Perturbative approach to the redshift space distortions

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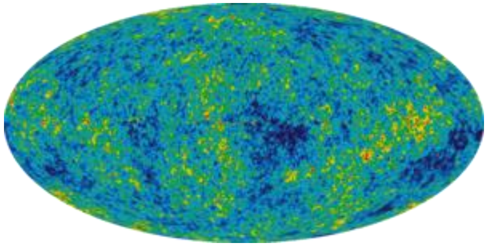
CosKASI-ICG-NAOC-YITP joint workshop @YITP, Kyoto

Observations

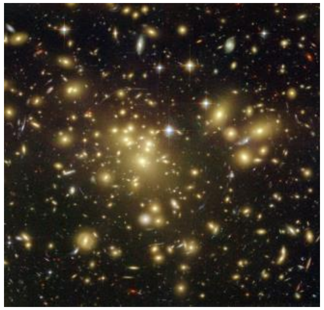
- Background

  CMB, BAO,SNe



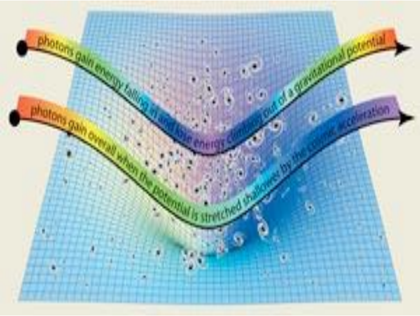
- Lensing potential $\Phi + \Psi$

  weak lensing



- Time variation of lensing potential

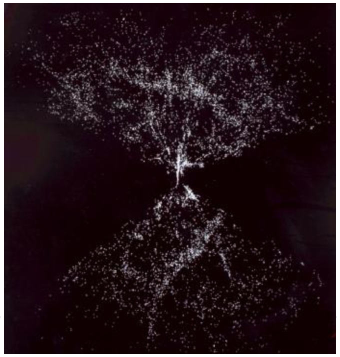
  Integrated Sachs-Wolfe effect

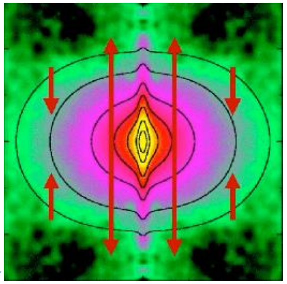


- Matter perturbations

  galaxy clustering δ_m

  peculiar velocities θ_m





Consistency relation

Zhang & Jain Phys. Rev. D78 (2008) 063503
Song & KK JCAP 0901(2009) 048

- In GR, gravitation equations are given by

$$H^2 = \frac{8\pi G}{3}\rho_T, \quad \rho_T = \sum_i \rho_i$$

$$\frac{k^2}{a^2}\Phi = 4\pi G a^2 \rho_T \delta_T, \quad \rho_T\delta_T = \sum_i \rho_i \delta_i$$

- Consistency relation

$$\alpha(k,t) = \frac{2k^2}{3a^2H^2}\frac{(\Phi+\Psi)-\Psi}{\delta_T} = 1$$

background

Weak lensing

Peculiar velocity

$$k^2\Psi = \frac{d(a\theta_m)}{dt}$$

Galaxy distribution

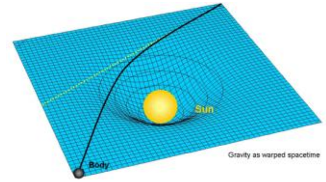
$$\delta_g = b_T\delta_T$$

We have just enough number of observations to check the relation

Amendola et.al JCAP 0804 (2008) 013
Zhao et.al. Phys. Rev. Lett. 103 (2009) 241301
Daniel, Linder et.al. Phys. Rev. D81 (2010) 123508

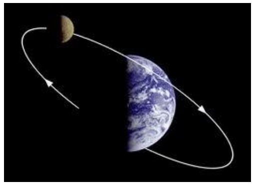
Parametrisation

- Parameterised modified Einstein eq.



$$k^2(\Psi+\Phi) = -8\pi G a^2 \Sigma(a,k)\rho_m\delta_m$$: Lensing

$$k^2\Psi = -4\pi G a^2 \mu(a,k)\rho_m\delta_m$$: Newton potential



- Brans-Dicke gravity

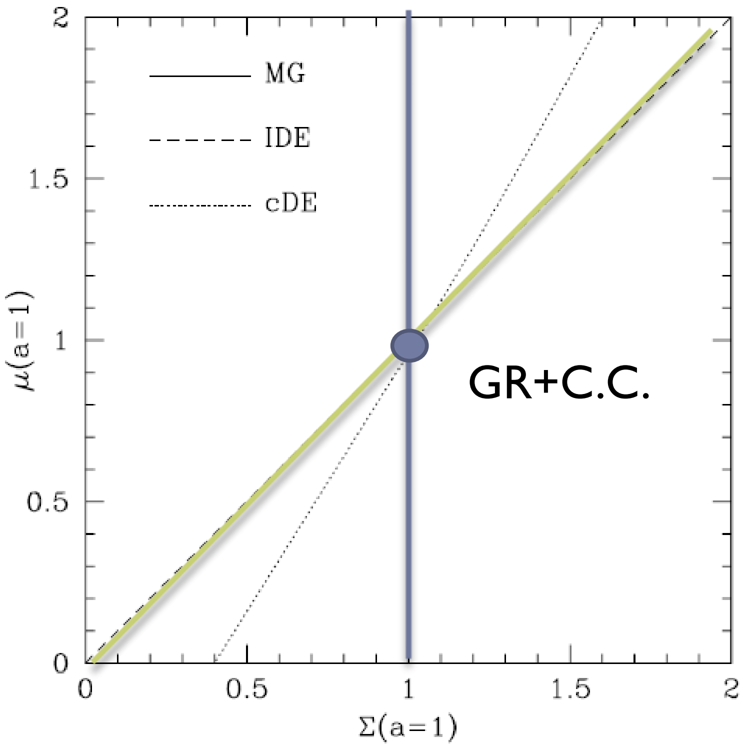
$$\Sigma(a,k) \simeq 1$$

$$\mu(a,k) \simeq \frac{2(2+\omega_{BD}) + \mu^2 a^2/k^2}{3+2\omega_{BD} + \mu^2 a^2/k^2}$$

