Entanglement-induced Quantum Radiation, Gravitational Redshift

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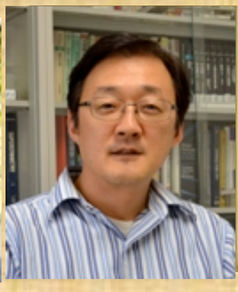
11 Feb. 2018 Tohoku

A. Higuchi

S. Iso



C. Hikage

K.Ueda

R. Tatsukawa

S. Yamaguchi

Y. Nan

D. Sakuma

Results 2017

1. Quantum vacuum physics Entanglement-induce quantum radiation

A. Higuchi, S. Iso, R. K. Ueda, K.Y., PRD96 083531 (2017),
"Entanglement of the Vacuum between Left, Right, Future, and Past: The Origin of Entanglement-Induced Quantum Radiation"

S. Iso, R. Tatsukawa, K. Ueda, K.Y., PRD96 045001 (2017),
"Entanglement-induced quantum radiation"

2. Test of GR and galaxy clustering model Gravitational redshift

D. Sakuma, A. Terukina, K.Y., C. Hikage, arXiv:1709.05756
"Gravitational Redshifts in Clusters and Voids"

Y. Nan, K.Y., C. Hikage, arXiv:1706.03515
"Higher multipoles of the bispectrum of galaxies in redshift space"

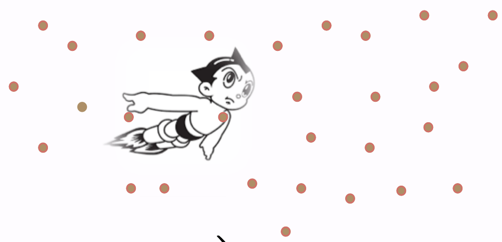
1. Quantum vacuum physics

☑ A hint for a cosmological constant problem?

☑ Origin of the cosmic structure, vacuum fluctuation in de Sitter space

☑ Unruh effect, detector model in de Sitter spacetime (Nambu-san's talk)

- A uniformly accelerating observer sees the Minkowski vacuum as a thermally excited state:



a

acceleration

Unruh temperature

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

An intense laser generates huge acceleration

$$T_U = \frac{a}{2\pi} \sim 7\times 10^{5} K \left(\frac{eE}{10^{13} eV/cm}\right)$$

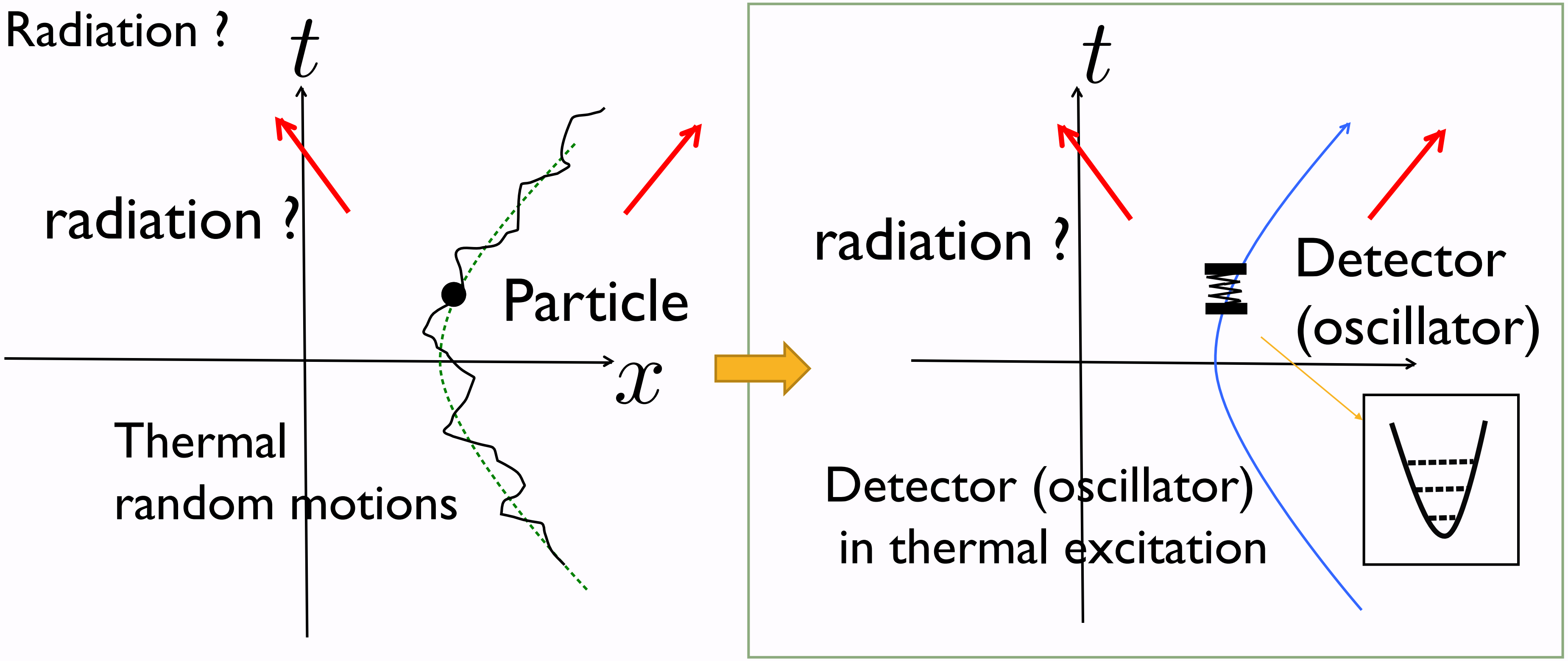
Chen Tajima (99)

Schutzhold, et al (06, 08)

Thermal random motions → a uniformly accelerating particle due to the Unruh → Radiation ?

