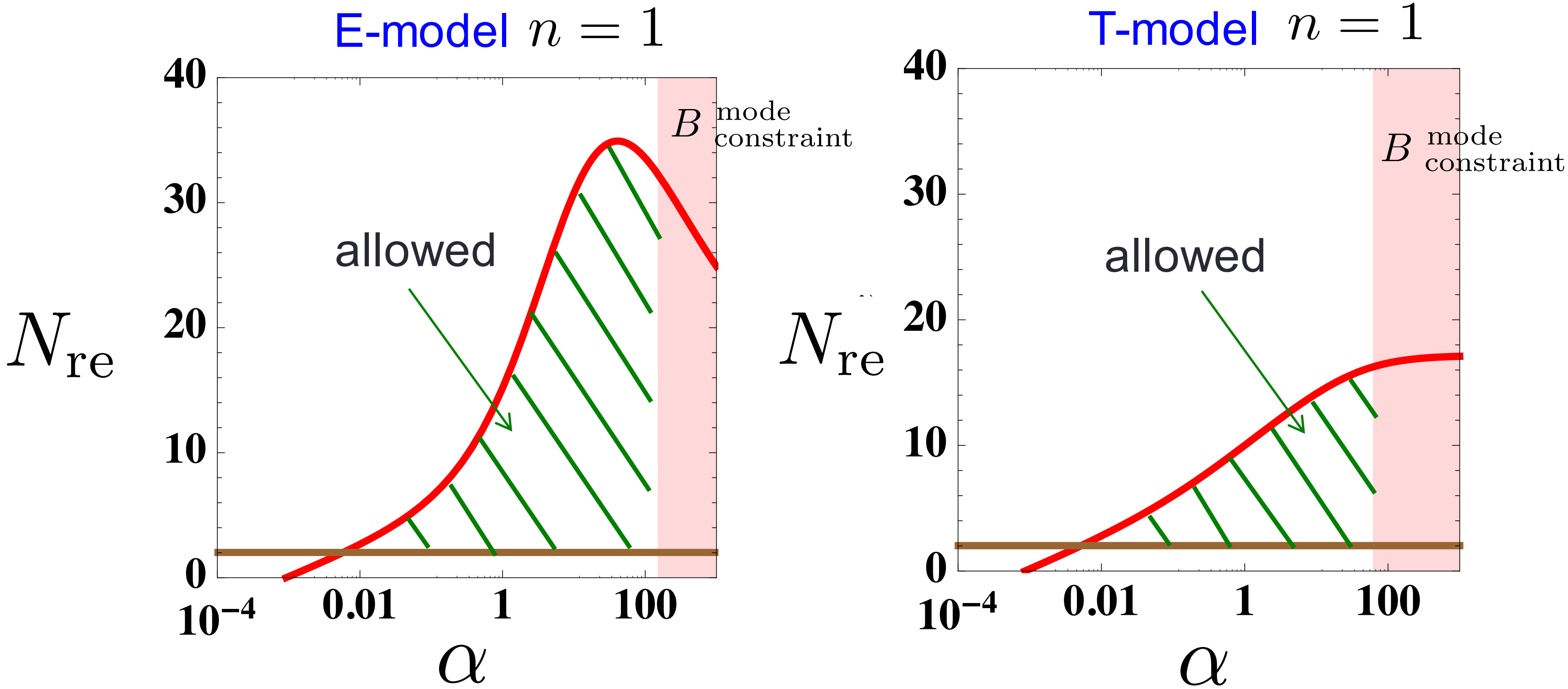


Equation of state parameter during reheating

$$V(\phi) \propto \phi^{2n} \quad \dashrightarrow \quad w_{\rm re} = \frac{n-1}{n+1}$$

Virial equilibrium
for oscillation energy

Constraint on the e-folding of reheating N_{re}



Perturbative reheating scenario

$$L_I = -g\phi\chi^2$$

Decay rate

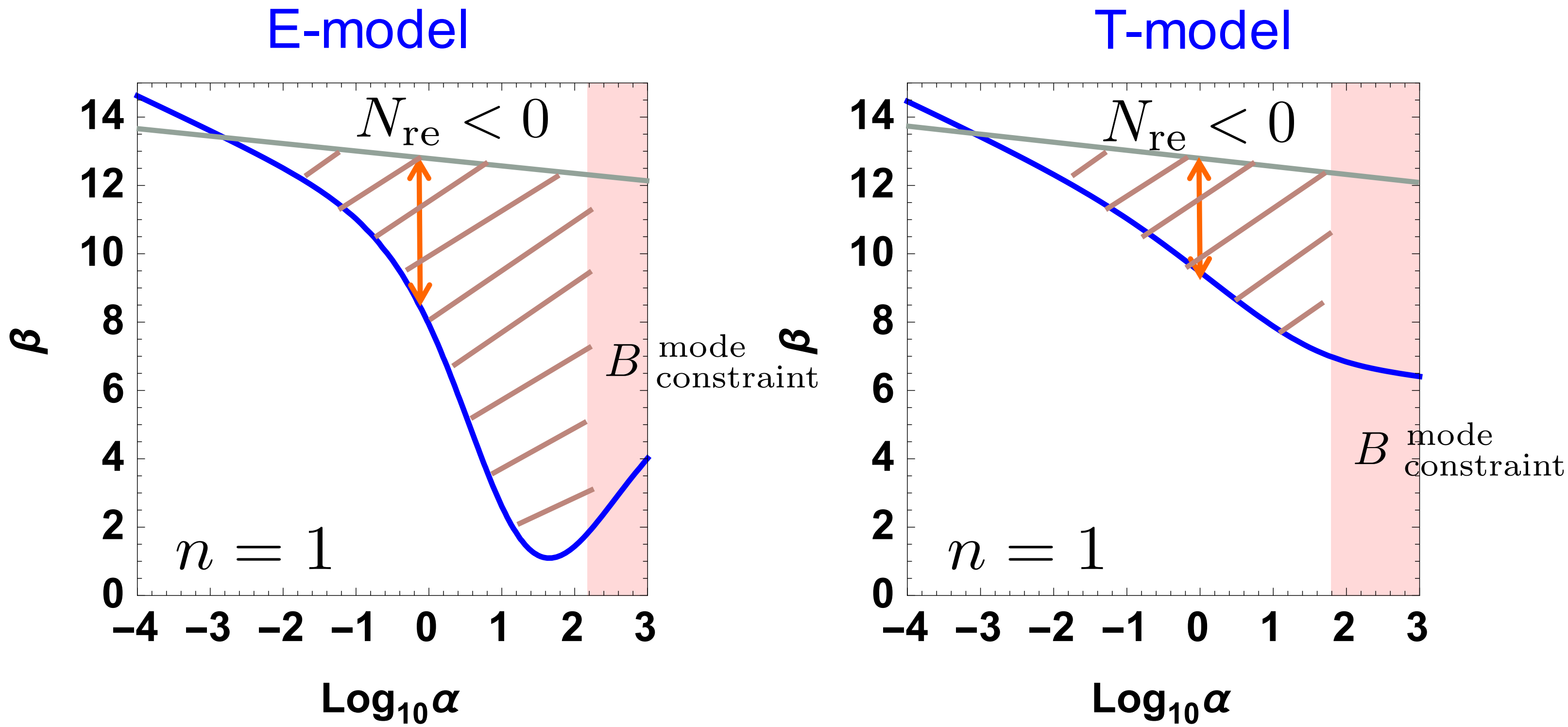
$$\Gamma_{\phi\to\chi\chi} = \frac{g^2}{8\pi m_\phi}$$

duration of reheating

Constraint on the coupling constant *g*

$$g = 10^{\beta}\left(\frac{\Lambda}{10^{15}\mathrm{GeV}}\right)\mathrm{GeV}$$

$$m_\phi = 10^{13}\mathrm{GeV}$$



$\alpha = 1$ $\alpha = 1$

$10^{8}\mathrm{GeV} < g < 10^{13}\mathrm{GeV}$ $10^{9.5}\mathrm{GeV} < g < 10^{13}\mathrm{GeV}$

more stringent constraint in future

$$\Lambda = 10^{15}\mathrm{GeV}$$

2. *Quantum vacuum physics*

S. Iso N.Oshita R. Tatsukawa
+ S. Zhang + K. Ueda

Unruh effect Unruh (1976)

Entanglement in Unruh effect Wald, Unruh (1984)

signal of the Unruh effect
→quantum radiation produced by the entanglement of quantum fields
→testing entanglement of quantum fields

cf. entanglement in cosmology

Quantum nonlocal correlation in cosmology Maldacena (2016)

Entangled initial quantum state in inflations Albrecht, et al (2014)
Kanno (2015)