- dark energy model

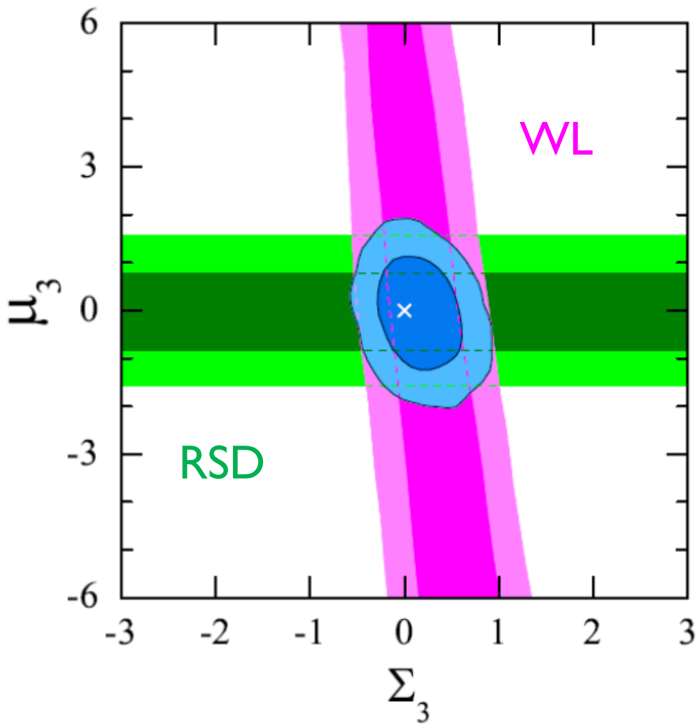
no anisotropic stress

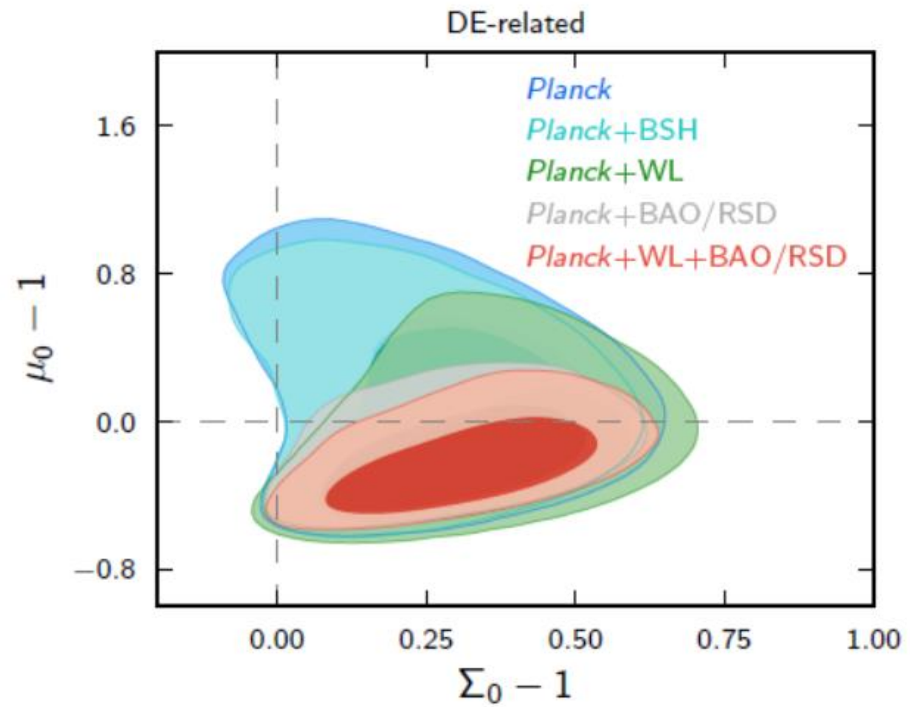
$$\Sigma = \mu = \left(1 + \frac{\rho_{DE}\delta\rho_{DE}}{\rho_m}\right)$$



Current constraints

- Weak Lensing (WL)+ Red-Shift Distortion (RSD)





$$\mu(a) = \mu_s(1 + a^s), \Sigma(a) = \Sigma_s(1 + a^s)$$

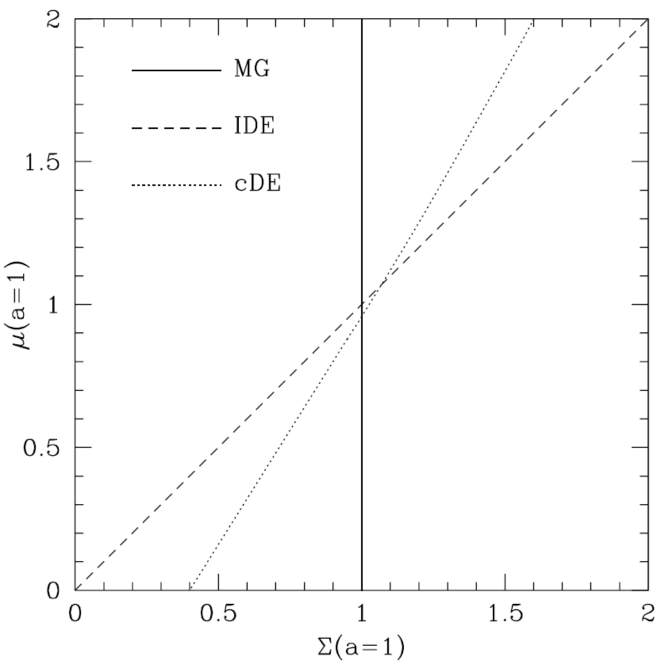
$$\mu(a,k) = \mu_0 \Omega_L(a), \quad \Sigma(a,k) = \Sigma_0 \Omega_L(a)$$

Song et.al. PRD84 (2011) 083523

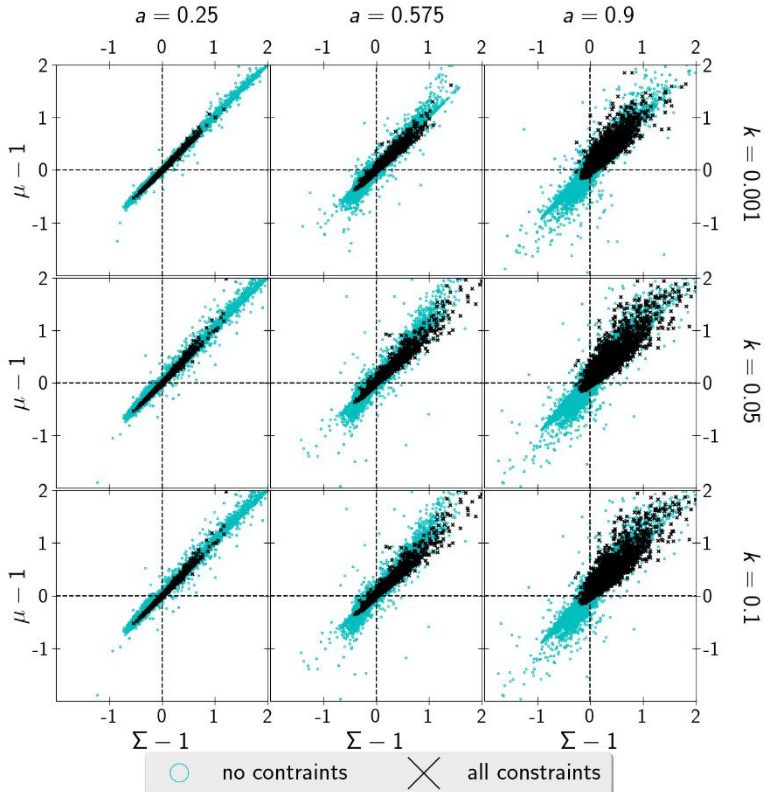
Planck 2015 "Modified gravity and dark energy"
(Simpson et.al. MNRAS 429 (2013) 2249)

Theoretical priors

- Theoretical predictions (linear theory)



Song et.al. 1001.0969



Peirone, Raveri, Pogosian, Silvestri Koyama in preparation

Going beyond linear scales

- **Ample information on non-linear scales**

  Parametrisation is valid only for linear perturbations

  Conservative cut-offs are required to remove data on non-linear scale, which significantly degrade the constraining power

- **Extraction of linear information**

  For RSD, non-linear modelling is required to extract the linear growth rate, which is done normally within LCDM