Chen Tajima (99)

Schutzhold, et al (06, 08)

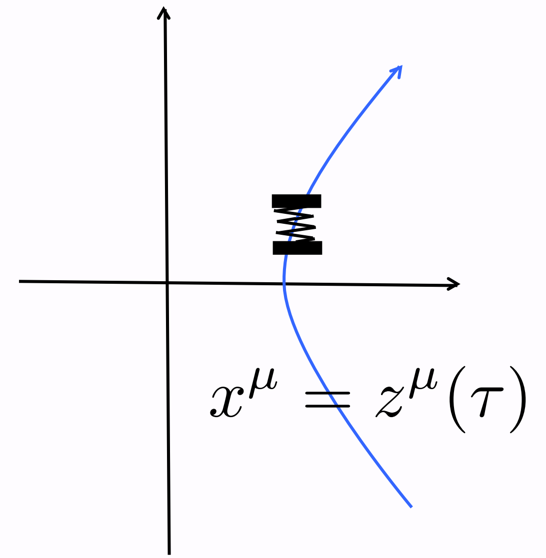


Does a detector in thermal excitation due to Unruh effect produce radiation?

A. There is quantum radiation

B. There is no radiation because the detector is in thermal equilibrium.

Detector-field model model



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

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

vacuum fluctuations

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

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

☑ $\ddot{Q}(\tau) + \Omega_0^2 Q(\tau) = \lambda \phi(z(\tau))$

$\ddot{Q}(\tau) + 2\gamma \dot{Q}(\tau) + \Omega^2 Q(\tau) = \lambda \phi_{\mathrm{h}}(z(\tau))$ This can be solved

$\langle E \rangle \simeq \frac{a}{2\pi} = T_U$

dissipation term

$\gamma = \lambda^2 / 8\pi$

random force from vacuum fluctuations

inhomogeneous solution

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

$$= \lambda^2 \int d\tau \int \frac{d\omega}{2\pi} e^{-i\omega\tau} h(\omega) G_R(x-z(\tau))\varphi(\omega)$$

$$h(\omega) = \frac{1}{-m\omega^2 + m\Omega^2 - i\frac{\omega\lambda^2}{4\pi}}$$

homogeneous solution

→ vacuum solution

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

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

vacuum fluctuation 2point function + interference term + inhomogeneous solution term

A + B – B

Cancelation !

no radiation locally generated from thermal excitation

$\langle T_{\mu\nu}\rangle$ Radiation flux

radiation rate $\frac{dE}{dt} \sim \frac{\lambda^2}{4\pi}\frac{a^3}{2\pi\Omega^2}$

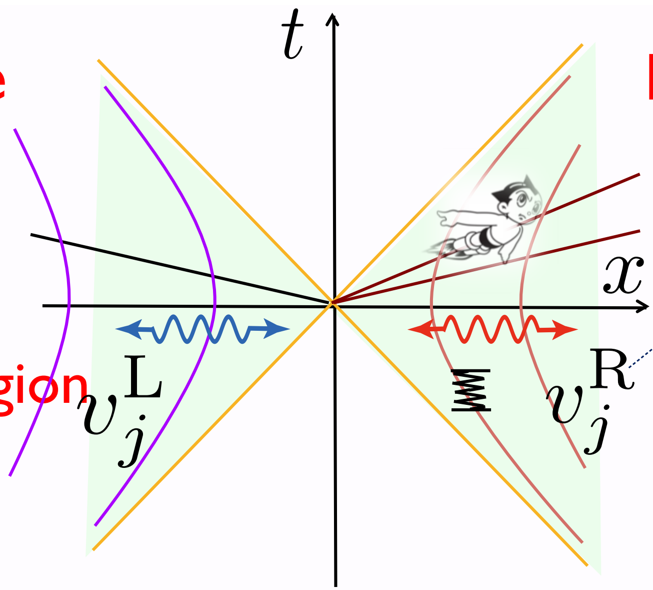
The term A leads to quantum radiation,. → What is the origin?

Left Rindler coordinate

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

$$\hat{\phi}(x) = \sum_j \left(\hat{a}_j^{\mathrm{II}} v_j^L(x) + \mathrm{h.c.}\right),$$

$$|n_j, \mathrm{II}\rangle$$



Right Rindler coordinate

R-region

(right) Rindler mode

(right) Rindler state

$$|n_j, \mathrm{I}\rangle \qquad j = (\omega, \mathbf{k}_\perp)$$

Unruh, Wald (1984)

$$|0, \mathrm{M}\rangle = \prod_j \left[N_j \sum_{n_j=0}^{\infty} e^{-\pi n_j \omega_j / a} |n_j, \mathrm{I}\rangle \otimes |n_j, \mathrm{II}\rangle \right] \qquad N_j = \sqrt{1 - e^{-2\pi\omega_j/a}}$$

Minkowski vacuum state is expressed as an entangled state of the right Rindler states and the left Rindler states

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

Partial trace of $|0, \mathrm{M}\rangle\langle 0, \mathrm{M}|$ with respect to the left Rindler states yields the thermal state with the Unruh temperature

$\longrightarrow$ Entanglements is an aspect of the Unruh effect

Expanding Kasner coordinate F-region

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

$$\phi(x) = \sum_j \left(\hat{a}_j^{\rm II} v_j^{F,d}(x) + \hat{a}_j^{\rm I} v_j^{F,s}(x) + \text{h.c.} \right),$$

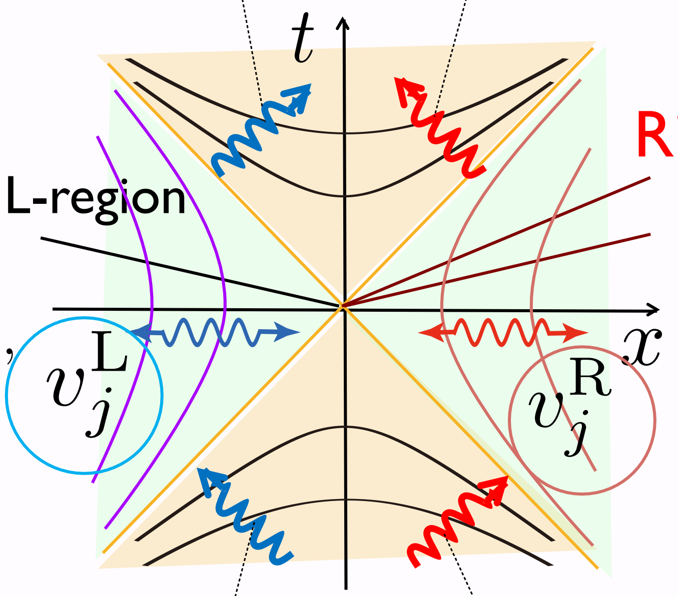
Right moving wave + left moving wave

Left Rindler coordinate

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

$$\hat{\phi}(x) = \sum_j \left(\hat{a}_j^{\rm II} v_j^{L}(x) + \text{h.c.} \right),$$