Entanglement in quantum fluctuations in de Sitter spacetime
Nambu (2008, 2013)
Kanno, Jonathan, Soda (2015)
Kanno, Tanaka, Sasaki (2017)

roles in quantum gravity

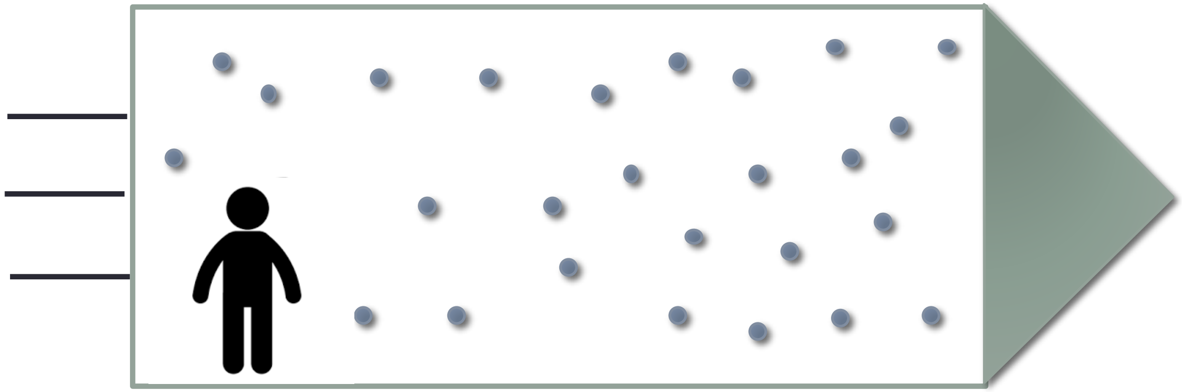
Unruh (1976)

Unruh effect

- A observer in an uniformly accelerated motion sees the Minkowski vacuum as a thermally excited state.

a

acceleration



Unruh Temperature $$T_U = \frac{a}{2\pi} = 4\times 10^{-20}\,\mathrm{K}\left(\frac{a}{9.8\,\mathrm{m/s^2}}\right)$$

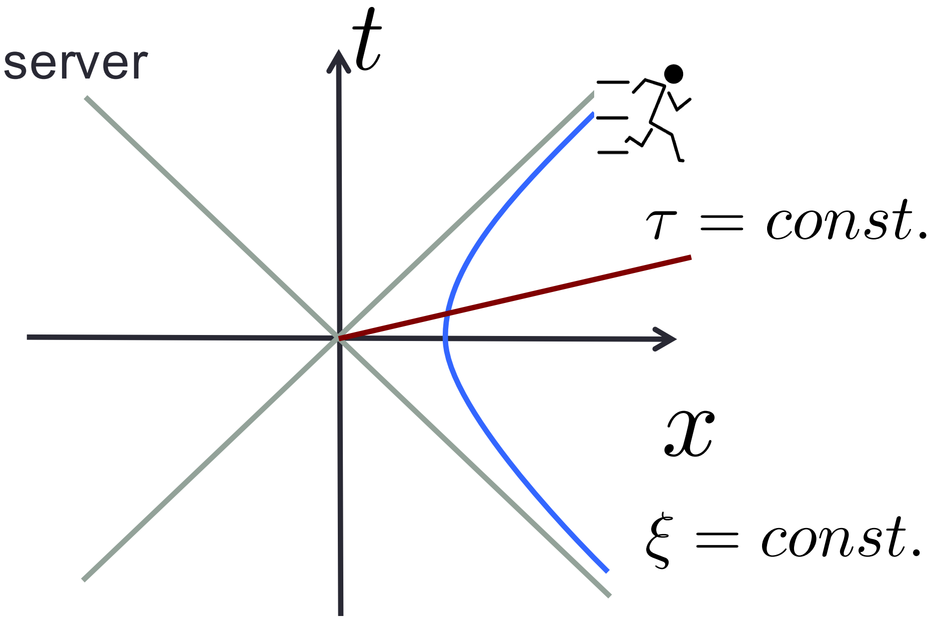
Signals of the Unruh effect will be tiny ,
but discussions of detecting the signal

Rindler coordinate for a observer in a uniformly accelerating motion

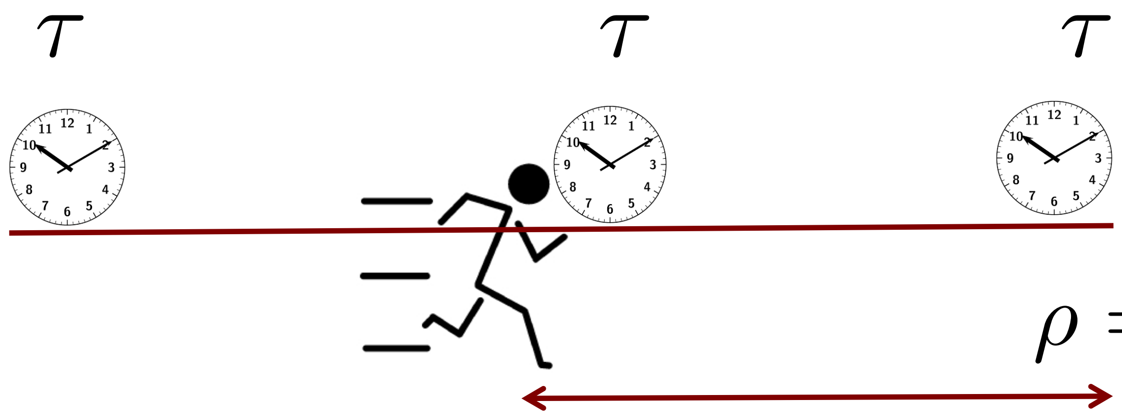
trajectory of the observer

$$t = \frac{1}{a}\sinh a\tau$$

$$x = \frac{1}{a}\cosh a\tau$$

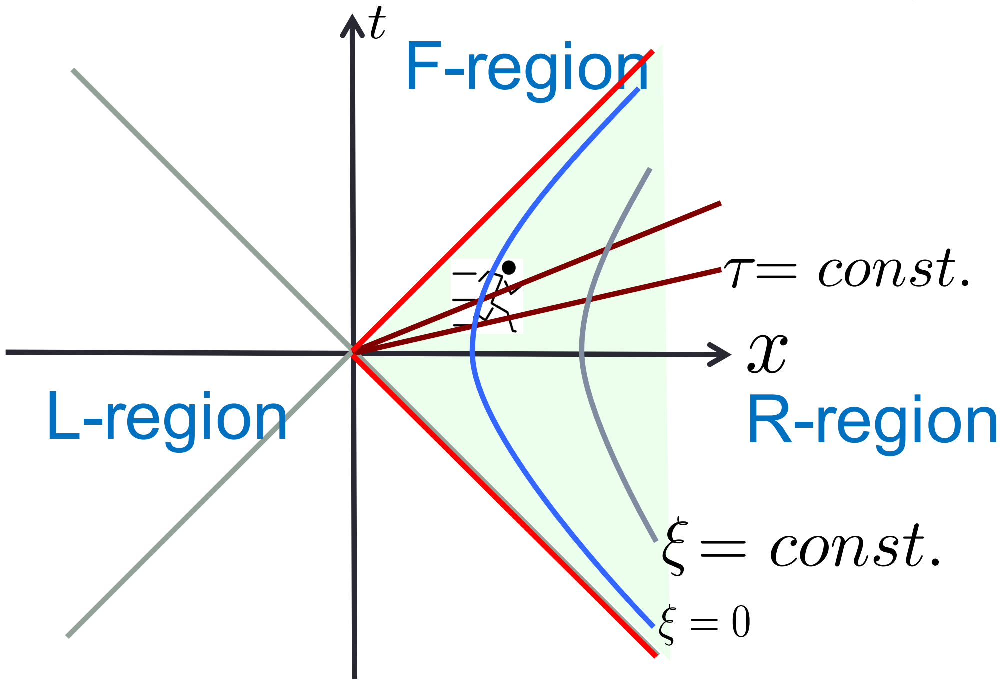


A observer in a uniformly accelerating motion has a stick of the length ρ and the clock τ