- **New information on non-linear scales**

  On non-linear scales, screening mechanisms can be important leaving interesting signatures

Perturbative approach

- Perturbation theory approach

On small scales, it is enough to go beyond linear order for the Newtonian potential

Koyama et.al. 0902.0618
Taruya et. al. 1309.6783, 1408.4232
Bose and Koyama 1606.02520

$$-\left(\frac{k}{aH}\right)^2 \Phi = \frac{3\Omega_m(a)}{2}\mu(k,a)\,\delta(\boldsymbol{k}) + S(\boldsymbol{k})$$

$$S(\boldsymbol{k}) = \int \frac{d^3\boldsymbol{k}_1 d^3\boldsymbol{k}_2}{(2\pi)^3}\delta_D(\boldsymbol{k}-\boldsymbol{k}_{12})\gamma_2(\boldsymbol{k},\boldsymbol{k}_1,\boldsymbol{k}_2;a)\delta(\boldsymbol{k}_1)\,\delta(\boldsymbol{k}_2)$$
$$+\int \frac{d^3\boldsymbol{k}_1 d^3\boldsymbol{k}_2 d^3\boldsymbol{k}_3}{(2\pi)^6}\delta_D(\boldsymbol{k}-\boldsymbol{k}_{123})\gamma_3(\boldsymbol{k},\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3;a)\delta(\boldsymbol{k}_1)\,\delta(\boldsymbol{k}_2)\,\delta(\boldsymbol{k}_3)$$

Solve continuity and Euler equation numerically $\theta \equiv \nabla \cdot \boldsymbol{v}/(a\,H)$

$$a\frac{\partial\delta(\boldsymbol{k})}{\partial a} + \theta(\boldsymbol{k}) = -\int \frac{d^3\boldsymbol{k}_1 d^3\boldsymbol{k}_2}{(2\pi)^3}\delta_D(\boldsymbol{k}-\boldsymbol{k}_1-\boldsymbol{k}_2)\alpha(\boldsymbol{k}_1,\boldsymbol{k}_2)\,\theta(\boldsymbol{k}_1)\delta(\boldsymbol{k}_2),$$

Taruya 1606.02168

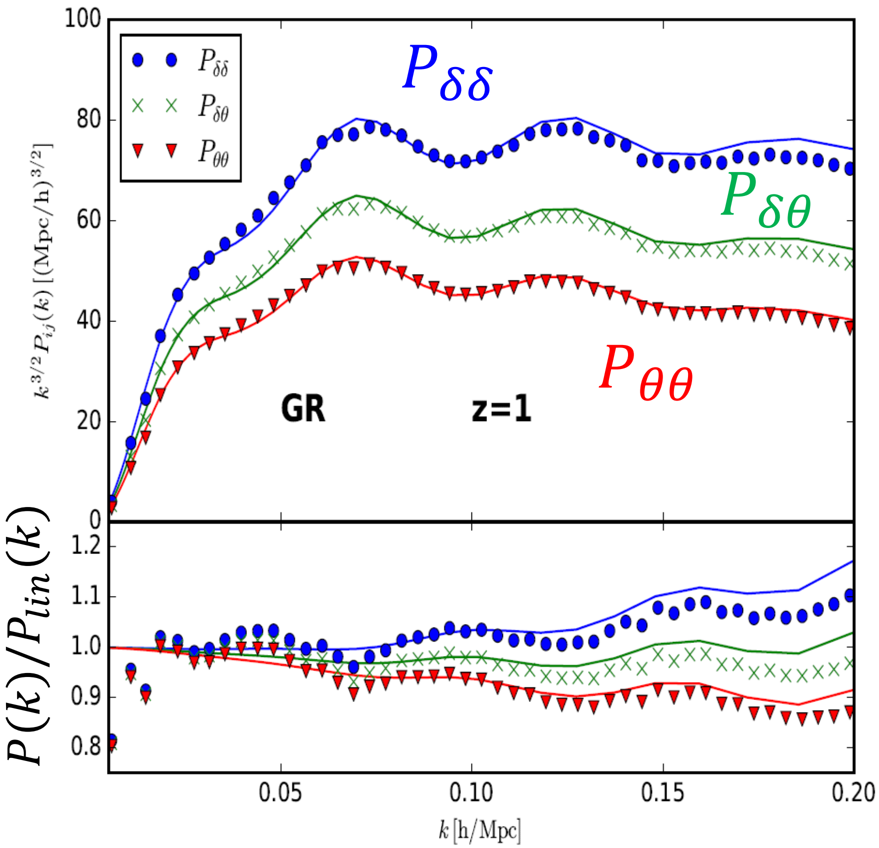
$$a\frac{\partial\theta(\boldsymbol{k})}{\partial a} + \left(2+\frac{aH'}{H}\right)\theta(\boldsymbol{k}) - \left(\frac{k}{a\,H}\right)^2\Phi(\boldsymbol{k}) = -\frac{1}{2}\int \frac{d^3\boldsymbol{k}_1 d^3\boldsymbol{k}_2}{(2\pi)^3}\delta_D(\boldsymbol{k}-\boldsymbol{k}_1-\boldsymbol{k}_2)\beta(\boldsymbol{k}_1,\boldsymbol{k}_2)\,\theta(\boldsymbol{k}_1)\theta(\boldsymbol{k}_2)$$

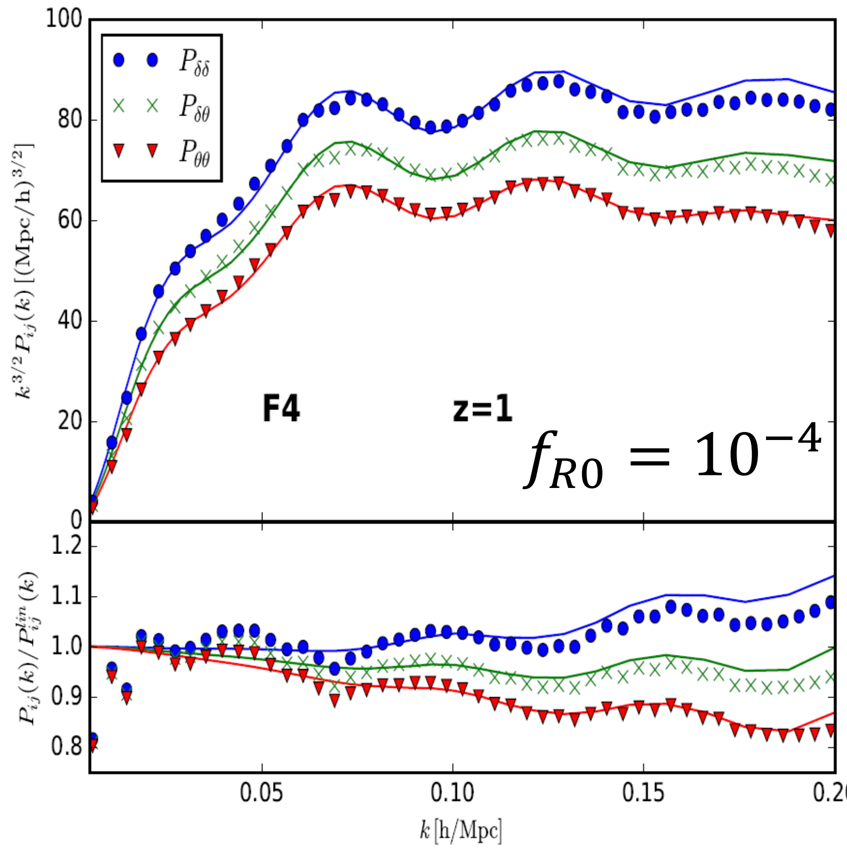
$$\alpha(\boldsymbol{k}_1,\boldsymbol{k}_2) = 1+\frac{\boldsymbol{k}_1\cdot\boldsymbol{k}_2}{|\boldsymbol{k}_1|^2}, \qquad \beta(\boldsymbol{k}_1,\boldsymbol{k}_2) = \frac{(\boldsymbol{k}_1\cdot\boldsymbol{k}_2)\,|\boldsymbol{k}_1+\boldsymbol{k}_2|^2}{|\boldsymbol{k}_1|^2|\boldsymbol{k}_2|^2}$$

