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YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Cosmic propagators

~powerful tool to characterize large-scale structure~

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Contents

A fresh look at perturbation theory of large-scale structure
with a concept of propagators

Multi-point propagator expansion

Dark matter: generic damping tail behaviors
even in modified gravity models

Halo/galaxy: scale-dependent & non-local bias

Collaborators

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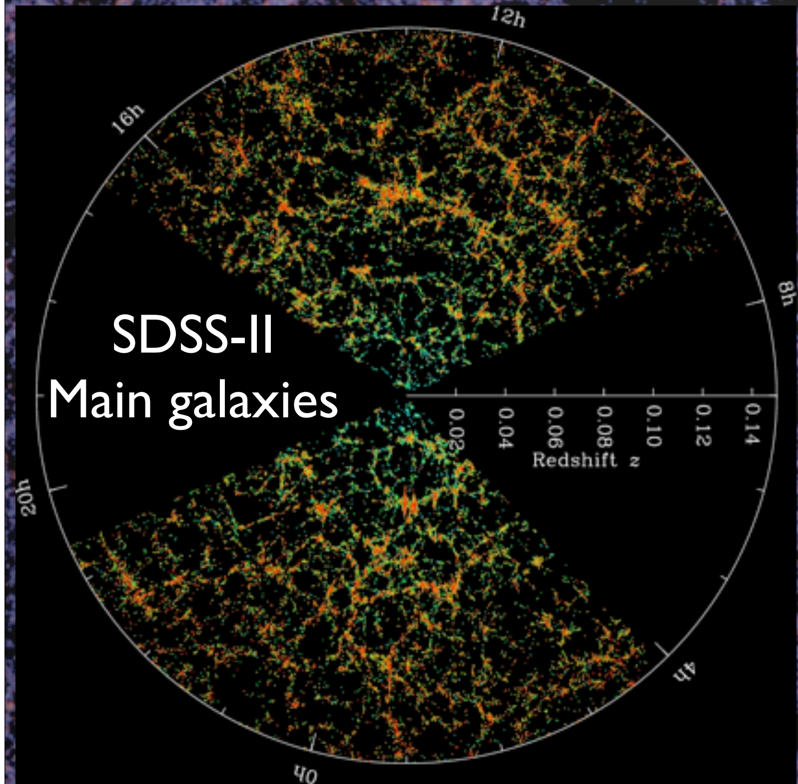
T. Matsubara (KMI), T. Nishimichi (IAP)

Large-scale structure (LSS)

Spatial inhomogeneity of mass distribution at 1~10^3 Mpc

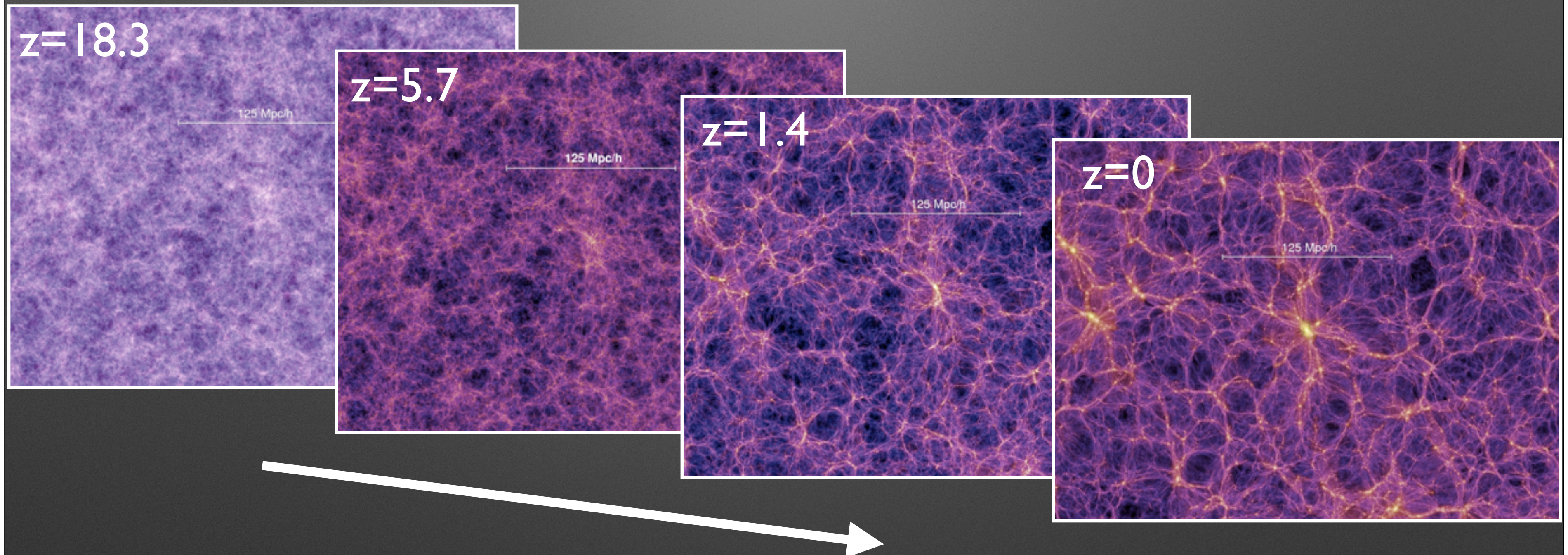


- It is traditionally traced by galaxy clustering via galaxy redshift surveys
- LSS has evolved under the influence of gravity & cosmic expansion

Statistical nature of LSS carries rich cosmological information

Theoretical issues

How to accurately describe the evolution of LSS



Confronting theory of LSS with precision observations:

Reducing and/or controlling non-linear effects

- Non-linear gravity
- Redshift-space distortions
- Galaxy biasing

Mapping initial cond. to observables

$\delta_0(\boldsymbol{k})$

initial density field (Gaussian)

Initial power spectrum

$P_0(k)$

from linear theory

(CMB Boltzmann code)

$\delta(\boldsymbol{k}; z)$

Evolved density field (non-Gaussian)