$$\rho = \frac{1}{a}(e^{a\xi} - 1)$$

Rindler coordinate



$$t = \frac{e^{a\xi}}{a}\sinh a\tau \qquad x = \frac{e^{a\xi}}{a}\cosh a\tau$$

$$ds^2 = e^{2a\xi}(d\tau^2 - d\xi^2) - d\mathbf{x}_\perp^2$$

massless scalar field

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi)$$

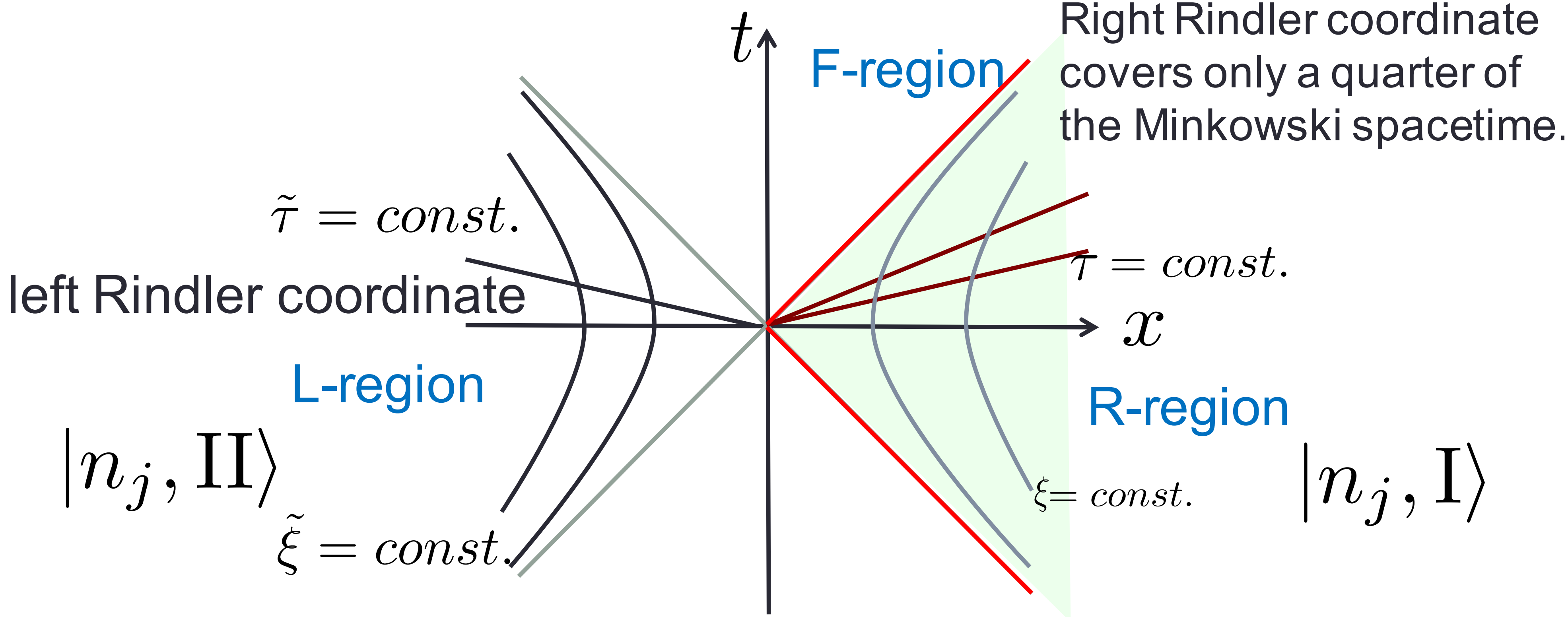
quantization

$$\hat{\phi}_R(x_R) = \int_0^\infty d\omega \int d^2k_\perp \left(\hat{a}^I_{\omega,\mathbf{k}_\perp} v^R_{\omega,\mathbf{k}_\perp}(x_R) + \mathrm{h.c.}\right),$$

$$v^R_{\omega,\mathbf{k}_\perp}(x_R) = \sqrt{\frac{\sinh \pi\omega/a}{4\pi^4 a}}\, e^{-i\omega\tau} K_{i\omega/a}\left(\frac{\kappa e^{a\xi}}{a}\right) e^{i\mathbf{k}_\perp\cdot\mathbf{x}_\perp},$$

right Rindler vacuum state $\hat{a}^I_{\omega,\mathbf{k}_\perp}|0,\mathrm{I}\rangle = 0$ for any $\omega, \mathbf{k}_\perp$

excited state $|n_j,\mathrm{I}\rangle = \frac{1}{\sqrt{n_j!}}(\hat{a}^{I\dagger}_{\omega,\mathbf{k}_\perp})^{n_j}|0,\mathrm{I}\rangle \qquad j = (\omega, \mathbf{k}_\perp)$



Minkowski vacuum is expressed as the entangled state between the right-Rindler states and the left-Rindler states.

Wald, Unruh (1984)

$$|0, \mathrm{M}\rangle = \prod_j \left[N_j \sum_{n_j=0}^{\infty} e^{-\pi n_j \omega_j / a} |n_j, \mathrm{I}\rangle \otimes |n_j, \mathrm{II}\rangle \right]$$

$$j = (\omega, \mathbf{k}_\perp)$$

$$N_j = \sqrt{1 - e^{-2\pi\omega_j / a}}$$

$$\hat{\rho}_R = Tr_L(|0, M\rangle\langle 0, M|) = \prod_j [\sum_{n_j=0}^{\infty} e^{-2\pi n \omega_j / a} |n_j, I\rangle\langle n_j, I|]$$

thermal state with Unruh temperature

Entanglement is an important aspect of Unruh effect

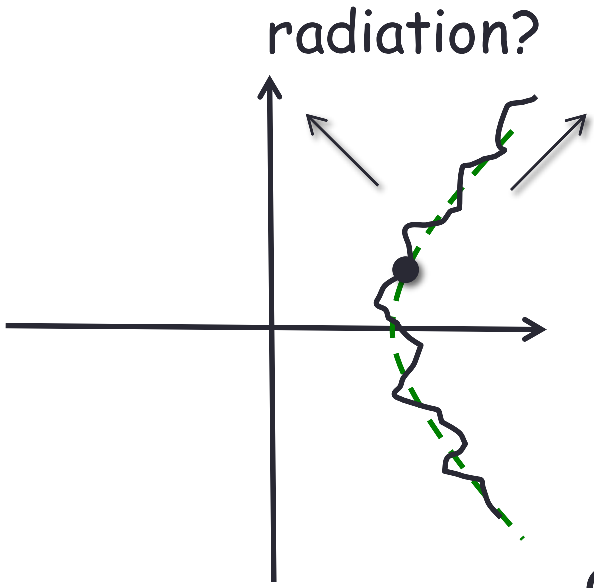
possibility of detecting the Unruh effect ?

electron acceleration with an intense laser

Chen, Tajima (99)
Schutzhold, et al (06)

electric field ~ $eE = 10^{13}\,\mathrm{eV/cm}$

for an electron, $T_U = \dfrac{\hbar a}{2\pi c k_B} = 7\times 10^{5}\,\mathrm{K}\left(\dfrac{eE}{10^{13}\,\mathrm{eV/cm}}\right)$



radiation from a particle coupled to the vacuum fluctuations ?

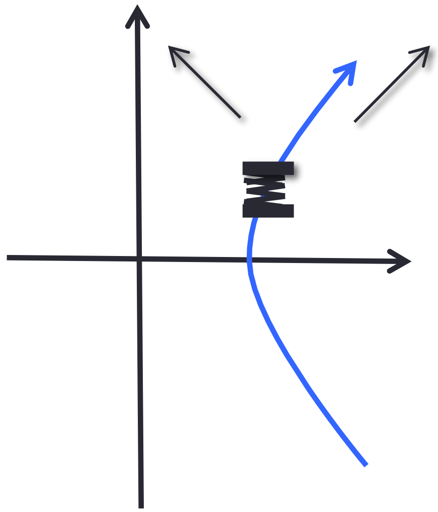
Thermal random motions produce quantum radiation ?

Iso et al (2011)
Oshita, KY, Zhang (2016)

Our research → answer of this question

Unruh de Witt detector in a uniformly accelerating motion

(Harmonic Oscillator)



radiation ?

Unruh-deWitt detector +Massless scalar field + Coupling term

$$S[Q,\phi] = \frac{m}{2}\int d\tau \left((\dot{Q}(\tau))^2 - \Omega_0^2 Q^2(\tau)\right) + \frac{1}{2}\int d^4x \partial^\mu\phi(x)\partial_\mu\phi(x) + S_{\rm int}[Q,\phi]$$

$$S_{\rm int}[Q,\phi] = \lambda\int d^4x d\tau Q(\tau)\phi(x)\delta^4(x - z(\tau))$$

③

☑ $$\boxed{\partial^\mu\partial_\mu\phi(x) = \lambda\int d\tau Q(\tau)\delta_D^{(4)}(x - z(\tau))}$$

$$\longrightarrow \phi(x) = \phi_{\rm h}(x) + \phi_{\rm inh}(x)$$

☑ $$\boxed{\left(\frac{d^2}{d\tau^2} + 2\gamma\frac{d}{d\tau} + \Omega^2\right)Q(\tau) = \frac{\lambda}{m}\phi_h(z(\tau))}$$

$$\langle E\rangle = \frac{m}{2}\left(\langle\dot{Q}^2(\tau)\rangle + \Omega^2\langle Q^2(\tau)\rangle\right)$$

$$\simeq \frac{a}{2\pi} = T_U$$

Energy equi-partition relation

Two point function of the field

$$\phi(x) = \phi_{\rm h}(x) + \phi_{\rm inh}(x)$$

$$\langle\phi(x)\phi(y)\rangle = \langle\phi_{\rm h}(x)\phi_{\rm h}(y)\rangle + \underline{\langle\phi_{\rm h}(x)\phi_{\rm inh}(y)\rangle + \langle\phi_{\rm inh}(x)\phi_{\rm h}(y)\rangle} + \langle\phi_{\rm inh}(x)\phi_{\rm inh}(y)\rangle$$

vacuum fluctuation + interference term + inhomogeneous term

A + B — B

cancelation!