$$|n_j, \text{II}\rangle$$



Right Rindler coordinate

R-region

$$|n_j, \text{I}\rangle$$

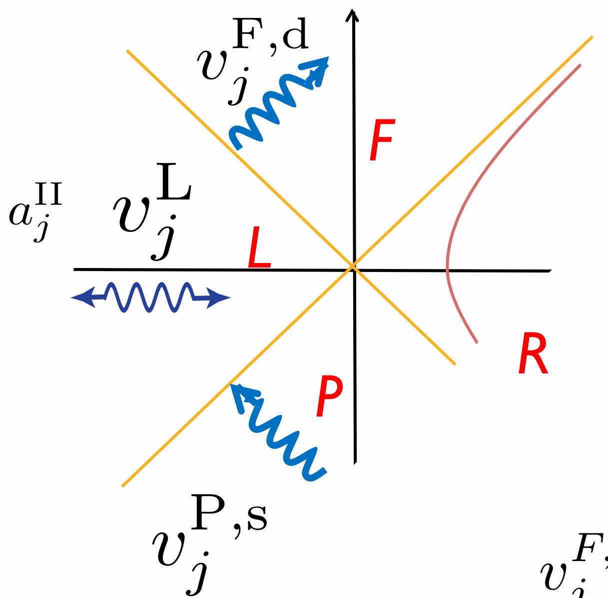
$$j = (\omega, \mathbf{k}_\perp)$$

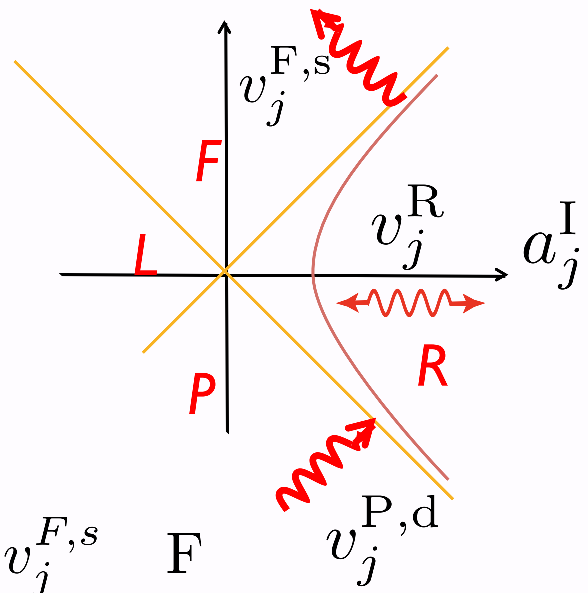
Unruh, Wald (1984)

$$\phi(x) = \sum \left(\hat{a}_j^{\rm II} v_j^{P,s}(x) + \hat{a}_j^{\rm I} v_j^{P,d}(x) + \text{h.c.} \right),$$

Shrinking Kasner coordinate P-region

Description of the Minkowski vacuum state with entanglement





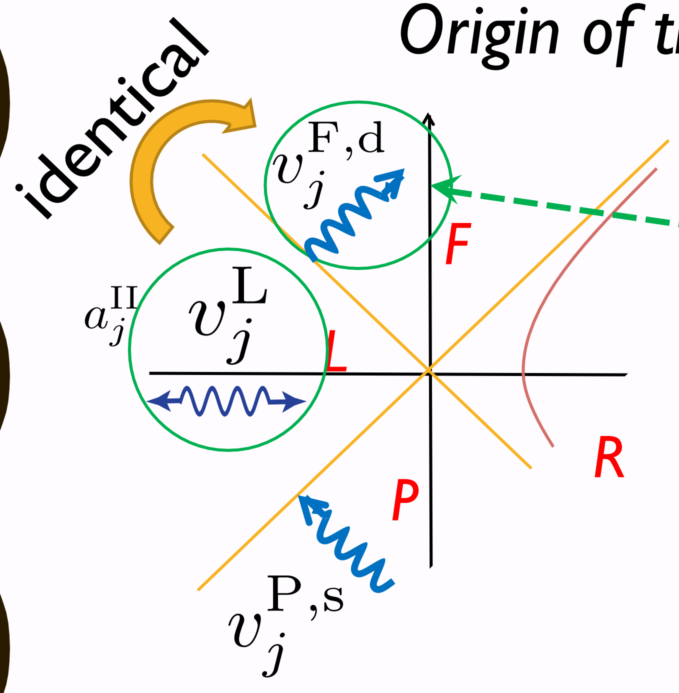
$$v_j^{\mathrm{II}}(x) = \begin{cases} v_j^{F,d} & \mathrm{F} \\ 0 & \mathrm{R} \\ v_j^{L} & \mathrm{L} \\ v_j^{P,s} & \mathrm{P} \end{cases} \qquad v_j^{\mathrm{I}}(x) = \begin{cases} v_j^{F,s} & \mathrm{F} \\ v_j^{R} & \mathrm{R} \\ 0 & \mathrm{L} \\ v_j^{P,d} & \mathrm{P} \end{cases}$$

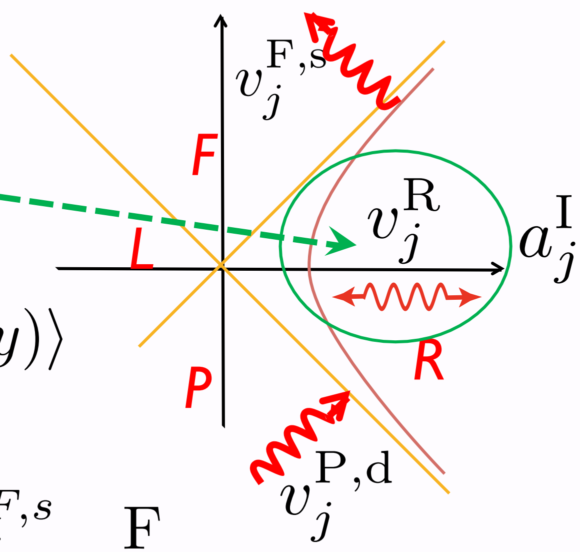
$$\hat{\phi}(x) = \sum_j \left(\hat{a}_j^{\mathrm{I}} v_j^{\mathrm{I}}(x) + \hat{a}_j^{\mathrm{II}} v_j^{\mathrm{II}}(x) + \mathrm{h.c.}\right),$$