Observables

$P(k; z)$

$B(k_1, k_2, k_3; z)$

$T(k_1, k_2, k_3, k_4; z)$

$\vdots$

of dark matter/galaxies/halos

Concept of '*propagator*' in physics/mathematics may be useful

Propagator in physics

- ✦ Green's function in linear differential equations
- ✦ Probability amplitude in quantum mechanics

Schrödinger Eq.

$$\left(-i\hbar\frac{\partial}{\partial t}+H_x\right)\psi(x,t)=0$$

$$G(x,t;x',t')\equiv\frac{\delta\psi(x,t)}{\delta\psi(x',t')}$$

$$\left(-i\hbar\frac{\partial}{\partial t}+H_x\right)G(x,t;x',t')=-i\hbar\,\delta_D(x-x')\delta_D(t-t')$$

$$\Rightarrow\quad \psi(x,t)=\int_{-\infty}^{+\infty}dx'G(x,t;x',t')\,\psi(x',t')\ ;\quad t>t'$$

Cosmic propagators

Propagator should carry information of

non-linear evolution & statistical properties

Crocce & Scoccimarro ('06)

Evolved (non-linear) density field

$$\left\langle \frac{\delta\,\delta_{\rm m}(\boldsymbol{k};t)}{\delta\,\delta_0(\boldsymbol{k}')} \right\rangle \equiv \delta_{\rm D}(\boldsymbol{k}-\boldsymbol{k}')\,\Gamma^{(1)}(k;t)$$

Propagator

Initial density field

Ensemble w.r.t randomness of initial condition

Contain statistical information on *full-nonlinear* evolution

(Non-linear extension of Green's function)

but

This is not sufficient to describe nonlinear mode-coupling of LSS

Multi-point propagators

Bernardeau, Crocce & Scoccimarro ('08)

As a natural generalization,

Multi-point propagator

$$\left\langle \frac{\delta^n\,\delta_{\rm m}(\boldsymbol{k};t)}{\delta\,\delta_0(\boldsymbol{k}_1)\cdots\delta\,\delta_0(\boldsymbol{k}_n)}\right\rangle = (2\pi)^{3(1-n)}\,\delta_{\rm D}(\boldsymbol{k}-\boldsymbol{k}')\,\Gamma^{(n)}(\boldsymbol{k}_1,\cdots,\boldsymbol{k}_n;t)$$

With this multi-point prop.

- Building blocks of a new perturbative theory (PT) expansion

  --------- Γ-expansion or Wiener-Hermite expansion

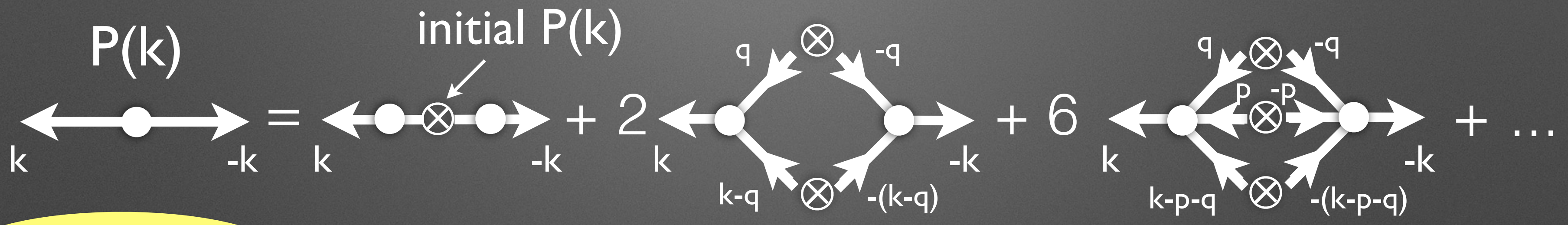
- A good convergence of PT expansion is expected

  (c.f. standard PT)

Power spectrum

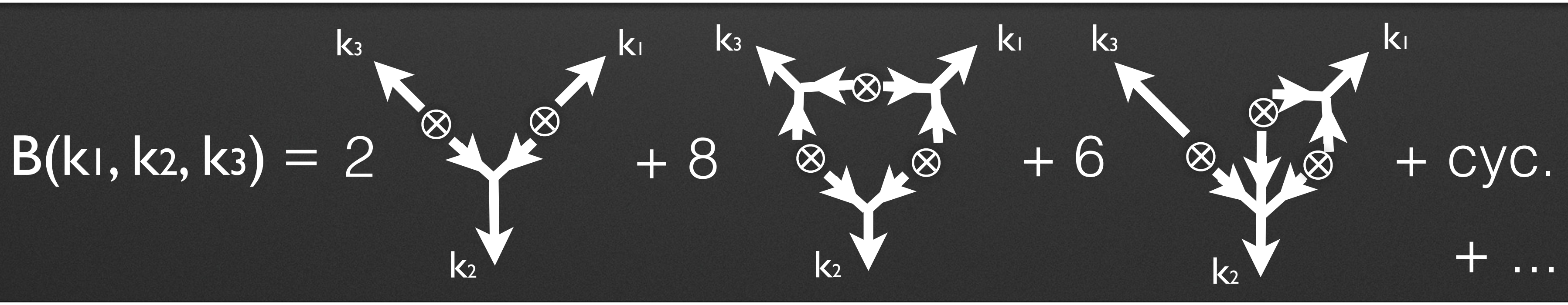
$$P(k;t) = \left[\Gamma^{(1)}(k;t)\right]^2 P_0(k) + 2\int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \left[\Gamma^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q};t)\right]^2 P_0(q)P_0(|\boldsymbol{k}-\boldsymbol{q}|)$$

$$+ 6\int \frac{d^6\boldsymbol{p}d^3\boldsymbol{q}}{(2\pi)^6} \left[\Gamma^{(3)}(\boldsymbol{p},\boldsymbol{q},\boldsymbol{k}-\boldsymbol{p}-\boldsymbol{q};t)\right]^2 P_0(p)P_0(q)P_0(|\boldsymbol{k}-\boldsymbol{p}-\boldsymbol{q}|) + \cdots$$