$$\langle\phi_{\rm h}(x)\phi_{\rm inh}(y)\rangle + \langle\phi_{\rm inh}(x)\phi_{\rm h}(y)\rangle + \langle\phi_{\rm inh}(x)\phi_{\rm inh}(y)\rangle = A$$

Energy flux can be derived from the two point function

$$T_{0i} = \lim_{y\to x}\left\langle \frac{\partial\phi(x)}{\partial x^0}\frac{\partial\phi(y)}{\partial y^i}\right\rangle = \lim_{y\to x}\frac{\partial}{\partial x^0}\frac{\partial}{\partial y^i}\left\langle\phi(x)\phi(y)\right\rangle$$

$$\frac{dE}{dt} \sim \frac{a\lambda}{4\pi m}\frac{a^2}{2\pi\Omega^2}$$

non-vanishing radiation flux

consistent with Lin and Hu (2006)

Angular distribution of the energy flux

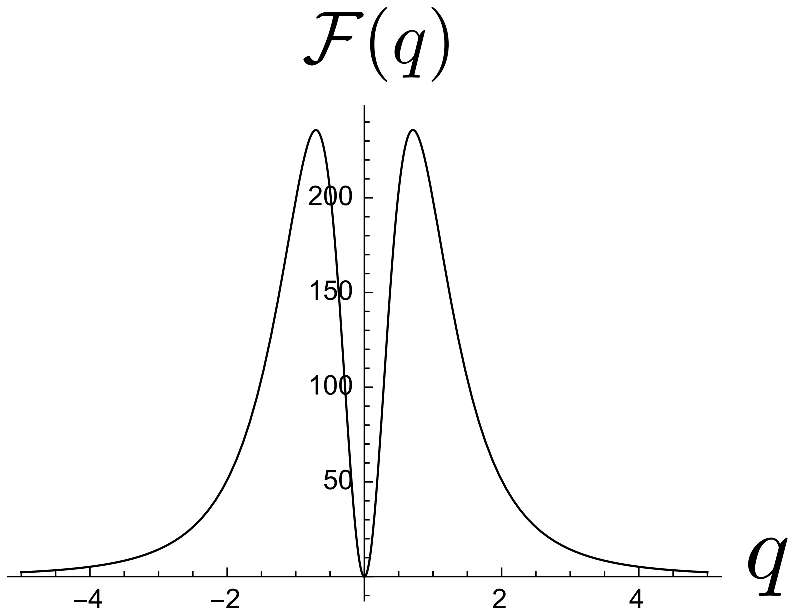
$$T_{0i} = \lim_{y \to x} \left\langle \frac{\partial \phi(x)}{\partial x^0} \frac{\partial \phi(y)}{\partial y^i} \right\rangle = \lim_{y \to x} \frac{\partial}{\partial x^0} \frac{\partial}{\partial y^i} \left\langle \phi(x)\phi(y) \right\rangle$$

$$f = -\sum_i T_{0i} n^i = \frac{a\lambda^2}{(4\pi)^2 m r^2 \sin^4\theta} \mathcal{F}(q)$$

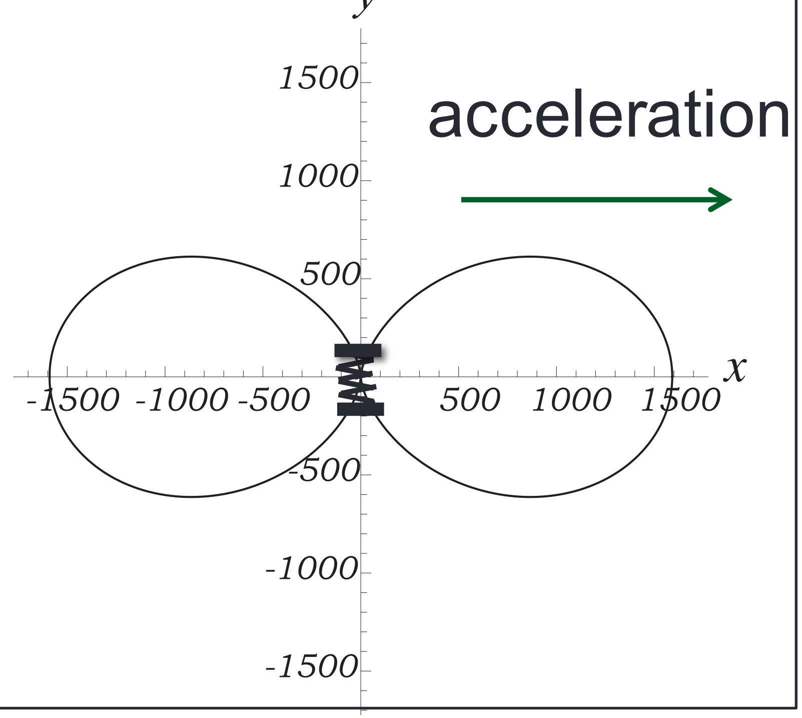
$$n^i = \frac{x^i}{r}$$

$$q = \frac{a}{\sin\theta}\left(t - r - \frac{1}{2a^2 r}\right)$$

$$\frac{\lambda}{8\pi m a} = 1 \qquad \frac{\Omega}{a} = 0.01$$



Polar plot of the radiation flux emitted at $\tau = 0$



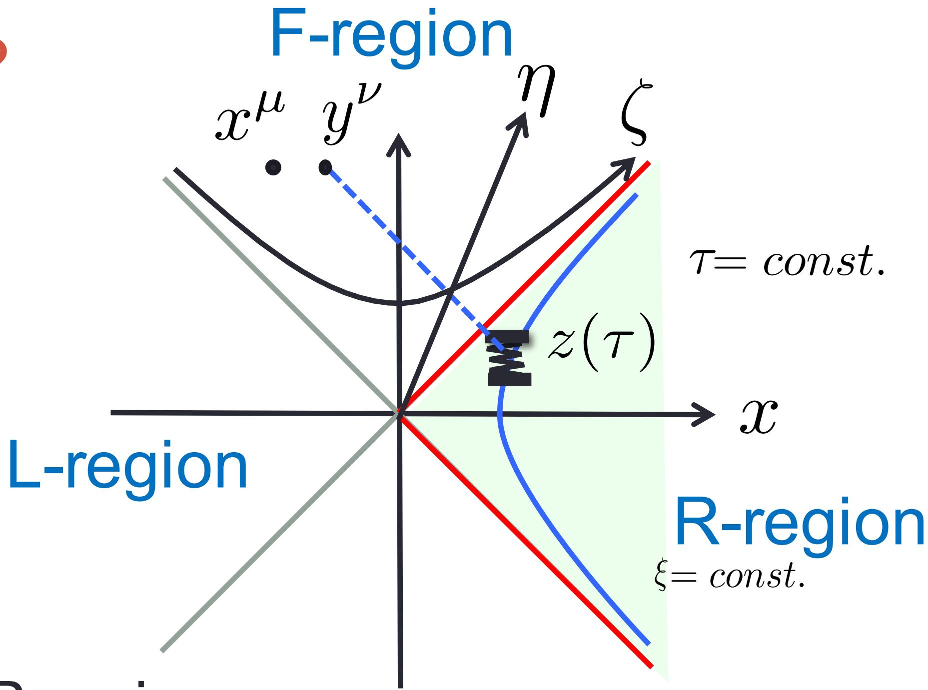
Origin of the quantum radiation?

$$\langle \phi_{\rm h}(x)\phi_{\rm inh}(y)\rangle$$

$$\phi_{\rm inh}(x) = \lambda \int d\tau Q(\tau) G_R(x - z(\tau))$$

$$\left(\frac{d^2}{d\tau^2} + 2\gamma\frac{d}{d\tau} + \Omega^2\right) Q(\tau) = \frac{\lambda}{m}\phi_h(z(\tau))$$