An example: real space power spectrum

- Comparison with N-body

Taruya et. al. 1309.6783, 1408.4232
Bose and Koyama 1606.02520



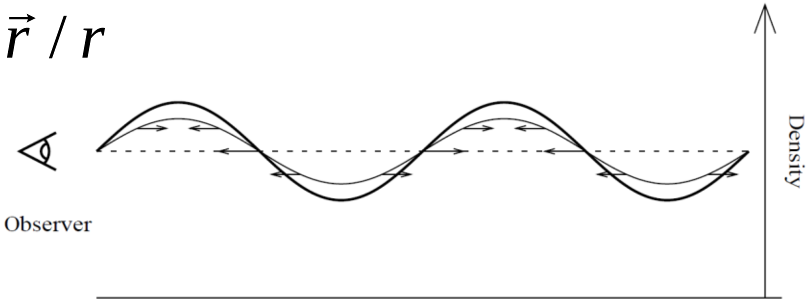


Red-Shift Distortion

- RSD

  In redshift space, the clusteing is anisotropic due to peculiar velocities $\vec{s} = \vec{r} + (\vec{v}\cdot\vec{n})\vec{n}/\mathcal{H}, \quad \vec{n} = \vec{r}/r$

  $$P(k,\mu),\ \ \mu = k_{\parallel}/k$$



- Non-linear modelling

  ex). TNS mode   Taruya, Nishimichi and Saito 1006.0699

$$P^S(k,\mu) = \mathrm{D_{FoG}}(k\mu\sigma_v)\{P_{\delta\delta}(k) - 2\mu^2 P_{\delta\theta}(k) + \mu^4 P_{\theta\theta}(k) + A(k,\mu) + B(k,\mu)\}$$

$$D_{FoG}(k\mu\sigma_v) = \exp\left(-k^2\mu^2\sigma_v^2\right)$$

σ_v: free parameter

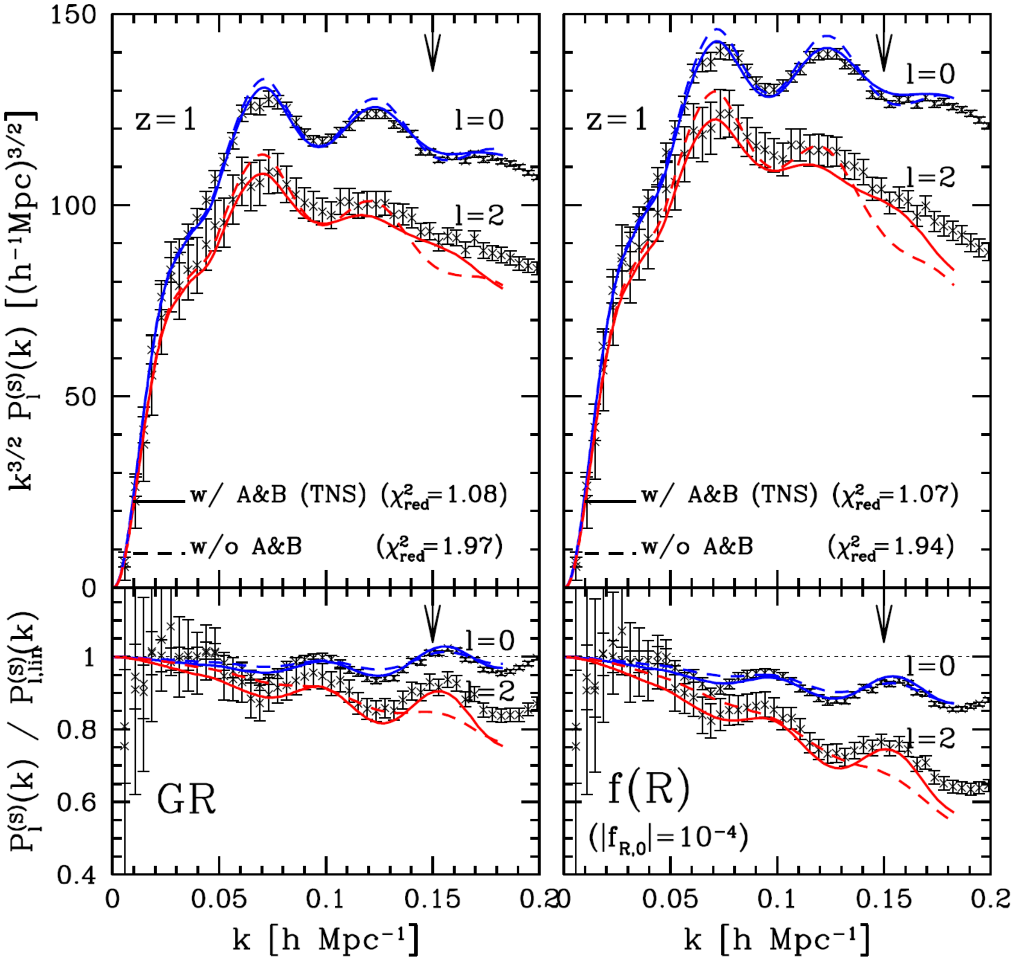
Perturbation theory

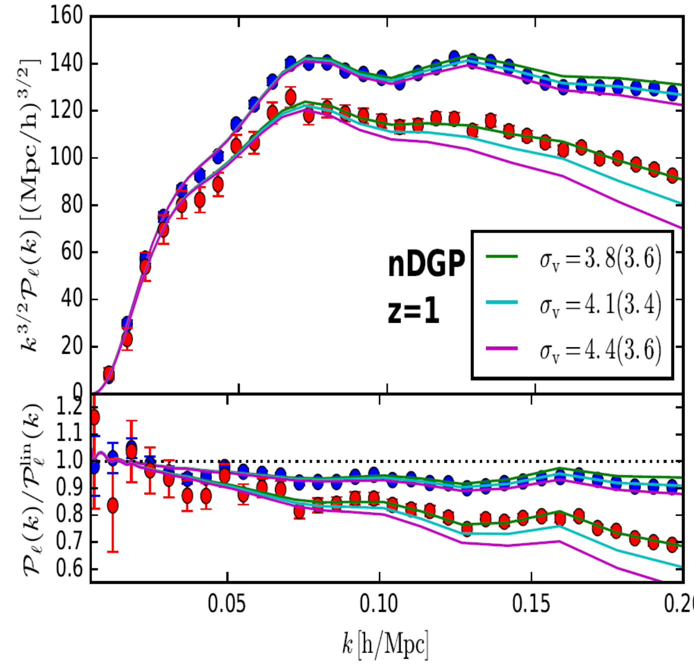
$$P(k,\mu) = \sum_\ell P_\ell(k) L_\ell(\mu), \quad \left.\frac{P_2}{P_0}\right|_{linear} = \frac{\frac{4}{3}f + \frac{4}{7}f^2}{1+\frac{2}{3}f+\frac{1}{5}f^2}, \quad f = \frac{d\ln\delta}{d\ln a}$$