Bispectrum

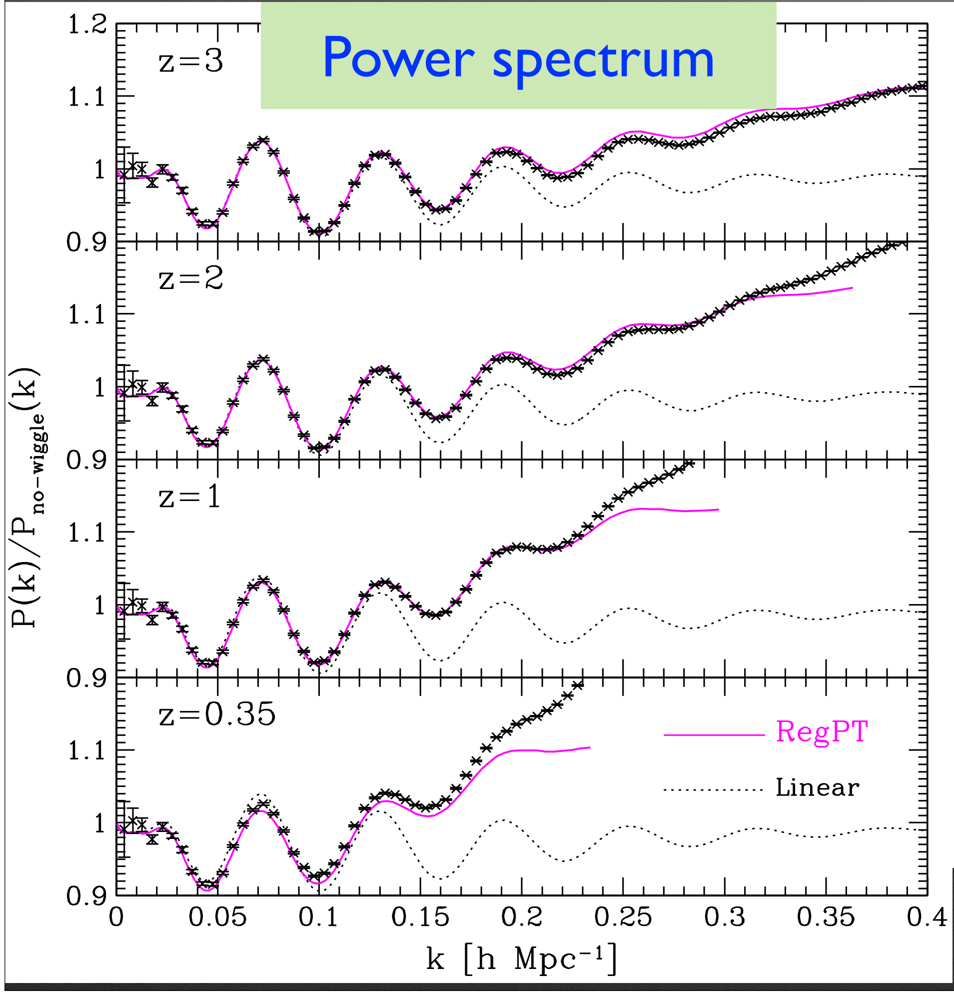
$$\begin{aligned} B(k_1,k_2,k_3) &= 2\,\Gamma^{(2)}(\mathbf{k}_1,\mathbf{k}_2)\,\Gamma^{(1)}(k_1)\,\Gamma^{(1)}(k_2)\,P_0(k_1)P_0(k_2) + \text{cyc.} \\ &+ \Big[8\int d^3q\,\Gamma^{(2)}(\mathbf{k}_1-\mathbf{q},\mathbf{q})\Gamma^{(2)}(\mathbf{k}_2+\mathbf{q},-\mathbf{q})\Gamma^{(2)}(\mathbf{q}-\mathbf{k}_1,-\mathbf{k}_2-\mathbf{q})P_0(|\mathbf{k}_1-\mathbf{q}|)P_0(|\mathbf{k}_2+\mathbf{q}|)P_0(q) \\ &+ 6\int d^3q\,\Gamma^{(3)}(-\mathbf{k}_3,-\mathbf{k}_2+\mathbf{q},-\mathbf{q})\Gamma^{(2)}(\mathbf{k}_2-\mathbf{q},\mathbf{q})\Gamma^{(1)}(\mathbf{k}_3)P_0(|\mathbf{k}_2-\mathbf{q}|)P_0(q)P_0(k_3) + \text{cyc.}\Big]. \end{aligned}$$