$\langle \phi_h(x)\phi_h(z(\tau))\rangle$ Key quantity



Correlation between F region and R region

Quantum field theory in the F-region (Kasner expanding universe)

$$ds^2 = e^{2a\eta}(d\eta^2 - d\zeta^2) - d\mathbf{x}_\perp^2$$

$$\hat{\phi}_F(x_F) = \int_{-\infty}^{+\infty} d\omega \int d^2k_\perp \left(\hat{a}^F_{\omega,\mathbf{k}_\perp} v^F_{\omega,\mathbf{k}_\perp}(x_F) + \text{h.c.}\right),$$

$$v^F_{k,\mathbf{k}_\perp}(x_F) = \frac{-i}{4\pi\sqrt{a\sinh(\pi|\omega|/a)}} e^{i\omega\zeta} J_{-i|\omega|/a}\left(\frac{\kappa e^{a\eta}}{a}\right) e^{i\mathbf{k}_\perp\cdot\mathbf{x}_\perp},$$

$$\hat{a}^F_{\omega,\mathbf{k}_\perp}|0,\mathrm{F}\rangle = 0$$

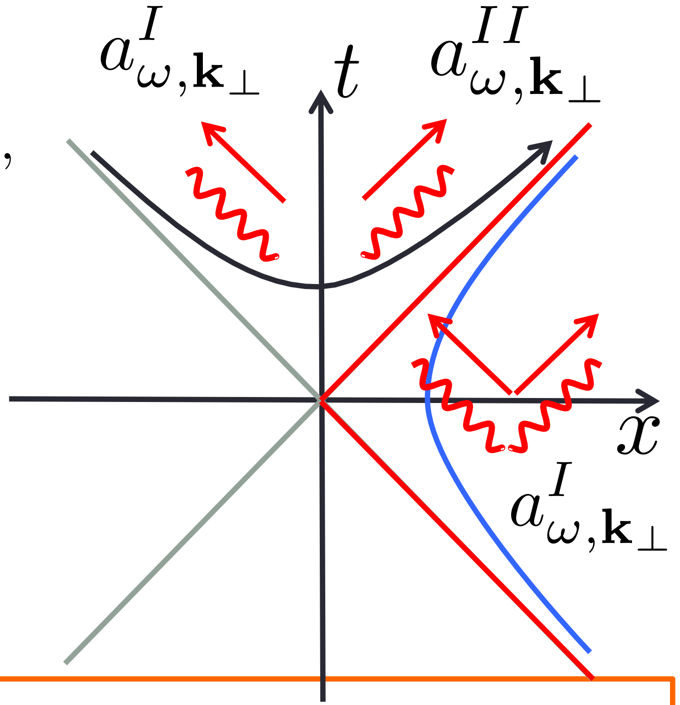
Separating the left moving mode (I) from the rigth-moving mode (II) in the Kasner expanding universe

$$\hat{\phi}_F(x_F) = \int_0^{+\infty} d\omega \int d^2k_\perp \left(\hat{a}^{II}_{\omega,\mathbf{k}_\perp} v^F_{\omega,\mathbf{k}_\perp}(x_F) + \hat{a}^{I}_{\omega,\mathbf{k}_\perp} v^F_{-\omega,-\mathbf{k}_\perp}(x_F) + \text{h.c.} \right),$$

right-moving wave Kasner mode — left-moving wave Kasner mode

$$\hat{\phi}_R(x_R) = \int_0^{\infty} d\omega \int d^2k_\perp \left(\hat{a}^{I}_{\omega,\mathbf{k}_\perp} v^R_{\omega,\mathbf{k}_\perp}(x_R) + \text{h.c.} \right),$$

right Rindler mode



$$|0, M\rangle = \prod_j \left[N_j \sum_{n_j=0}^{\infty} e^{-\pi n_j \omega/a} |n_j, \mathrm{I}\rangle \otimes |n_j, \mathrm{II}\rangle \right]$$

$$\boxed{\langle \phi_F(x_F)\phi_R(z(\tau))\rangle = -\frac{i}{8\pi^2 \rho_0(x)} \int_{-\infty}^{+\infty} d\omega e^{-i\omega\tau} \left(\frac{e^{\pi\omega/a}}{e^{2\pi\omega/a} - 1} e^{i\omega\tau^x_+} - \frac{1}{e^{2\pi\omega/a} - 1} e^{i\omega\tau^x_-} \right)}$$

correct two point function

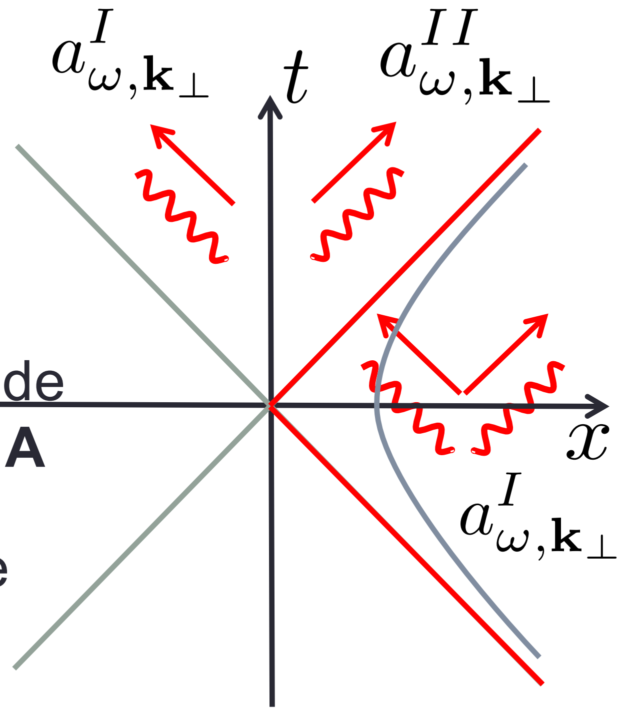
Entanglement of the states between F-region and R-region

$$|0, M\rangle = \prod_j \left[N_j \sum_{n_j=0}^{\infty} e^{-\pi n_j \omega/a} |n_j, \mathrm{I}\rangle \otimes |n_j, \mathrm{II}\rangle \right]$$

Minkowski vacuum = Entangled state of I and II

Right-moving wave Kasner mode and the Rindler mode are in the entangled state, their correlation → **Term A**

left-moving wave Kasner mode and the Rindler mode are note entangled, their correlation → **Term B**



$$\boxed{\langle \phi_F(x_F)\phi_R(z(\tau))\rangle = -\frac{i}{8\pi^2\rho_0(x)}\int_{-\infty}^{+\infty} d\omega e^{-i\omega\tau}\left(\frac{e^{\pi\omega/a}}{e^{2\pi\omega/a}-1}e^{i\omega\tau_+^x} - \frac{1}{e^{2\pi\omega/a}-1}e^{i\omega\tau_-^x}\right)}$$

A
nonvanishing
quantum radiation

B
cancel out

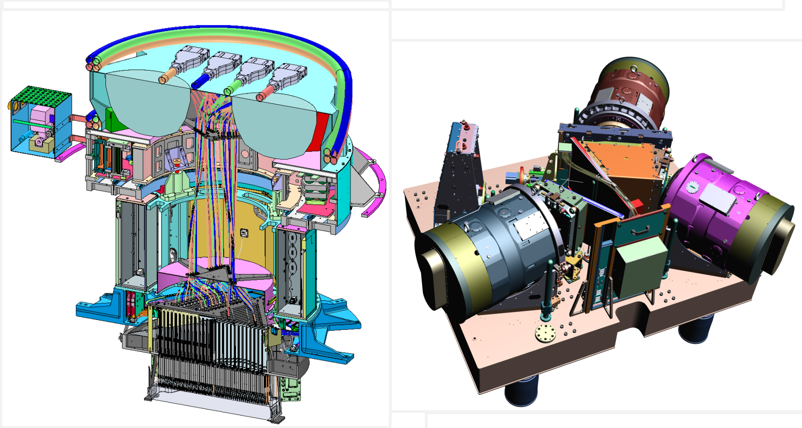
Origin of the quantum radiation is the entanglement between the right-moving Kasner mode and the Rindler mode.

3. Large scale structure of galaxies

Y. Nan C. Hikage

development of an analytic theoretical model
for galaxy bispectrum in redshift space

Prime focus - spectrograph



http://pfs.ipmu.jp

Bispectrum

→ 3-point statistics in Fourier space

Non-Gaussian,
Nonlinear properties

test of general relativity

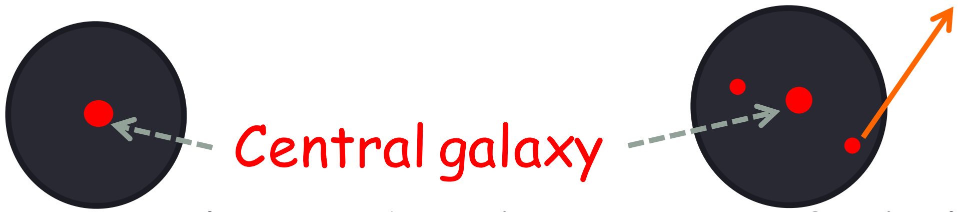
constraints on primordial non-Gaussianity

Realistic model in redshift space

behaviors of galaxy bispectrum in an analytic way,
application to the PFS galaxy redshift survey data analysis

Halo approach

Every DM and galaxy reside in dark matter halos, their distribution is described on the basis of the halo density profile with mass M and halo's correlation.