growth rate

Examples: f(R), nDGP

Taruya et. al. 1309.6783, 1408.4232
Bose, Koyama et.al. 1702.02348





f(R): scale dependent linear growth + chameleon screening

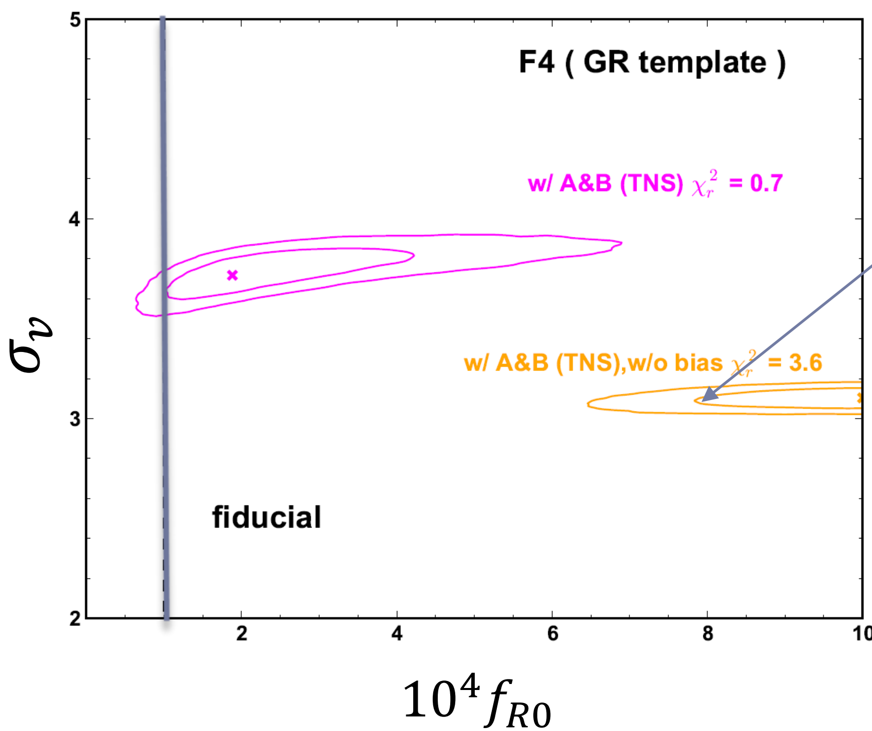
nDGP: scale independent linear growth + Vainshtein screening

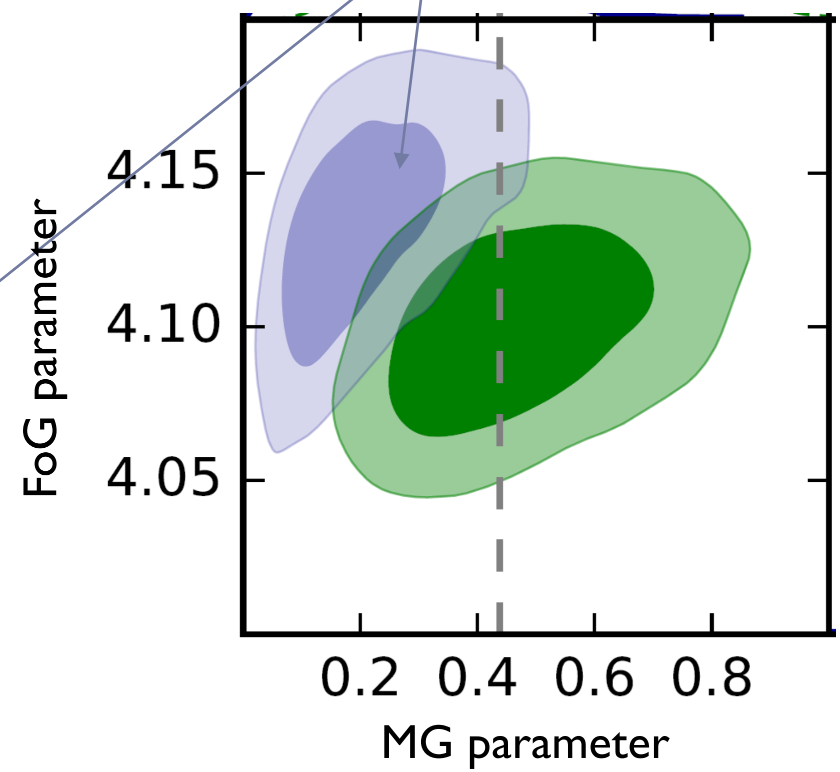
Parameter estimation

Taruya et. al. 1309.6783, 1408.4232
Bose, Koyama et.al. 1702.02348

- GR template is often used (i.e. BOSS, Wiggle-z,…)

Replace the linear growth rate $f = \frac{d\, log\, \delta}{d\, \log a}$ by f(k, z) in MG





The use of GR templates could bias the parameter estimation

Correlation function

Bose, Koyama et.al. 1705.09181

- Gaussian Streaming Model (GSM)

$$1+\xi^s_{\rm GSM}(r_\sigma, r_\pi) = \int [1+\xi^r(r)] e^{-[r_\pi - y - \mu v_{12}(r)]^2/2\sigma_{12}^2(r,\mu)} \frac{dy}{\sqrt{2\pi\sigma_{12}^2(r,\mu)}}$$

σ_{12}: velocity dispersions v_{12}: infall velocity

- Real space correlation function: RegPT

Taruya et.al. 1208.1191

$$\xi^r(r) = \int \frac{d^3k}{(2\pi)^3} e^{i\boldsymbol{k}\cdot\boldsymbol{x}} P_{\delta\delta}^{1-\mathrm{loop,RegPT}}(k)$$