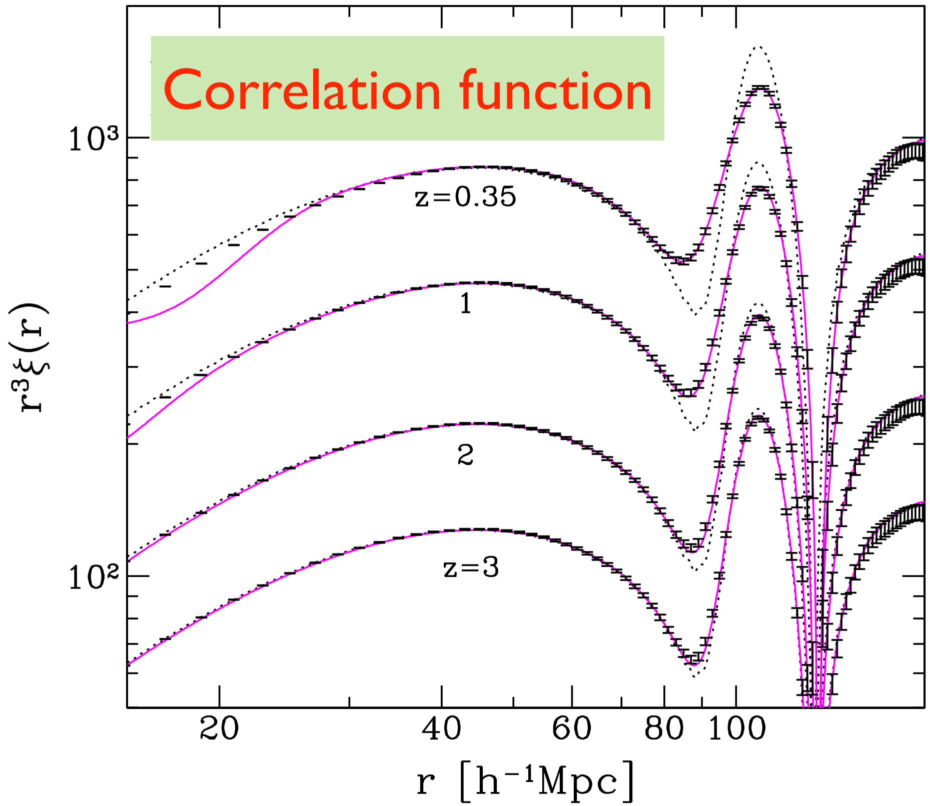


RegPT: fast PT calculation of P(k) & ξ(r)

A public PT code based on multi-point propagators at *2-loop*

http://www2.yukawa.kyoto-u.ac.jp/~atsushi.taruya/regpt_code.html



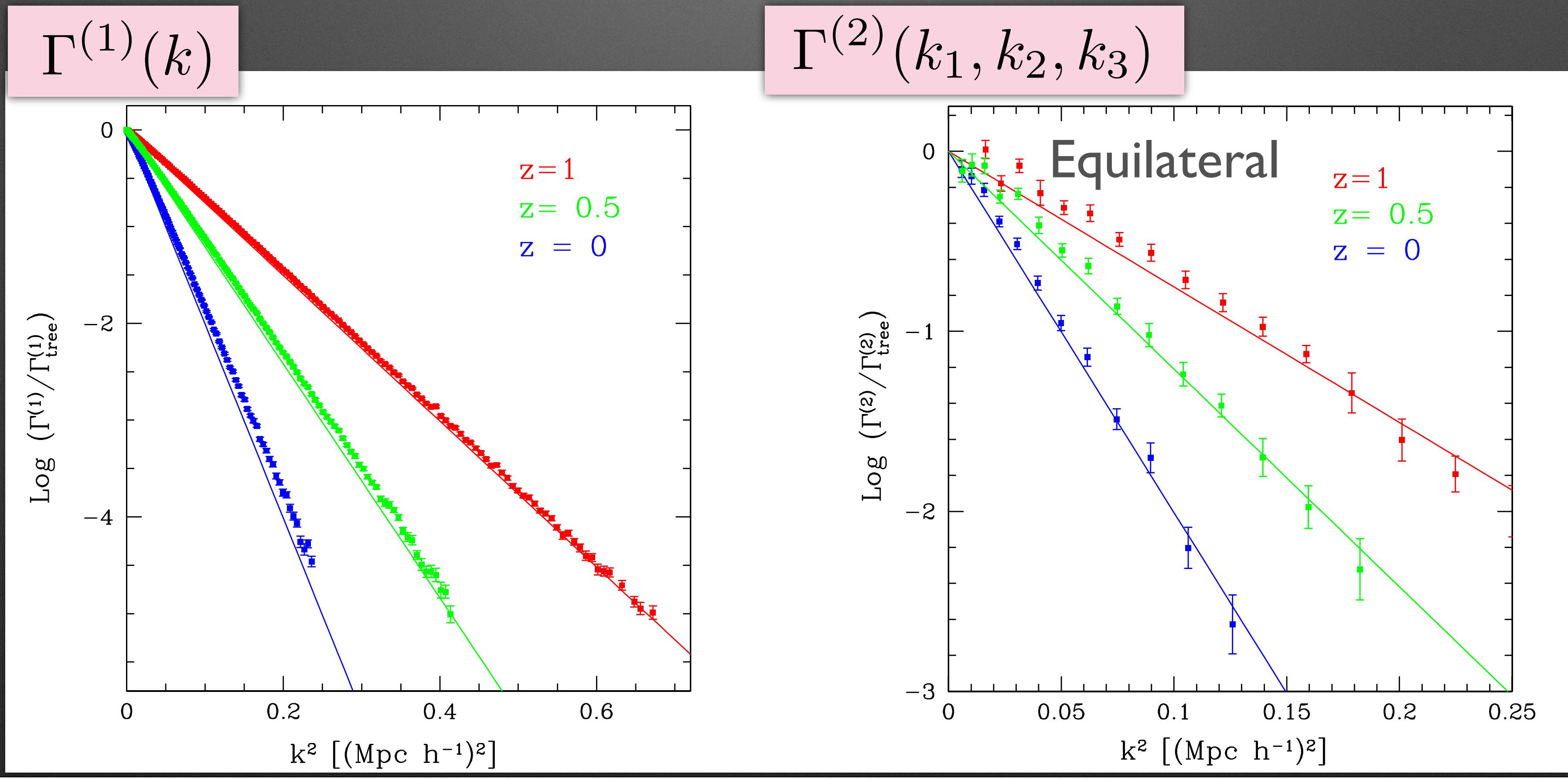


AT, Bernardeau, Nishimichi & Codis ('12)

Common properties

Crocce & Scoccimarro '06, Bernardeau et al. '08

$$\Gamma^{(n)} \xrightarrow{k\to+\infty} \Gamma^{(n)}_{\rm tree}\, e^{-k^2\sigma_{\rm v}^2/2} \quad ; \quad \sigma_{\rm v}^2 = \int \frac{dq}{6\pi^2} P_{\theta\theta}(q)$$