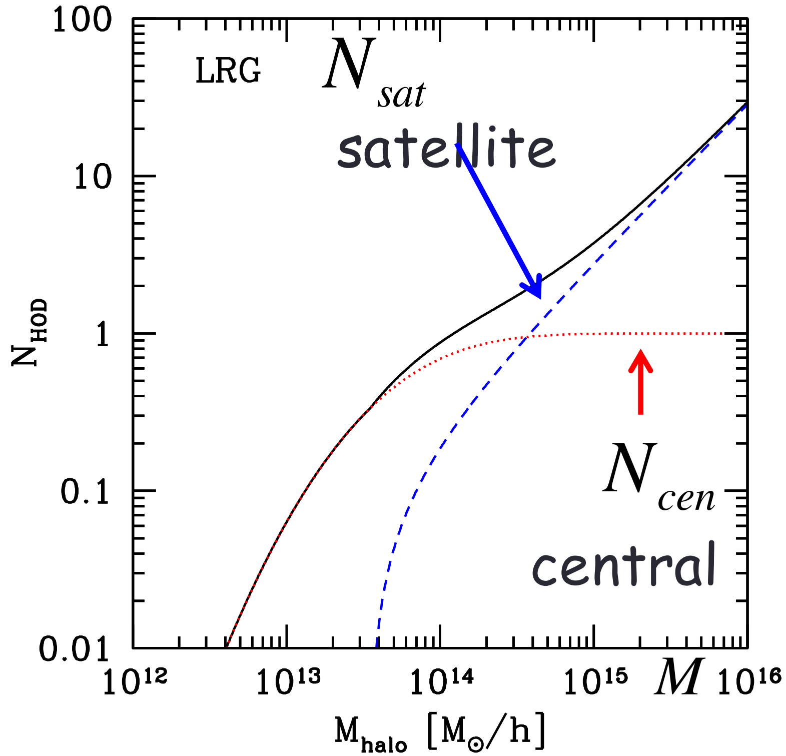


Satellite galaxy
(moving in a halo
with random velocity)

located in the center of a halo,
and the random velocity is negligible.

Halo occupation distribution (HOD)

galaxy number in a halo with mass M



Satellite galaxy ramdom velocity

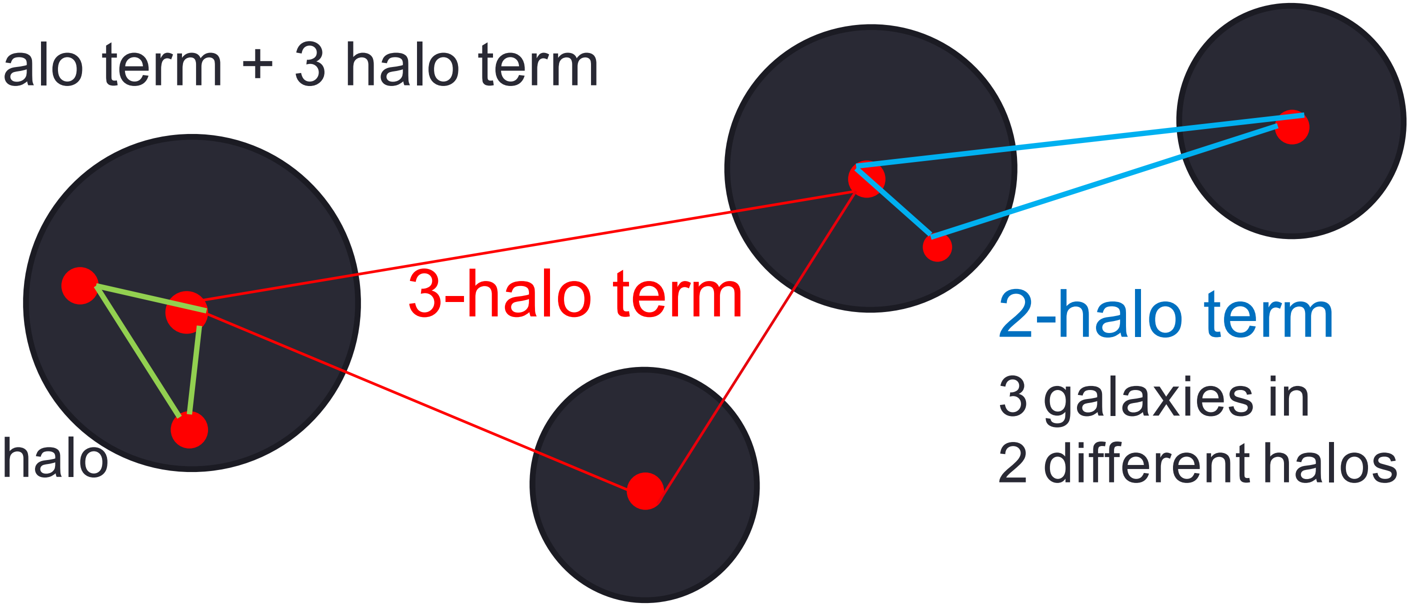
Virial random velocity dispersion

$$\sigma^2_{v,off} = \frac{GM}{2r_{\rm vir}}$$

Finger of God effect

Bispectrum of galaxies in halo approach

= 1 halo term + 2 halo term + 3 halo term



3 - halo term, dominant contribution on the large scales

2 - halo term, dominant contribution on the small scales

1 - halo term, Finger of God effect from satellite galaxies

→ redshift-space distortion on the small scale

Theoretical formula of the bispectrum in halo approach

$$B_g(t,\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = B_{g,1h}(t,\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) + B_{g,2h}(t,\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) + B_{g,3h}(t,\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

$$B_{g,1h}(t,\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = \frac{1}{\bar{n}^3}\int dM \frac{dn(M)}{dM}\Big[\langle N_c\rangle \langle N_s(N_s-1)\rangle \left(\widetilde{u}(\mathbf{k}_1,M)\widetilde{u}(\mathbf{k}_2,M) + 2\text{ cyclic terms}\right) + \langle N_s(N_s-1)(N_s-2)\rangle \widetilde{u}(\mathbf{k}_1,M)\widetilde{u}(\mathbf{k}_2,M)\widetilde{u}(\mathbf{k}_3,M)\Big]$$

$$B_{g,2h}(t,\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = \frac{1}{\bar{n}^3}\int dM_1 \frac{dn(M_1)}{dM_1}\Big[\langle N_c\rangle \langle N_s\rangle \left(\widetilde{u}(\mathbf{k}_1,M_1) + \widetilde{u}(\mathbf{k}_2,M_1)\right) + \langle N_s(N_s-1)\rangle \widetilde{u}(\mathbf{k}_1,M_1)\widetilde{u}(\mathbf{k}_2,M_1)\Big] \times \int dM_2 \frac{dn(M_2)}{dM_2}\left(\langle N_c\rangle + \langle N_c\rangle\langle N_s\rangle \widetilde{u}(\mathbf{k}_3,M_2)\right) P_{2h}(t,\mathbf{k}_3,M_1,M_2) + 2\text{ cyclic terms}$$

$$B_{g,3h}(t,\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = \frac{1}{\bar{n}^3}\int \prod_{i=1}^{3}\left[dM_i \frac{dn(M_i)}{dM_i}\langle N_c\rangle \left(1 + \langle N_s\rangle \widetilde{u}(\mathbf{k}_i,M_i)\right)\right] P_{3h}(t,\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,M_1,M_2,M_3)$$

$$P_{2h}(t,\mathbf{k}_3,M_1,M_2) = (b(M_1)+\mu_3^2 f)(b(M_2)+\mu_3^2 f)P_m(t,k_3)$$

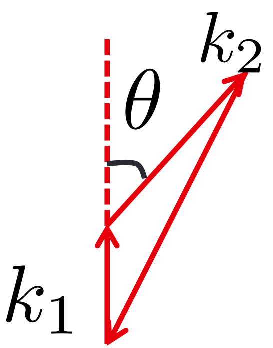
$$P_{3h}(t,\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,M_1,M_2,M_3) = 2P_m(t,k_1)P_m(t,k_2)(b(M_1)+f\mu_1^2)(b(M_2)+f\mu_2^2)Z_2(\mathbf{k}_1,\mathbf{k}_2,M_3)$$

$$Z_2(\mathbf{k}_1,\mathbf{k}_2,M_3) = b(M_3)F_2(\mathbf{k}_1,\mathbf{k}_2) + \frac{b_2(M_3)}{2} + f\mu_{12}^2 G_2(\mathbf{k}_1,\mathbf{k}_2) + \frac{1}{2}f\mu_{12}k_{12}\left\{\frac{\mu_1}{k_1}\left(b(M_3)+f\mu_2^2\right) + \frac{\mu_2}{k_2}\left(b(M_3)+f\mu_1^2\right)\right\}$$