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

⇨ Generalized description of the Minkowski vacuum state as an entangled state

Origin of the team A and the quantum radiation





The term A of $\langle \phi_{\mathrm{h}}(x)\phi_{\mathrm{inh}}(y)\rangle$ and quantum radiation flux

$$v_j^{\mathrm{II}}(x) = \begin{cases} v_j^{F,d} & \mathrm{F} \\ 0 & \mathrm{R} \\ v_j^{L} & \mathrm{L} \\ v_j^{P,s} & \mathrm{P} \end{cases} \qquad v_j^{\mathrm{I}}(x) = \begin{cases} v_j^{F,s} & \mathrm{F} \\ v_j^{R} & \mathrm{R} \\ 0 & \mathrm{L} \\ v_j^{P,d} & \mathrm{P} \end{cases}$$

- ✓ Entangled correlation of the right-moving Kasner mode and right Rinder mode →Two point function term A → Origin of the quantum two point function
- ✓ The nonlocal correlation of the field is the origin of the quantum radiation.

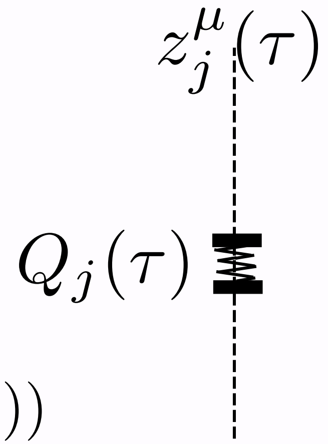
Generalization : the detector model in de Sitter spacetime

$$ds^2 = dt^2 - a^2(t) d^2\vec{x}^2 \qquad a(t) = e^{Ht}$$

Yamaguchi, et al.
in preparation

$$S[Q_j, \phi] = \sum_j \int d\tau \frac{1}{2}\left((\dot{Q}_j(\tau))^2 - \Omega_{0_j}^2 Q_j^2(\tau)\right)$$
$$+\frac{1}{2}\int d^4x\sqrt{-g}\left(g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \xi R\phi^2\right) + \lambda \sum_j \int d\tau Q_j(\tau)\phi(z_j(\tau))$$

Conformal coupling
to the curvature $\xi = \dfrac{1}{6}$



Equations of motion wit multi-detector

$$\frac{1}{a^3}\partial_t(a^3\partial_t\phi) - \frac{\triangle\phi}{a^2} + \xi R\phi = \frac{\lambda}{a^3}\sum_j \int d\tau Q_j(\tau)\delta_D^4(x - z_j(\tau))$$

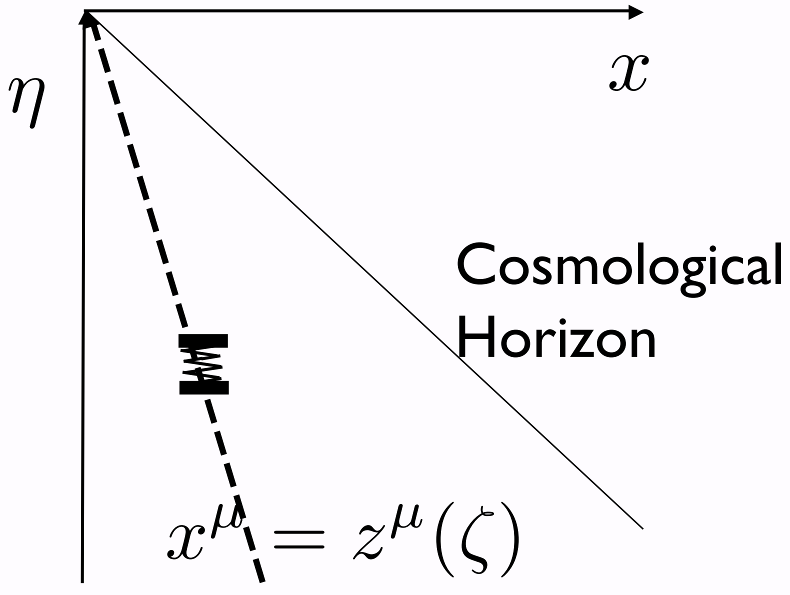
$$\ddot{Q}_j(\tau) + 2\gamma\dot{Q}_j(\tau) + \Omega^2 Q_j(\tau) = \lambda\phi_h(z_j(\tau)) + \frac{\lambda^2}{a(\tau)}\sum_{i\neq j}\frac{Q_i(\tau(\zeta - |\vec{x}_i - \vec{x}_j|))}{4\pi|\vec{x}_i - \vec{x}_j|}$$