Origin of Exp. damping

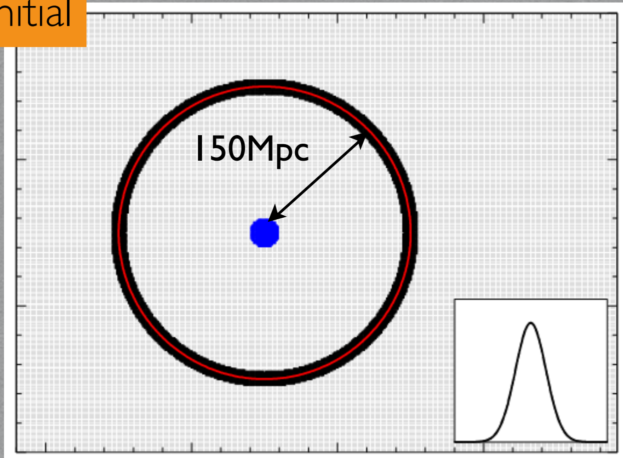
For Gaussian initial condition,

$$\langle \delta_{\rm m}(\boldsymbol{k};t)\,\delta_0(\boldsymbol{k}')\rangle = \Gamma^{(1)}(k;t)\,\underline{\langle \delta_0(\boldsymbol{k})\delta_0(\boldsymbol{k}')\rangle}$$

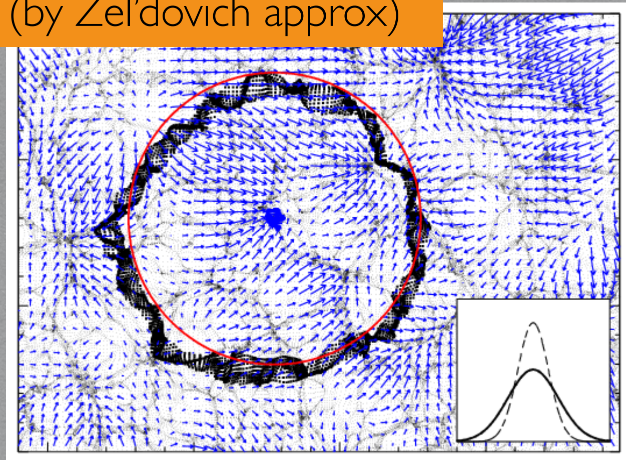
$// \; P_0(k)$ initial power spectrum

→ Cross correlation between initial & evolved density fields

initial



evolved (by Zel'dovich approx)



Padmanabhan et al. ('12)

Initial structure becomes blurred by the *local* cosmic flow

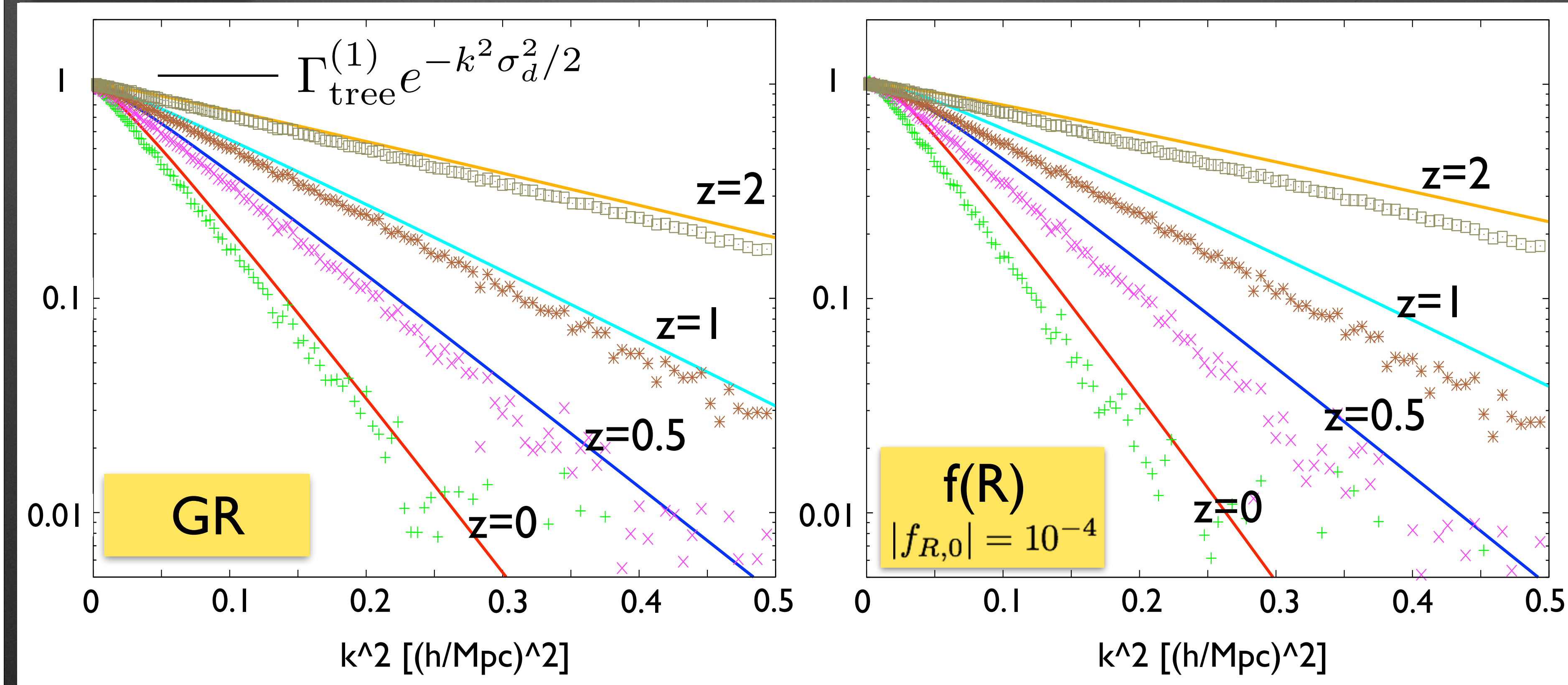
----- origin of Gaussian damping in propagator