$$P_{bc}(k;a) = \Gamma_b^{(1)}(k;a)\Gamma_c^{(1)}(k;a)P_0(k)$$

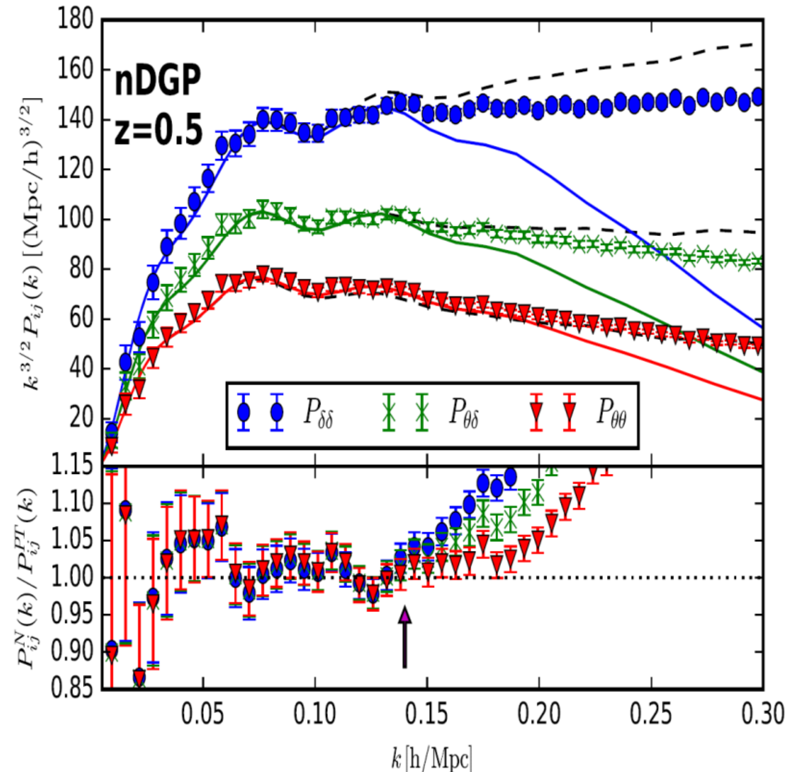
$$+2\int \frac{d^3\boldsymbol{q}}{(2\pi)^3}\Gamma_b^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q};a)\Gamma_c^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q};a)P_0(q)P_0(|\boldsymbol{k}-\boldsymbol{q}|)$$

$$\Gamma_b^{(1)}(k;a) = \Big[J_b^{(1)}(k;a)\{1+\frac{k^2\sigma_d^2}{2}\}$$

$$+3\int \frac{d^3\boldsymbol{q}}{(2\pi)^3} J_b^{(3)}(\boldsymbol{k},\boldsymbol{q},-\boldsymbol{q};a)P_0(q)\Big] \boxed{e^{-k^2\sigma_d^2/2}}$$

$$\Gamma_b^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q};a) = J_b^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q};a)\boxed{e^{-k^2\sigma_d^2/2}}$$

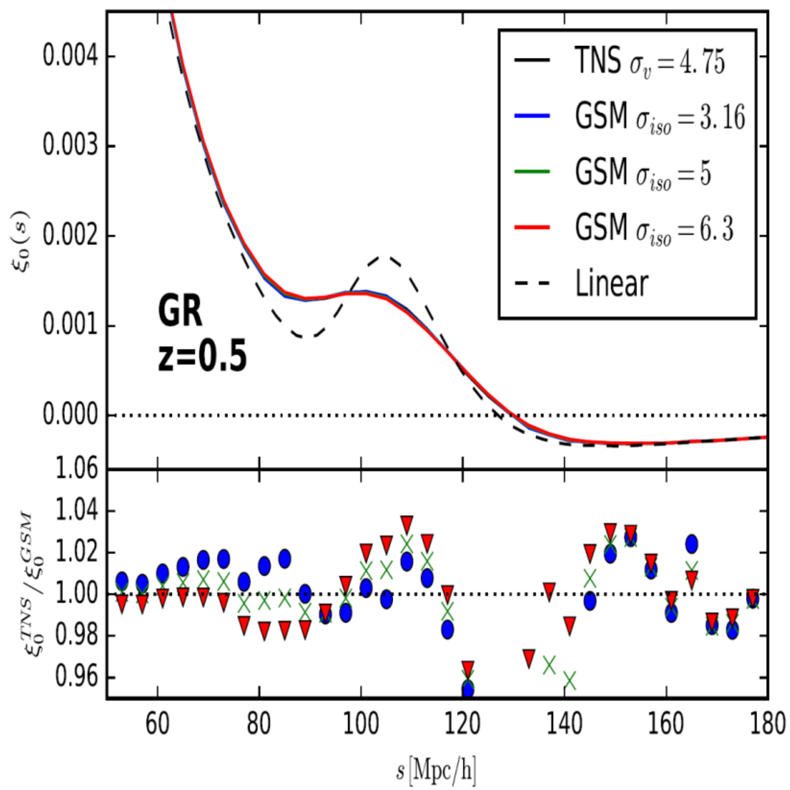
$$\sigma_d^2(k) = \int_0^{k/2}\frac{dq}{6\pi^2}F_1(q;a)^2P_0(q)$$



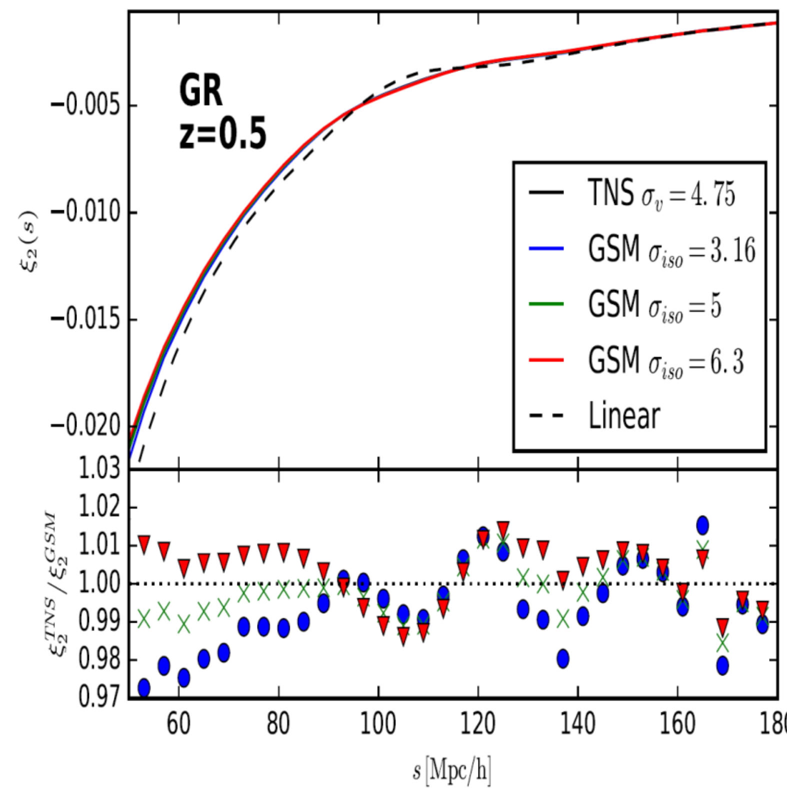
TNS v GSM (LCDM)