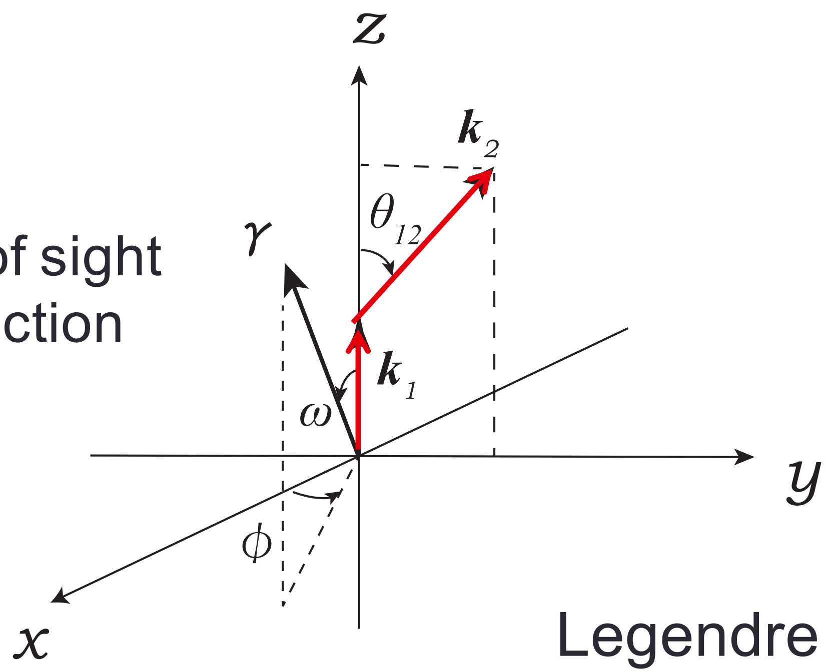
$$\mu_{12} = (\mathbf{k}_1+\mathbf{k}_2)\cdot\gamma/k_{12} \qquad k_{12} = |\mathbf{k}_1+\mathbf{k}_2| \qquad \mu_j = \mathbf{k}_j\cdot\gamma/k_j$$

Multipoles of bispectrum

$$B_g(\underbrace{k_1, k_2, \theta}, \underbrace{\omega, \phi}_{\gamma})$$



line of sight direction



Legendre polynomial

multipole expansion

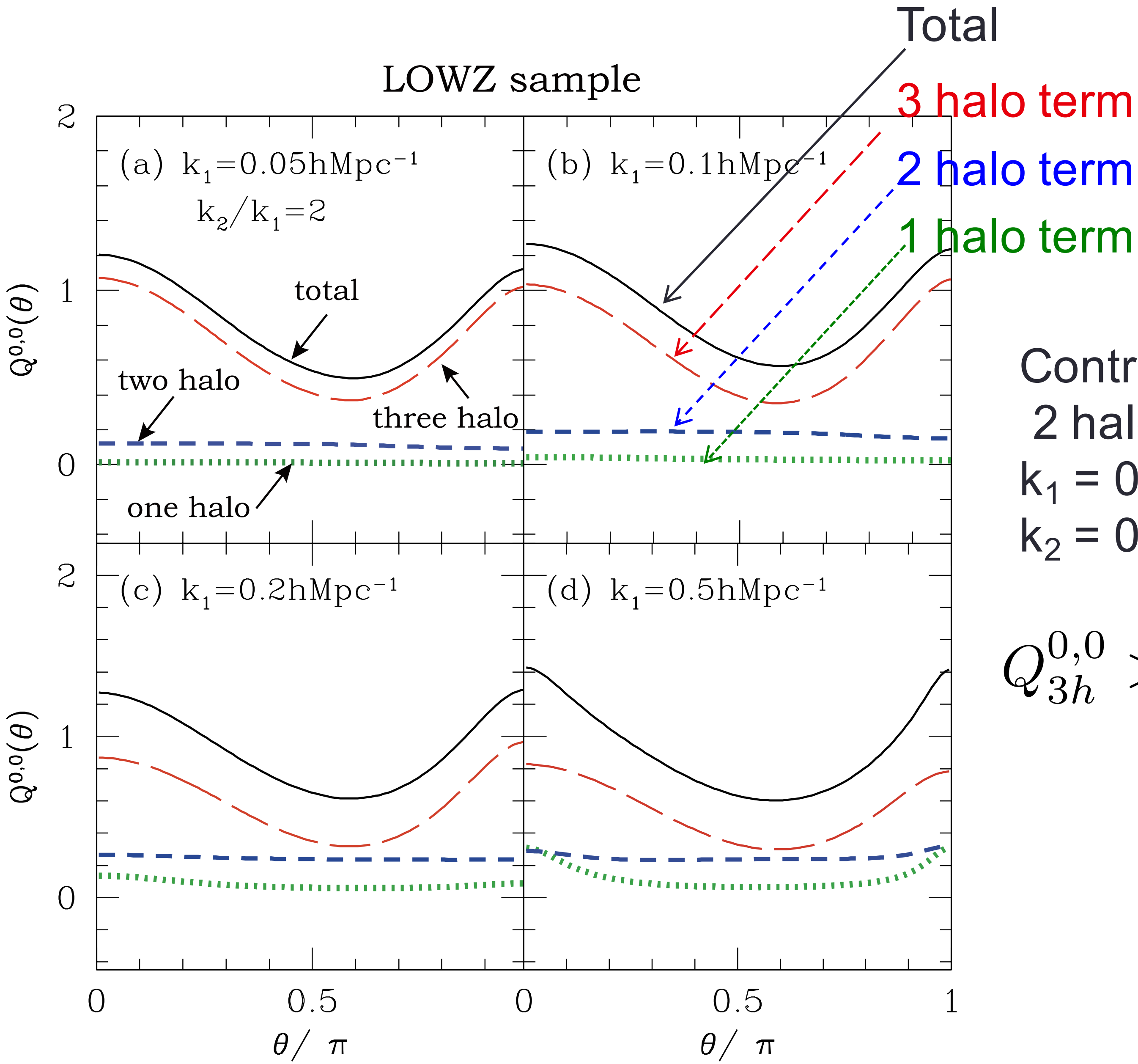
$$B^{\ell,0}(k_1, k_2, \theta) = \frac{1}{4\pi} \int_0^{2\pi} d\phi \int_{-1}^{+1} d\cos\omega B_g(k_1, k_2, \theta, \omega, \phi) \mathcal{L}_\ell(\cos\omega)$$

Scoccimarro et al (1999)

reduced bispectrum

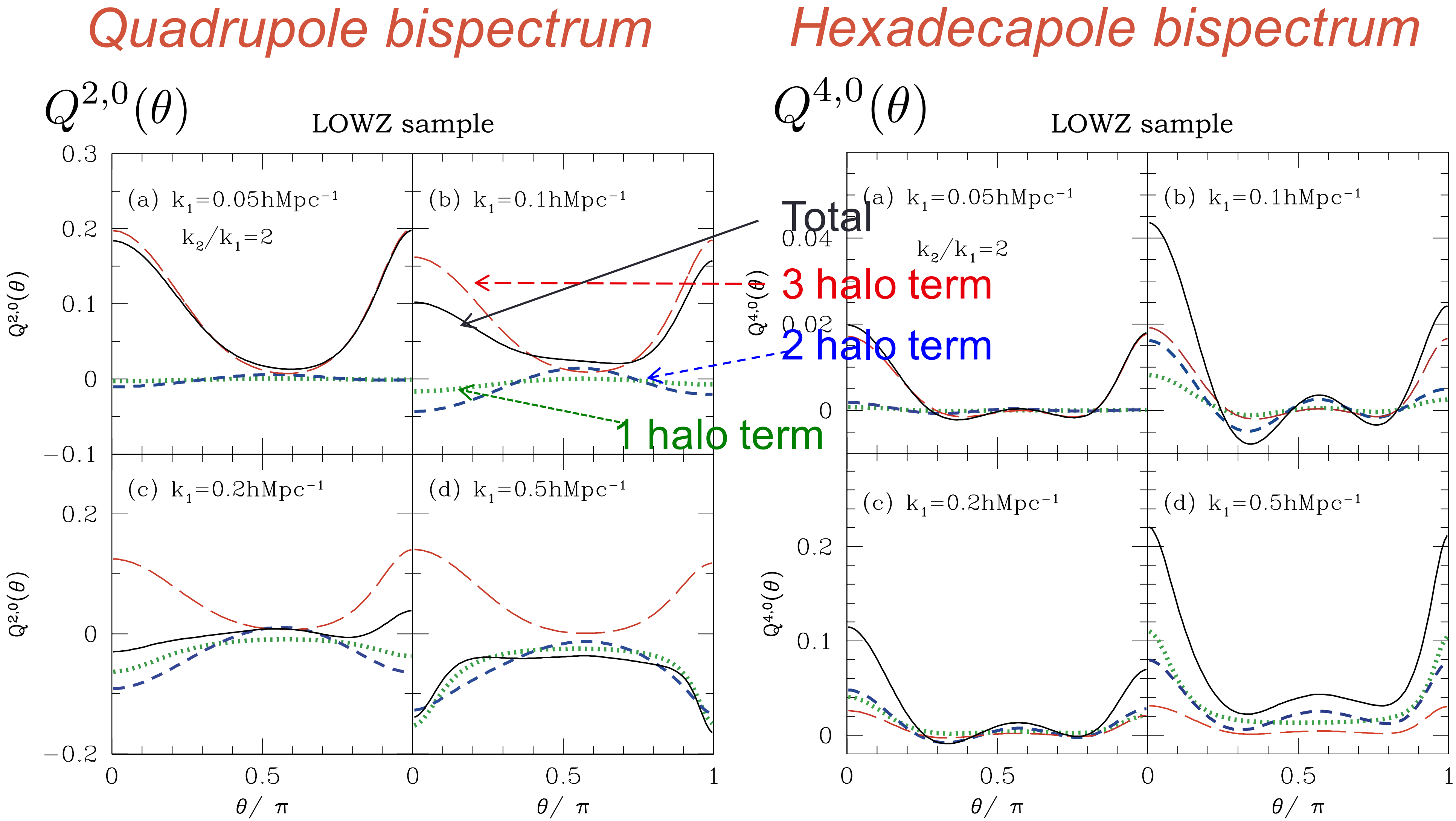
$$Q^{\ell,0}(k_1, k_2, \theta) = \frac{B^{\ell,0}(k_1, k_2, \theta)}{P_g^0(k_1)P_g^0(k_2) + P_g^0(k_2)P_g^0(k_3) + P_g^0(k_3)P_g^0(k_1)}$$