Generic damping behaviors

Exp. damping can appear even in modified gravity models

$\Gamma^{(1)}(k)$

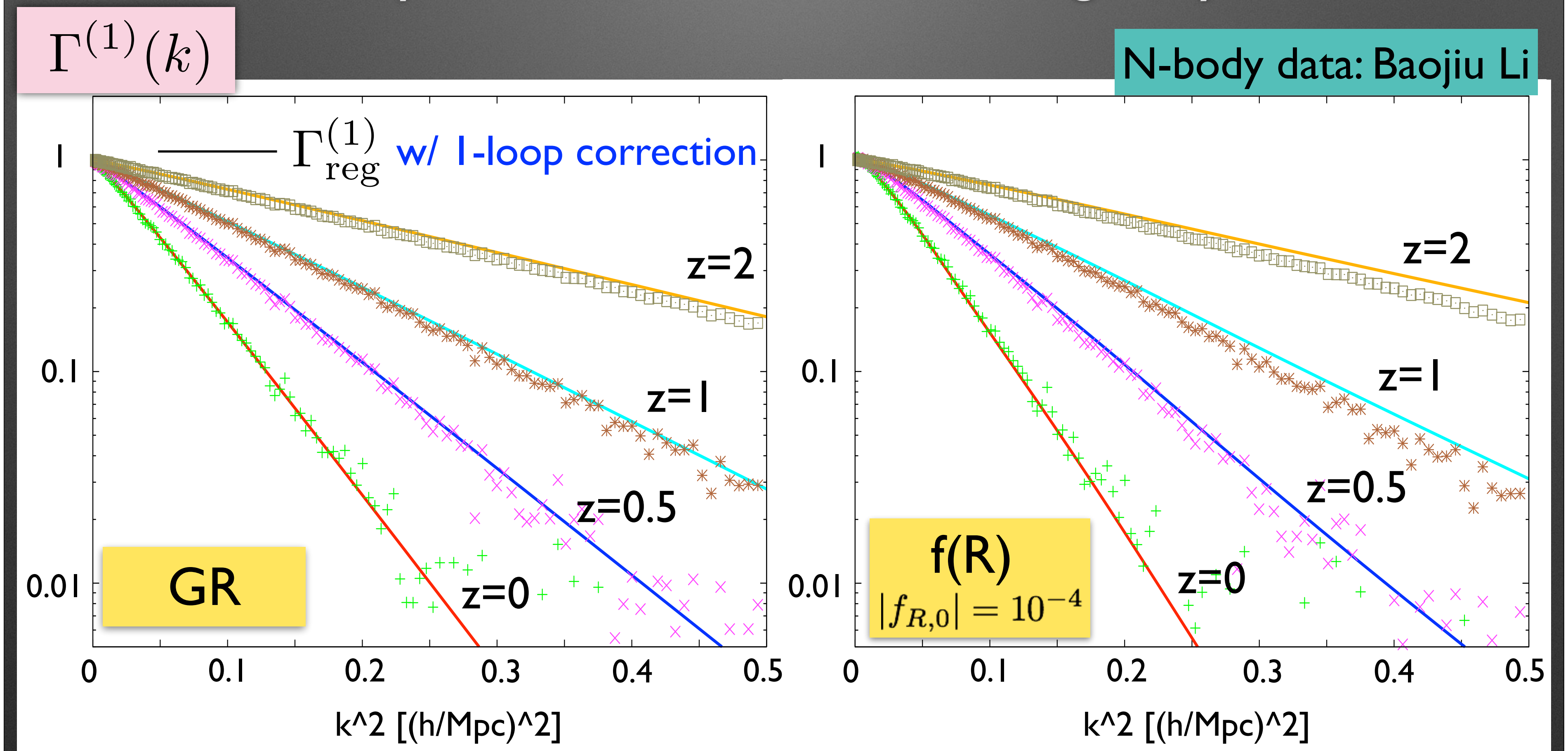
Data: Baojiu Li



AT, Nishimichi, Hiramatsu, et al. (in prep.)