Bose, Koyama et.al. 1705.09181

monopole



quadrupole

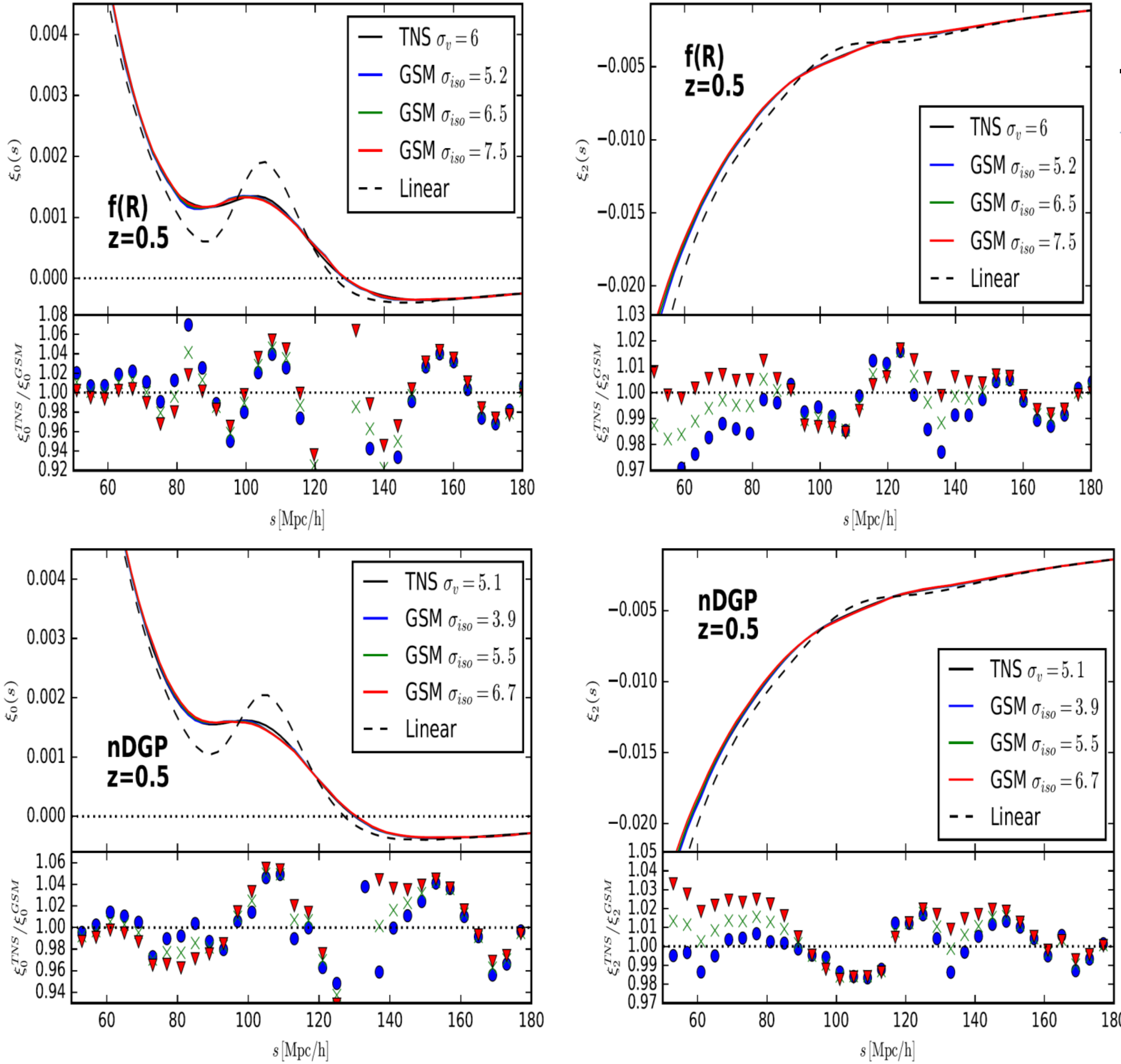


$$\xi_\ell^{(S)}(s) = \frac{i^\ell}{2\pi^2}\int dk k^2 P_\ell^{(S)}(k) j_\ell(ks) \qquad P_\ell^{(S)}(k) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu P_{\rm TNS}^{(S)}(k,\mu)\mathcal{P}_\ell(\mu)$$

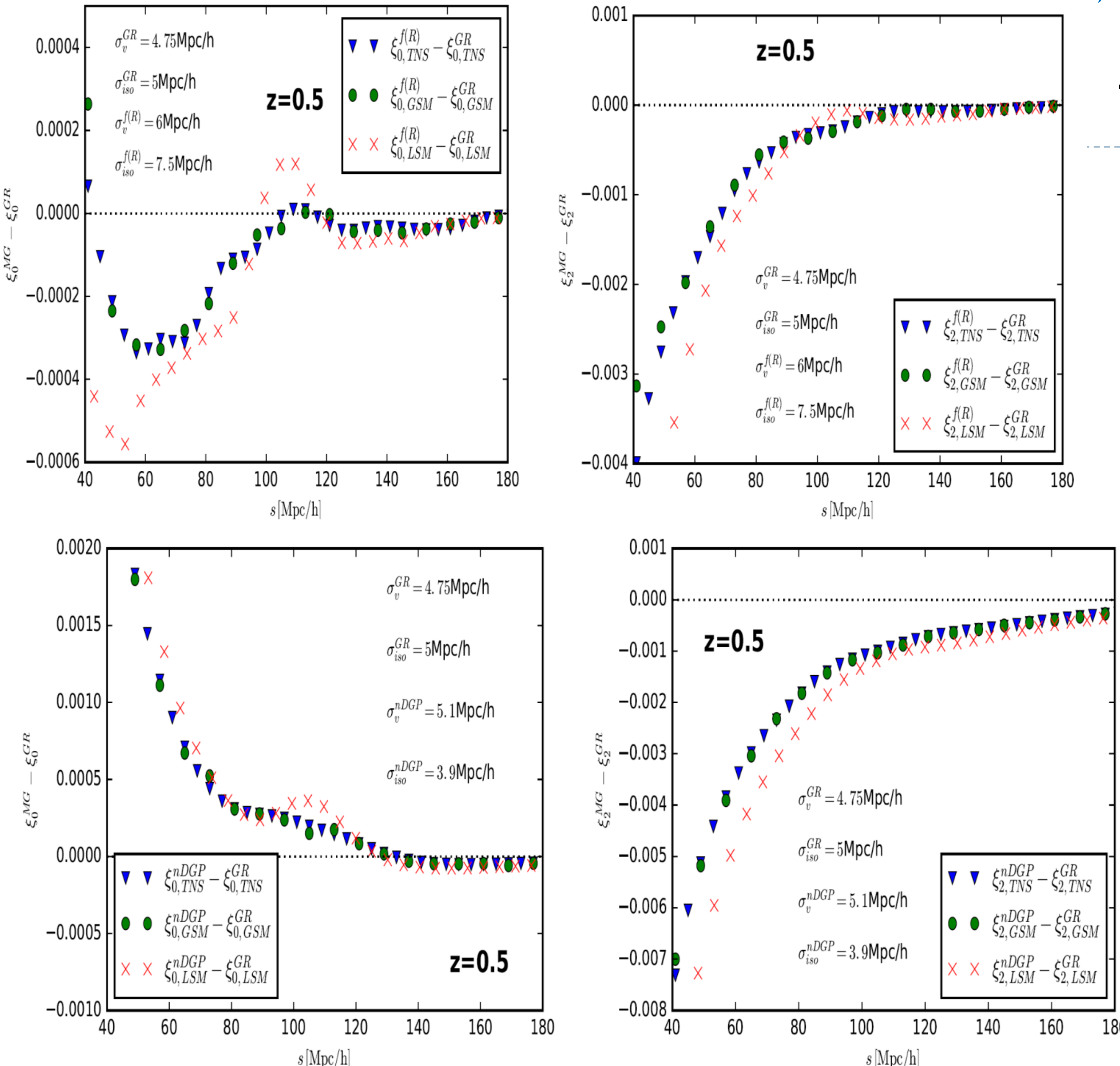
Bose, Koyama et.al. 1705.09181

TNS v GSM

Modified gravity (MG)