Quantum radiation from a uniformly accelerating detector

$$(\eta, x, y, z) = \frac{1}{H}(-e^{-\alpha\tau}, KHe^{-\alpha\tau}, 0, 0)$$

Trajectory of a uniform acceleration

$$a^\mu a_\mu = -\frac{H^4K^2}{1-H^2K^2} \equiv -a^2 = \text{constant}$$



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

$\mathcal{A} + \mathcal{B}$ $\qquad$ $-\mathcal{B}$

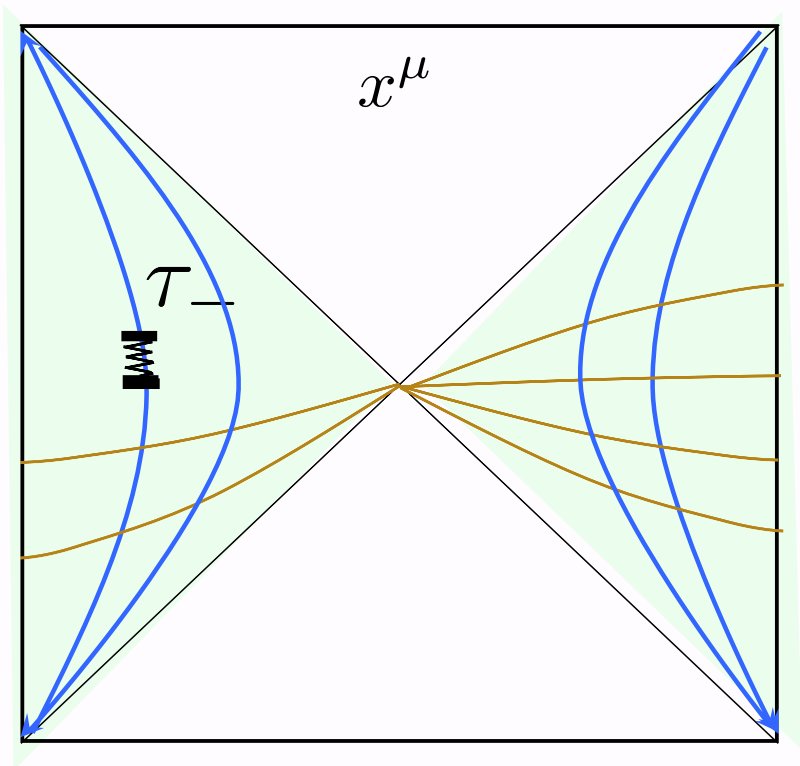
radiation rate

Cancelation !

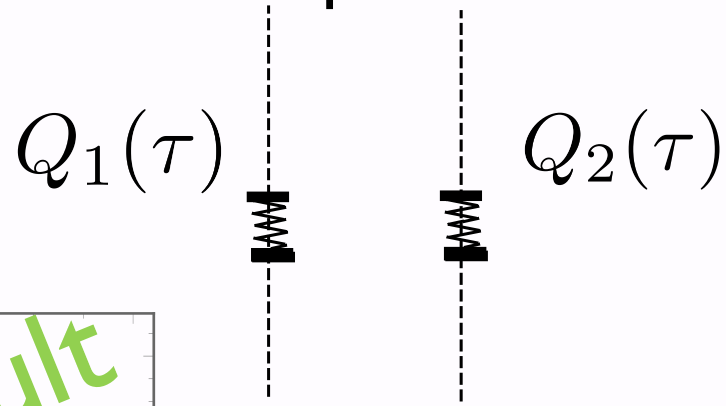
$$\frac{dE}{d\tau} \sim \frac{2}{3}\frac{\lambda^2\alpha^3}{(4\pi)^2\Omega^2} \qquad \alpha = \sqrt{a^2+H^2} = 2\pi\sqrt{T^2_\mathrm{Unruh} + T^2_{G.H.}}$$

An analogy with the Minkowski case

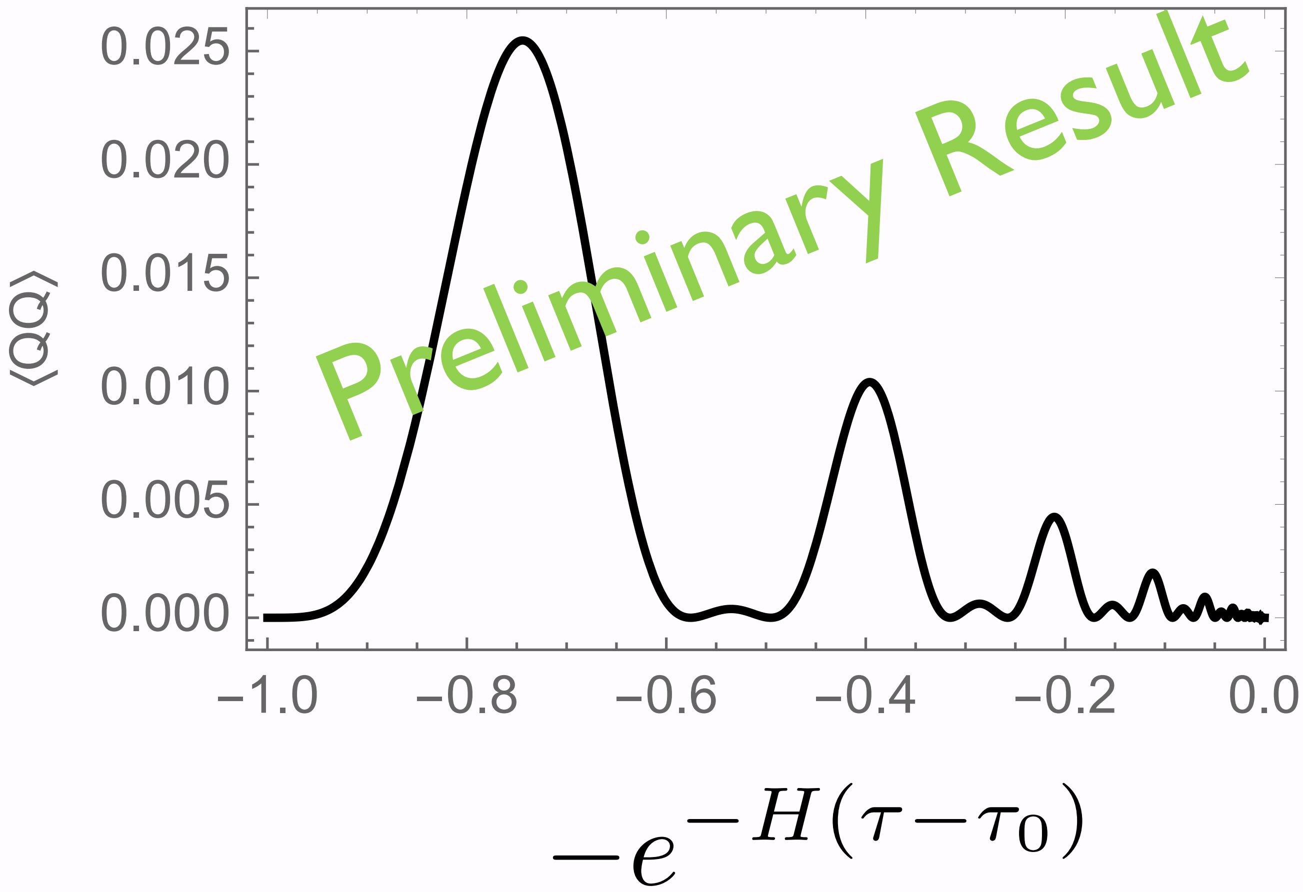
➡ the origin of the quantum radiation would be interpreted by an entanglement structure of states in de Sitter spacetime