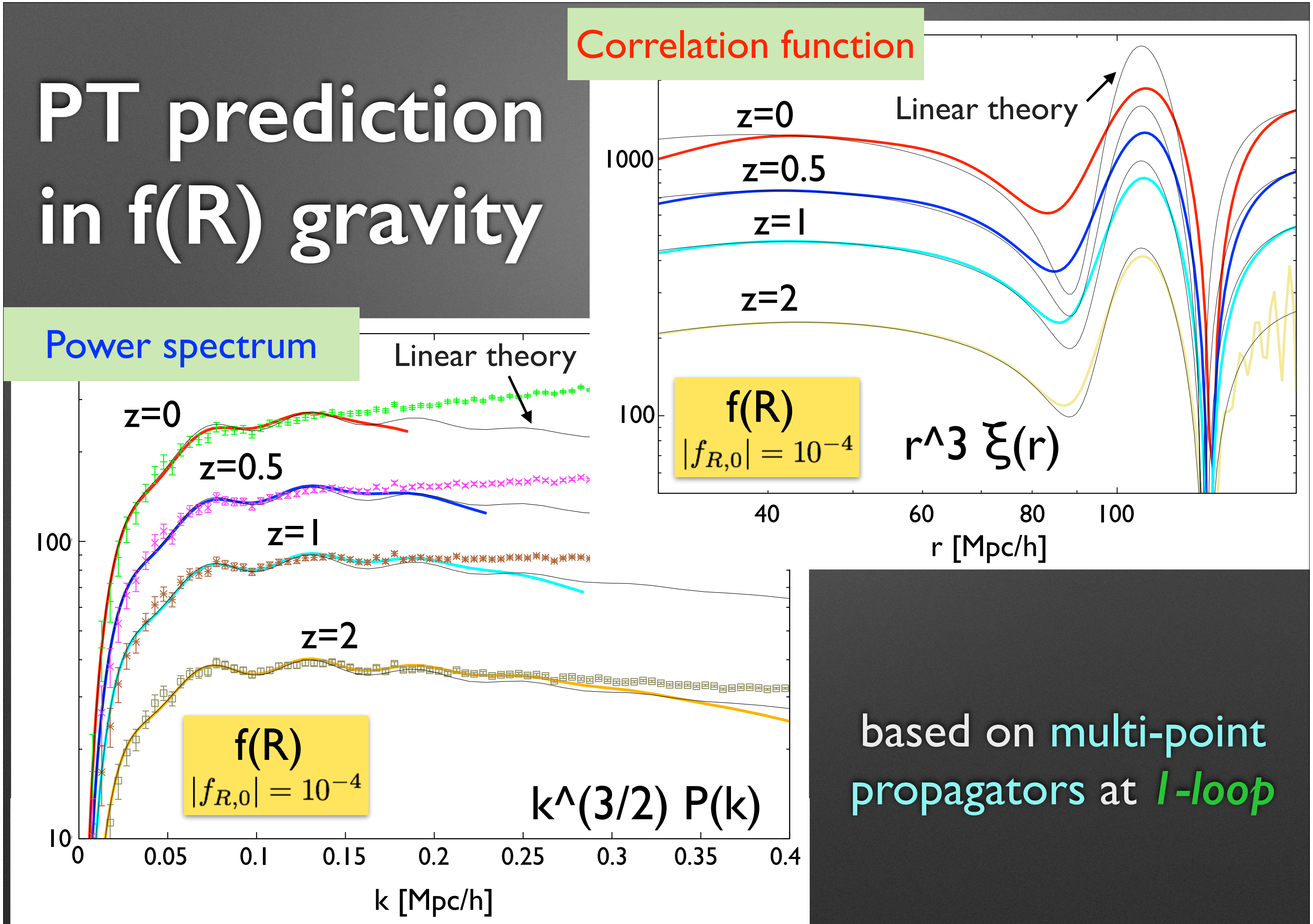
Generic damping behavior

Exp. damping generically holds
not only in GR but also in modified gravity models



AT, Nishimichi, Hiramatsu, Bernardeau et al. (in prep.)

PT prediction in f(R) gravity



based on multi-point propagators at *1-loop*

AT, Nishimichi, Hiramatsu, Bernardeau et al. (in prep.)

Characterizing halo/galaxy clustering with propagators

Concept of propagator is also useful for halo/galaxy clustering

Matsubara ('11, '12, '13)

Multi-point propagator of halos

Evolved (non-linear) halo density field

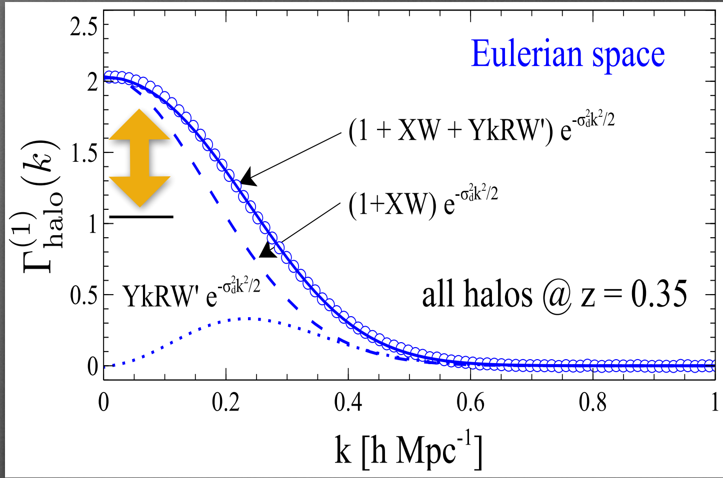
$$\left\langle \frac{\delta^n \delta_{\rm halo}(\boldsymbol{k};t)}{\delta\,\delta_0(\boldsymbol{k}_1)\cdots\delta\,\delta_0(\boldsymbol{k}_n)} \right\rangle = (2\pi)^{3(1-n)}\,\delta_{\rm D}(\boldsymbol{k}-\boldsymbol{k}_{12\cdots n})\,\Gamma^{(n)}_{\rm halo}(\boldsymbol{k}_1,\cdots,\boldsymbol{k}_n;t)$$

$$P_{\rm halo}(k) = \left\{\Gamma^{(1)}_{\rm halo}(k)\right\}^2 P_0(k) + 2\int\frac{d^3\boldsymbol{q}}{(2\pi)^3}\left\{\Gamma^{(2)}_{\rm halo}(\boldsymbol{q},\,\boldsymbol{k}-\boldsymbol{q})\right\}^2 P_0(q)P_0(|\boldsymbol{k}-\boldsymbol{q}|) + \cdots$$

--------- integrated PT

Propagator of halos

$$\Gamma^{(1)}_{\rm halo} \longrightarrow \{1 + c_1^{\rm L}(k)\}\, e^{-k^2\sigma_d^2/2}$$



$c_1^{\rm L}$ is related to Lagrangian halo bias $b_1^{\rm L}$

but more generally, it can be defined as Lagrangian propagator:

$$\left\langle \frac{\delta\, \delta^{\rm L}_{\rm halo}(\boldsymbol{k})}{\delta\, \delta_0(\boldsymbol{k}')} \right\rangle = \delta_D(\boldsymbol{k}-\boldsymbol{k}')\, c_1^{\rm L}(k)$$