Monopole (reduced) bispectrum



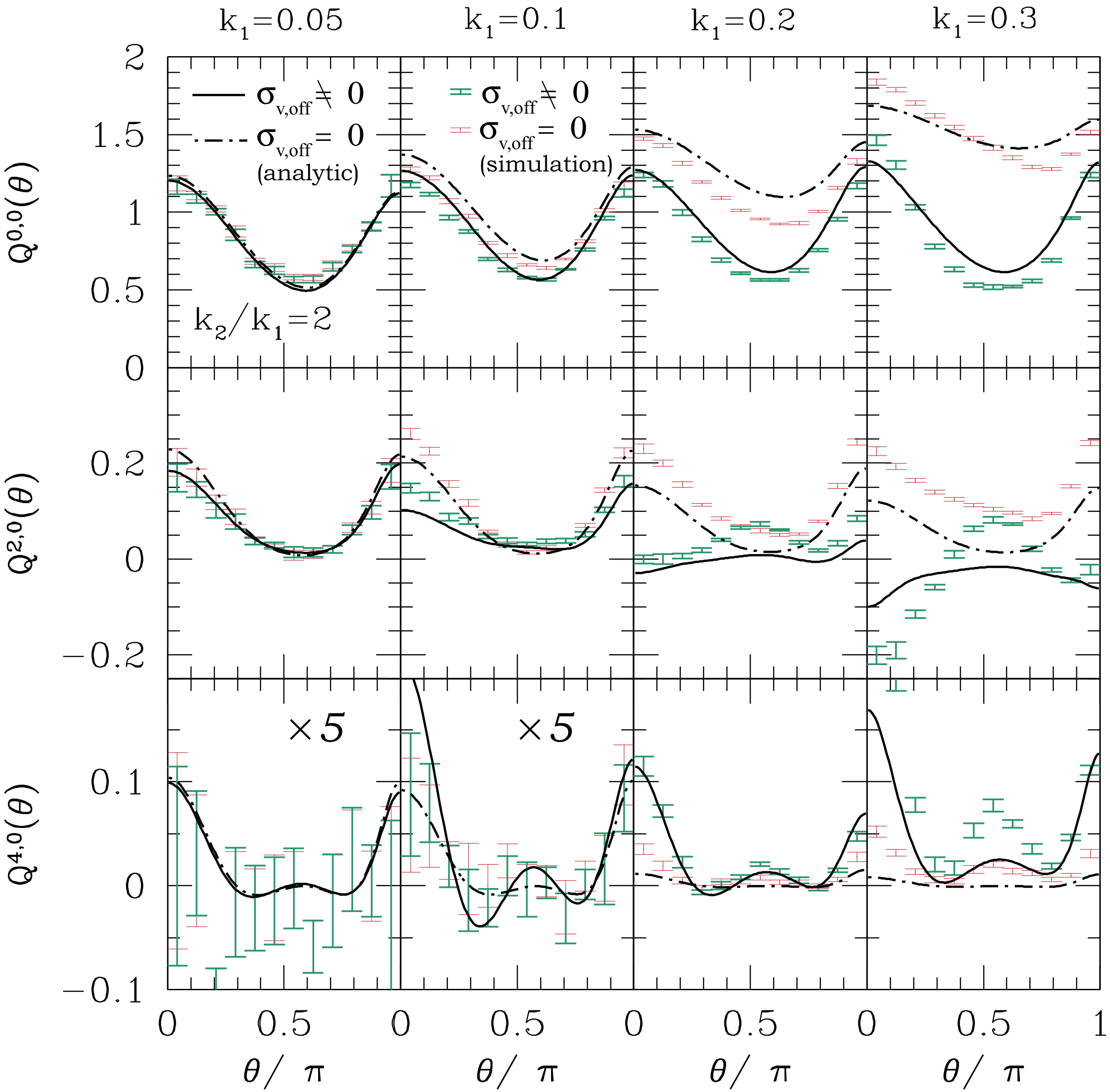
Contribution from 2 halo term at
k_1 = 0.1 hMpc^{-1}
k_2 = 0.2 hMpc^{-1}

$$Q^{0,0}_{3h} > Q^{0,0}_{2h} > Q^{0,0}_{1h}$$



significant contribution from 2 halo term and 1 halo term on the scale k $\gtrsim$ 0.1 hMpc^{-1} to the higher multipoles bispectrum

Comparison with mock catalogue from N-body simulation



LOWZ sample HOD

Our model
→ the behaviors of the numerical simulations at a qualitative level.

Summary: bispectrum research

development of analytic model for galaxy bispectrum in redshift-space

significant contribution from the two term to especially higher multipole bispectrum, k $\gtrsim$ 0.1 hMpc^{-1}.

qualitative understanding in an analytic way, e.g.,

→ complicated behavior of the bispectrum

1 halo term

$$B_{1h}^{0,0}(k_1,k_2,\theta) \simeq \frac{f_s^2}{\bar{n}^2}\left[3 - \frac{4}{3}\left(k_1^2 + k_2^2 + k_1 k_2 \cos\theta\right)\lambda_{v,\mathrm{off}}^2\right]$$

$$B_{1h}^{2,0}(k_1,k_2,\theta) \simeq -\frac{2}{15}\frac{f_s^2}{\bar{n}^2}\left(4k_1^2 + k_2^2(1+3\cos 2\theta) + 4k_1 k_2 \cos\theta\right)\lambda_{v,\mathrm{off}}^2$$

$$B_{1h}^{4,0}(k_1,k_2,\theta) = \mathcal{O}\left(\frac{f_s^2}{\bar{n}^2}\left(k^2\lambda_{v,\mathrm{off}}^2\right)^2\right)$$

2 halo term

$$B_{2h}^{\ell,0}(k_1,k_2,\theta) \sim \left(\frac{2f_s}{\bar{n}}\right)\left(\mathcal{O}(P_g^\ell(k_1) + P_g^\ell(k_2) + P_g^\ell(k_3)) - \mathcal{O}(P_g(k)k^2\lambda_{v,\mathrm{off}}^2)\right)$$

f_s satellite fraction

$\bar{n}$ galaxy number density

$$\lambda_{v,\mathrm{off}}^2 = \frac{\overline{\sigma}_{v,\mathrm{off}}^2}{2a^2H^2(z)}$$

satellite velocity dispersion

Summary, conclusions, and future works

- constraint on reheating process from the constraint of n_s

- new finding about the quantum vacuum physics

✓ non-vanishing quantum radiation due to Unruh effect
$\rightarrow$ its origin in the entanglement of the quantum fields

- analytic model of galaxy bispectrum in redshift space

✓ new multipoles bispectrum coefficient in the expansion $Y_{\ell m}(\omega, \phi)$

✓ measurement of the multipole bispectrum from galaxy samples

future works $\longrightarrow$ test of general relativity, and galaxy clustering

Thank you