Mutual correlation of two detectors in de Sitter spacetime



$$\langle Q_1(\tau) Q_2(\tau) \rangle$$

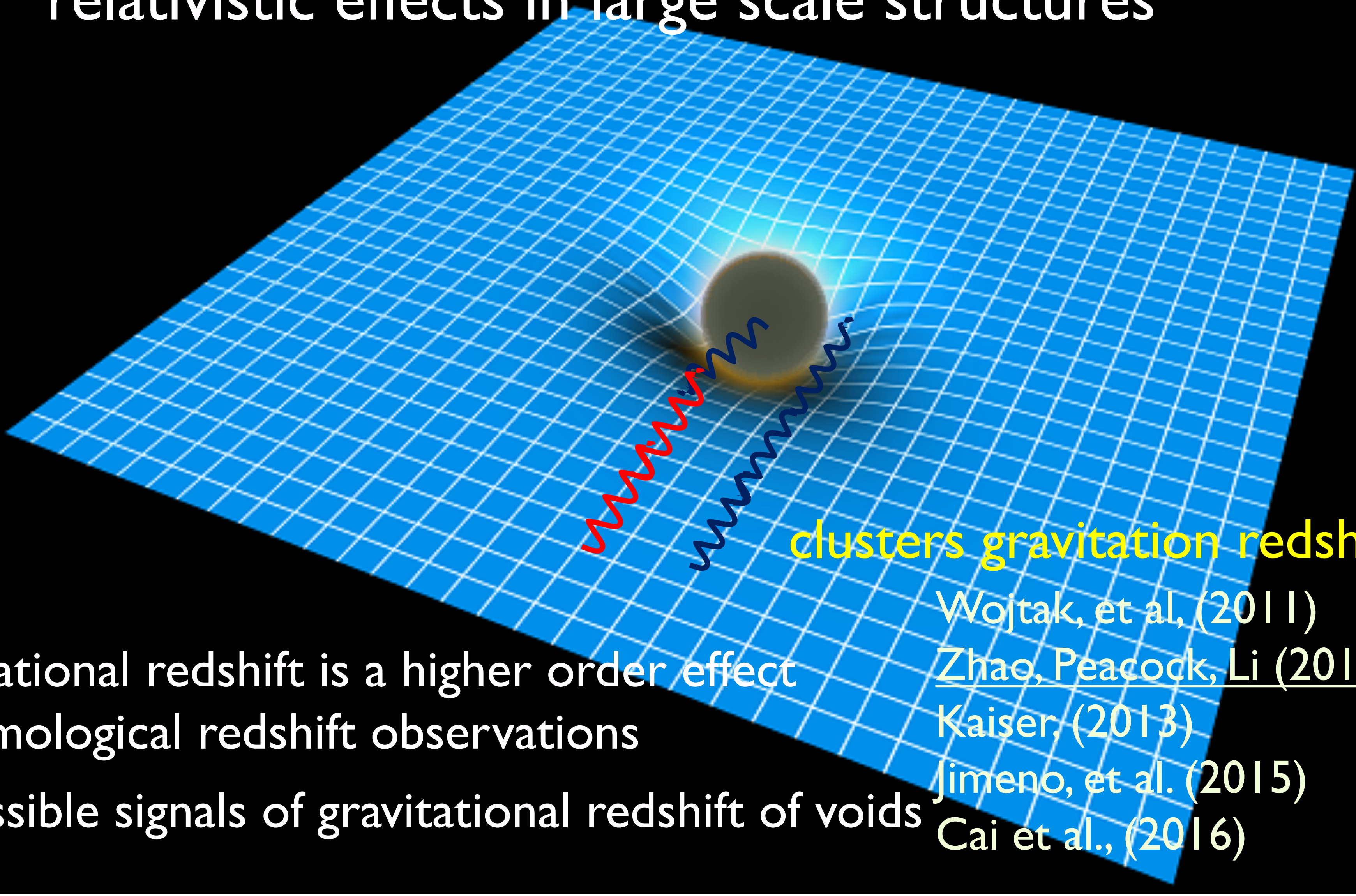


$$\frac{\Omega_1}{H} = \frac{\Omega_2}{H} = 10$$

$$\frac{\gamma}{H} = 0.5$$

2. Gravitational redshifts in (clusters and) voids

relativistic effects in large scale structures



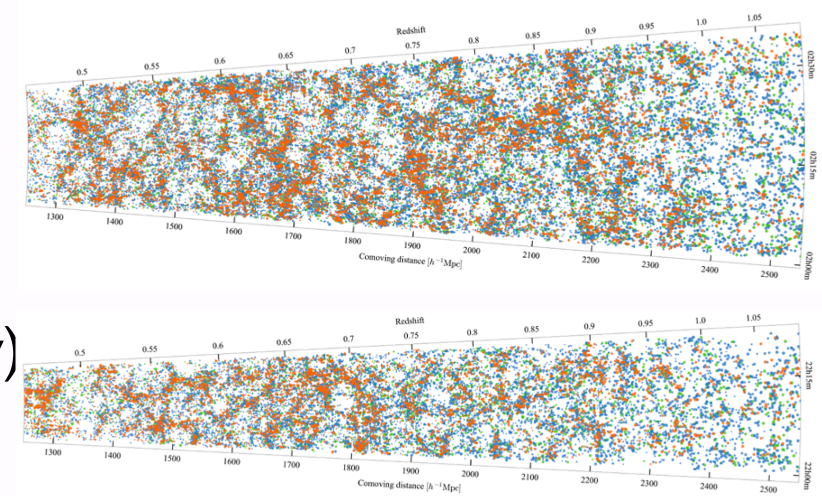
clusters gravitation redshift

Wojtak, et al, (2011)
Zhao, Peacock, Li (2013)
Kaiser, (2013)
Jimeno, et al. (2015)
Cai et al., (2016)