halo density field in *Lagrangian space*

It carries information on

scale-dependent & *non-local* *properties* of halo bias

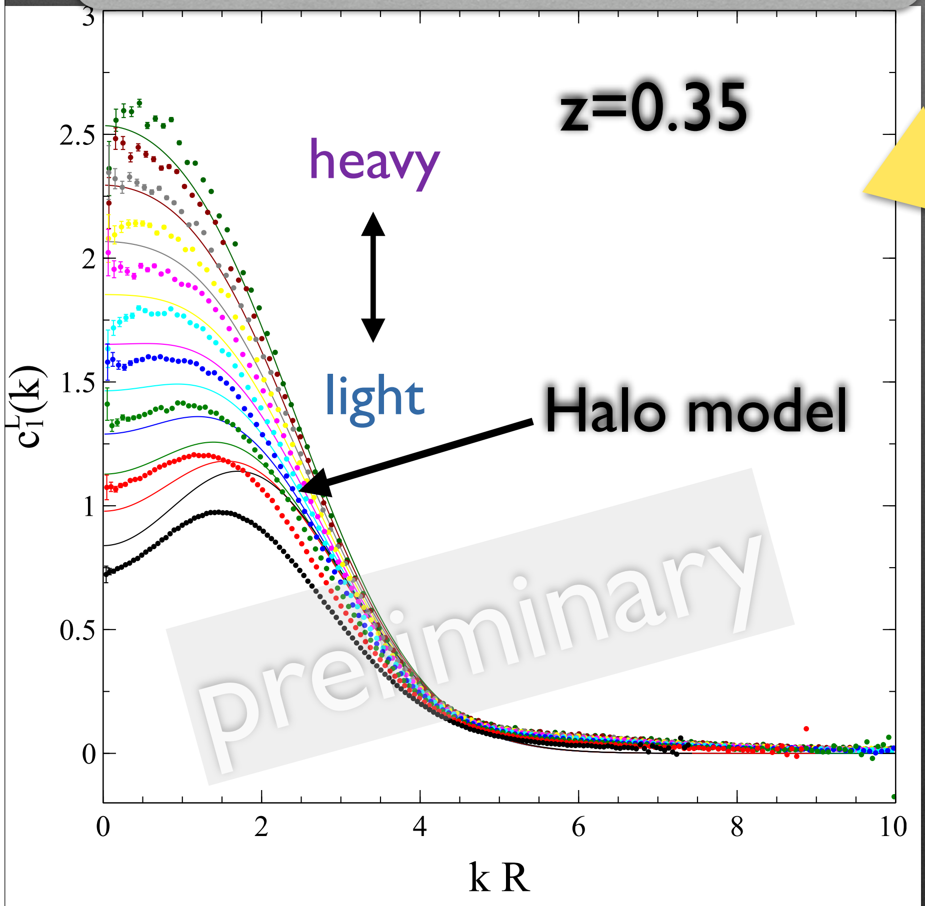
⟶ directly measurable quantity in N-body simulations

Lagrangian halo propagator

Nishimichi, Matsubara & AT (in prep.)

10 equal mass bins with mass range

$$2\times10^{13}\leq M/[h^{-1}\,M_\odot]\leq 2\times10^{14}$$



Lagrangian propagator measured in N-body simulations

Halo model (Matsubara '12)

$$c_1^{\rm L}(k)=A(M)\,W(kR)+B(M)\,\frac{dW(kR)}{d\,\ln(kR)}$$

$W(kR)$: Gaussian filter

halo model qualitatively explains scale-dependent behavior

Impact on baryon acoustic peak

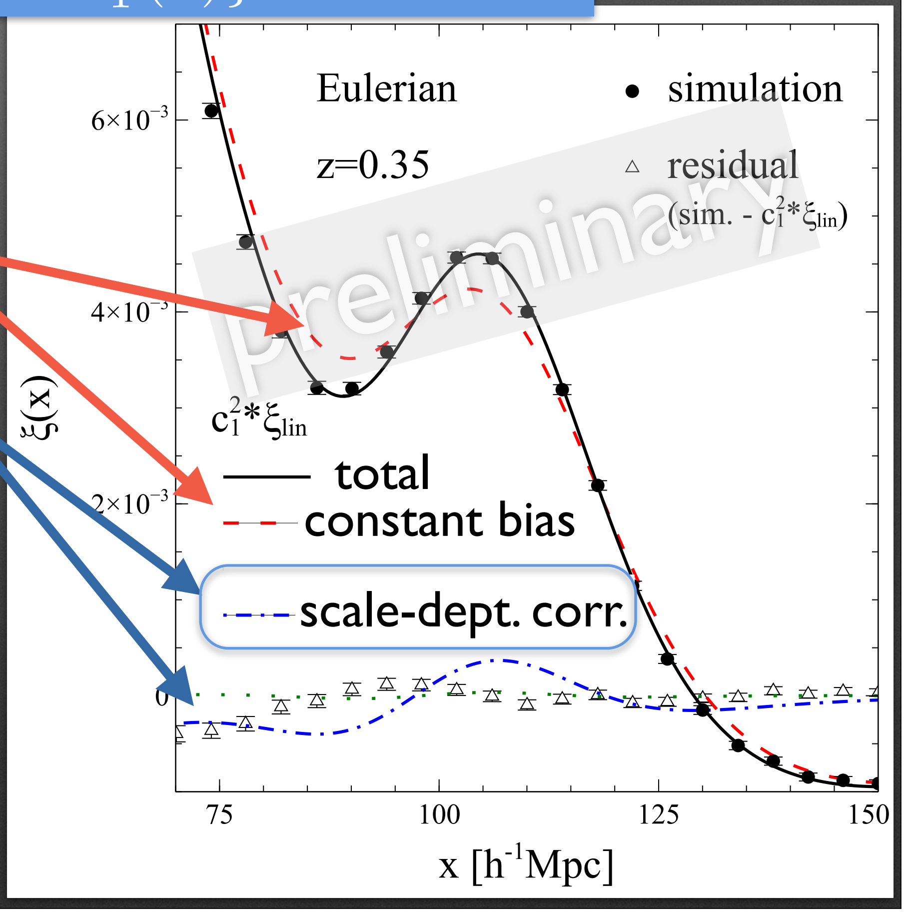
$$\xi_{\rm halo}(r) \simeq [\,(\Gamma^{(1)}_{\rm halo})^2 \otimes \xi_{\rm lin}\,](r) + \ldots$$

$$\Gamma^{(1)}_{\rm halo} = \{1 + c_1^{\rm L}(k)\}\, e^{-k^2\sigma_d^2/2}$$

induce *scale-dependent bias :*

- simple constant bias fails
- enhance BAO peak/trough

(c.f. Peak theory by Desjacques et al. ('12))



Nishimichi, Matsubara & AT (in prep.)

Summary

Cosmic propagators provide a useful way to characterize clustering property of LSS (dark matter/galaxy/halo)

Dark matter : PT prediction works well not only in GR but also in modified gravity (f(R) gravity)

Halo/galaxy : scale-dependent bias around BAO peak

Modeling LSS with PT is still developing, and a further quantitative study on halo/galaxy propagators is worth doing