Gravitational redshift is a higher order effect in cosmological redshift observations

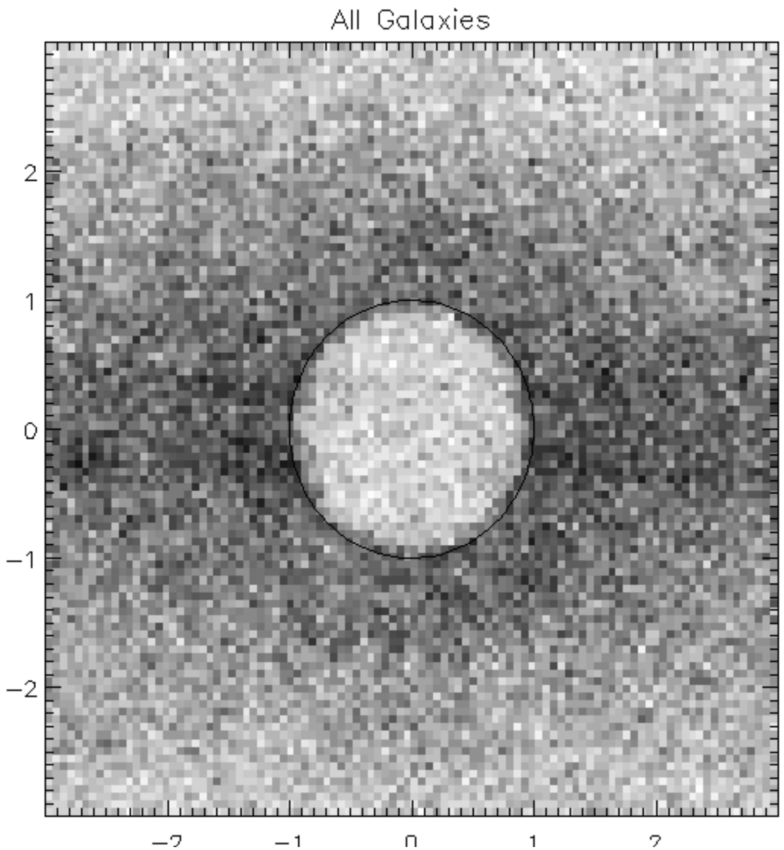
→ possible signals of gravitational redshift of voids

Gravitational redshifts of voids



Hawken et al. (2016)

Stacked voids in VIPERS (VIMOS Public Extragalactic Redshift Survey)



34600 galaxies

$0.55 < z < 0.9$

$1.6 \times 10^7\ (h^{-1}\mathrm{Mpc})^3$

822 voids

Inside voids is not empty

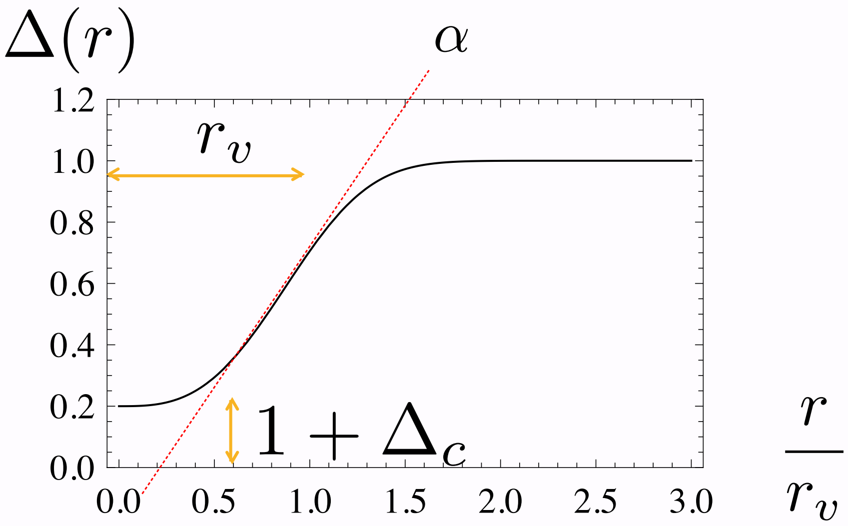
→ possible signal of gravitational potential of voids.

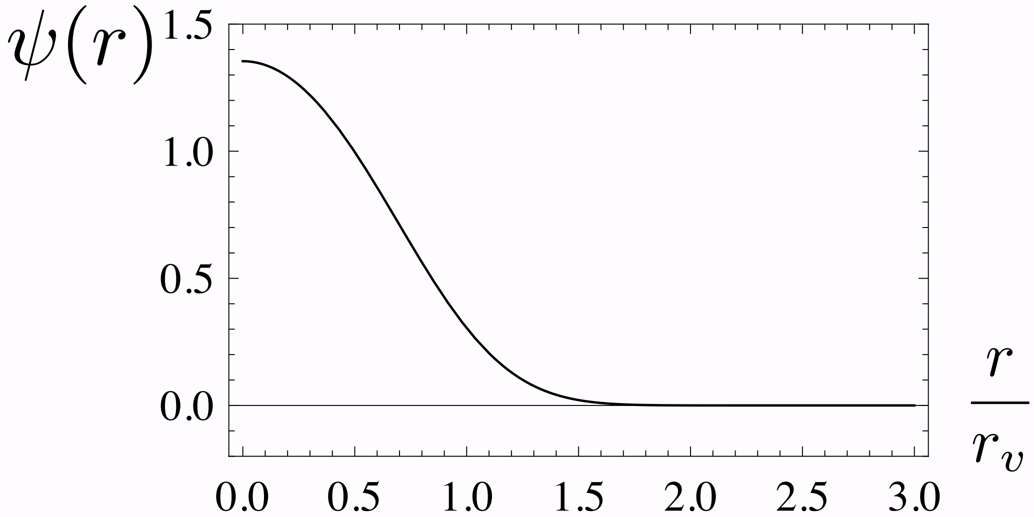
Simple analytic mode of void profile

Hawken et al 2016

$$\Delta(r) = \frac{M(<r)}{4\pi r^3/3} = \frac{3}{r^3}\int_0^r dr' r'^2 \delta(r') = \Delta_c e^{-(r/r_v)^\alpha}$$

$$\psi(r) = -\frac{3\Omega_m}{2a} H_0^2 \int_r^\infty dr' r' \frac{\Delta(r')}{3} = -\frac{H_0^2 r_v^2}{2}\frac{\Omega_m \Delta_c}{\alpha a}\Gamma(2/\alpha, (r/r_v)^\alpha)$$





gravitational potential has positive values inside a void.

Gravitational redshift causes an additional shift in the position of galaxies in redshift space

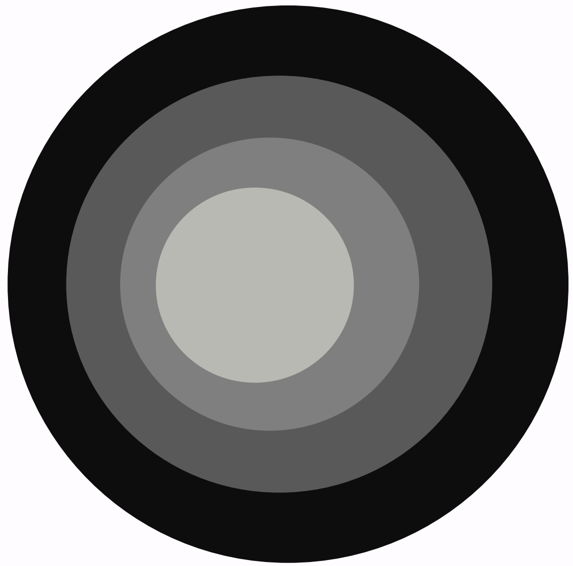
Shift of comoving distance

$$s = r + \frac{\delta z}{H(z)} \qquad \delta z = -(1+z_1)\psi < 0$$

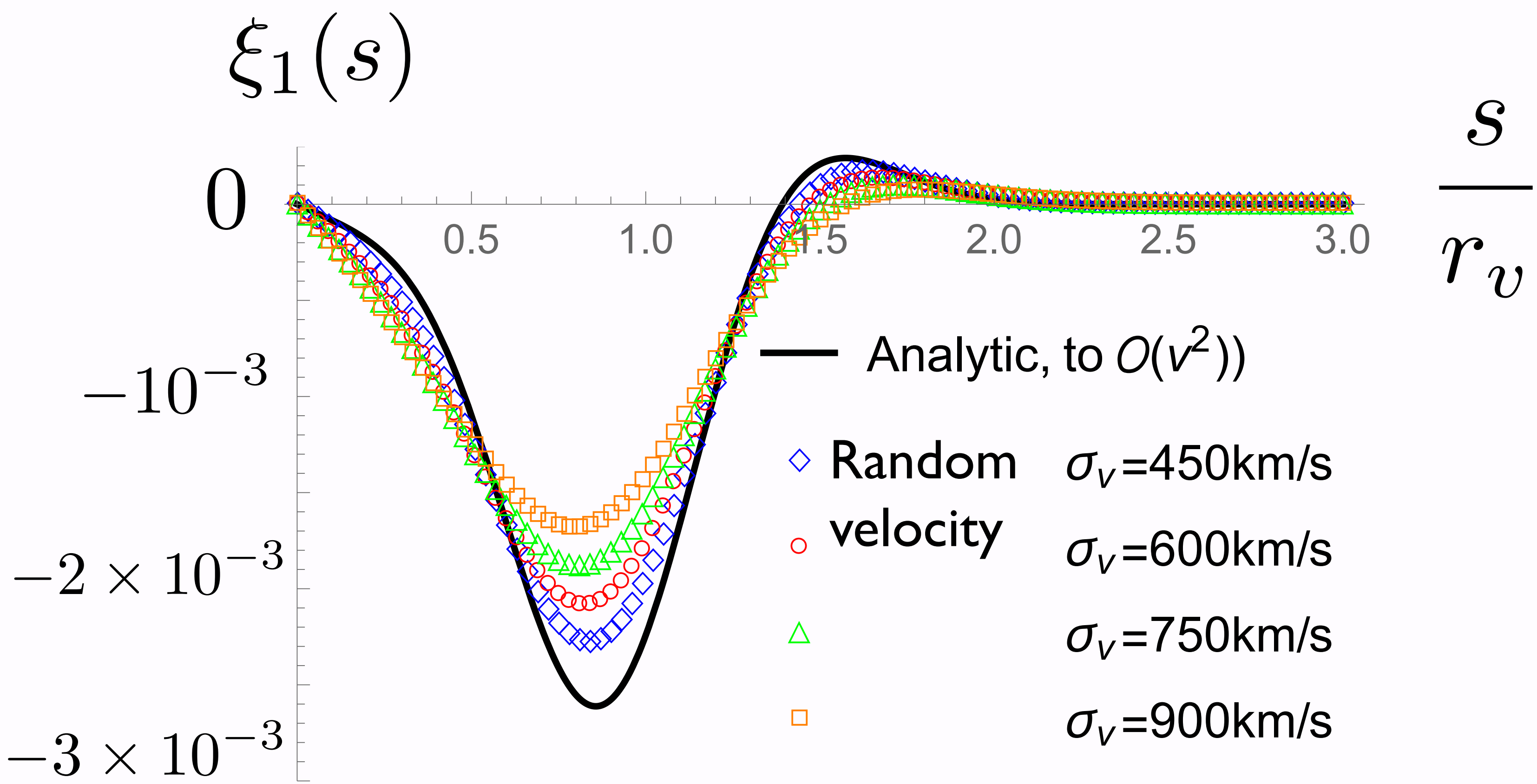
Dipole asymmetry in redshift-space

Line of sight direction

Observer →



Void – galaxy correlation function dipole component



Nan et al, in preparation

Summary and conclusions

1. Quantum vacuum physics

Description of the Minkowski vacuum as an entangled state between the states constructed in R, L, F, P regions

➡ Quantum radiation produced by a uniformly accelerating detector → entangled correlation of the right-moving Kasner mode and right Rinder mode → The nonlocal correlation of the field is the origin.

➡ generalization to the model in de Sitter spacetime

2. Gravitational Redshift signal in (clusters and) voids

Possible signals of gravitational potential of voids (and clusters).