Bose, Koyama et.al. 1705.09181

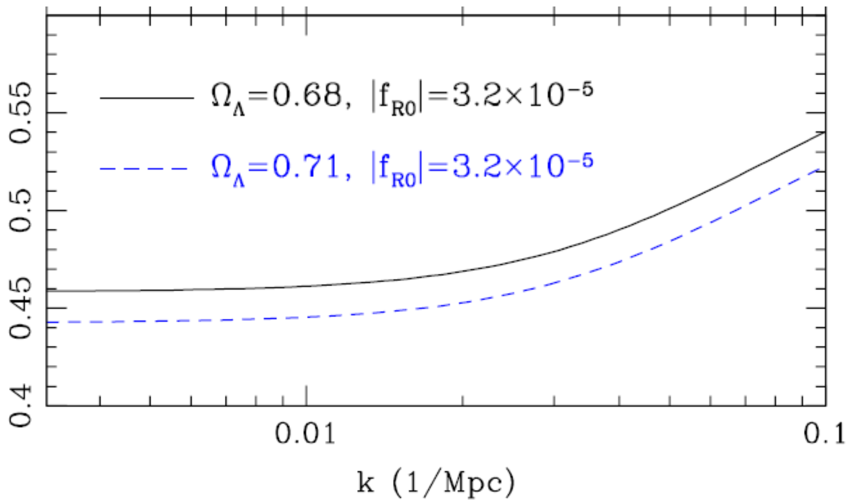


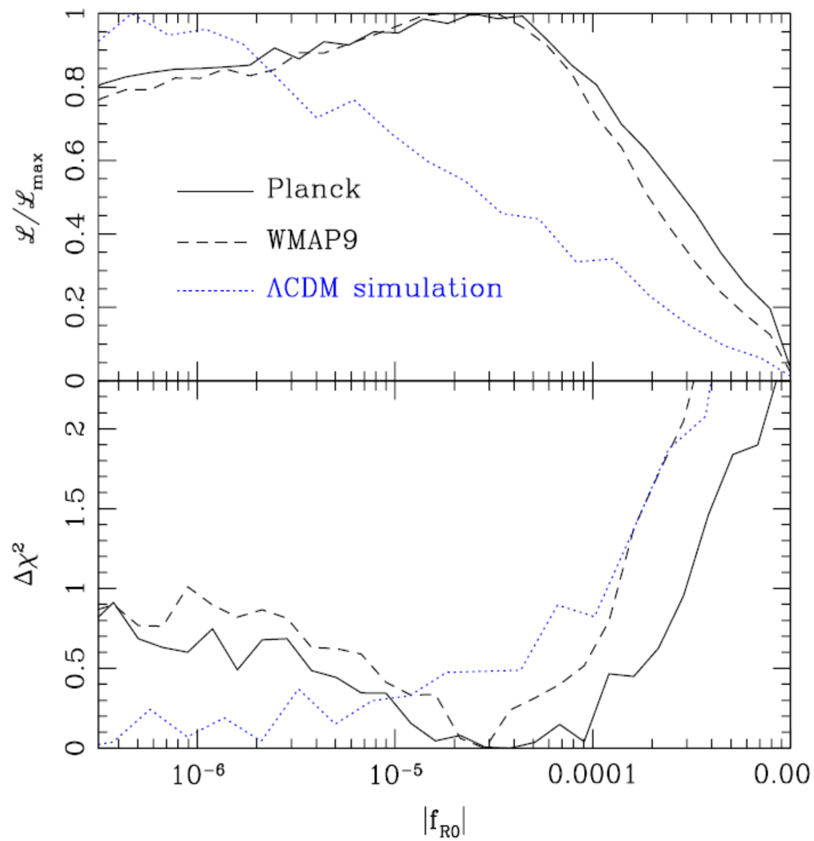
TNS v GSM

Difference between LCDM and MG

Applications to BOSS DR11

- f(R) gravity - scale dependent growth





BOSS DR11 constraints $|f_{R0}| < 8\times10^{-4}$

Song, Taruya, Linder, KK et.al. 1507.01592

Renormalised perturbation theory

- Recently, RPT has been criticised by several groups

The main objection is that RPT-type summations violate the equivalence principle (or Galilean invariance or consistency relation) Tassev & Zaldarriaga 1109.4939

"Long wavelength perturbations are considered as uniform (but time dependent) boosts for small wavelength perturbations and they can be absorbed in a change of frame"

RPT violates this principle and alternative IR resummations are proposed ("EFT of LSS")

Gamma expansion

Sugiyama & Futamase 1303.2748
Sugiyama & Spergel 1306.6660

- Follow Sugiyama & Futamase, Sugiyama & Spergel

$$\delta_n(\mathbf{k}) = \int \frac{d^3p_1}{(2\pi)^3} \cdots \int \frac{d^3p_n}{(2\pi)^3} (2\pi)^3 \delta_{\rm D}(\mathbf{k} - \mathbf{p}_{[1,n]}) F_n([\mathbf{p}_1, \mathbf{p}_n]) \delta_{\rm L}(\mathbf{p}_1) \cdots \delta_{\rm L}(\mathbf{p}_n)$$

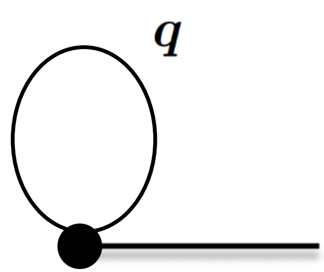
$$\Gamma^{(r)}(z, [\mathbf{k}_1, \mathbf{k}_r]) \equiv D^r \Gamma^{(r)}_{\rm tree}([\mathbf{k}_1, \mathbf{k}_r]) + \sum_{n=1}^{\infty} D^{r+2n} \Gamma^{(r)}_{\text{n-loop}}([\mathbf{k}_1, \mathbf{k}_r])$$

$$\Gamma^{(r)}_{\rm tree}([\mathbf{k}_1, \mathbf{k}_r]) \equiv F_r([\mathbf{k}_1, \mathbf{k}_r]),$$

$$\Gamma^{(r)}_{\text{n-loop}}([\mathbf{k}_1, \mathbf{k}_r])$$

$$\equiv \frac{1}{r!} \frac{(r+2n)!}{2^n n!} \int \frac{d^3p_1}{(2\pi)^3} \cdots \int \frac{d^3p_n}{(2\pi)^3} F_{r+2n}([\mathbf{k}_1, \mathbf{k}_r], \mathbf{p}_1, -\mathbf{p}_1, \ldots, \mathbf{p}_n, -\mathbf{p}_n) P_{\rm L}(p_1) \cdots P_{\rm L}(p_n)$$

$\delta_0(\boldsymbol{k}_1)$



$F_3(\boldsymbol{k}, -\boldsymbol{q}, \boldsymbol{q})$

Power spectrum

- Power spectrum

$$P(z,k) = \sum_{r=1}^{\infty} P_\Gamma^{(r)}(z,k)$$

$$P_\Gamma^{(r)}(z,k) \equiv r! \int \frac{d^3k_1}{(2\pi)^3} \cdots \int \frac{d^3k_r}{(2\pi)^3} (2\pi)^3 \delta_D(\mathbf{k} - \mathbf{k}_{[1,r]}) \left[\Gamma^{(r)}(z, [\mathbf{k}_1, \mathbf{k}_r])\right]^2 P_\mathrm{L}(k_1) \cdots P_\mathrm{L}(k_r)$$

- "High-k" limit (IR loop contributions $p_n \to 0$)

$$\Gamma^{(r)}_{\text{n-loop}}([\mathbf{k}_1, \mathbf{k}_r])$$
$$\equiv \frac{1}{r!} \frac{(r+2n)!}{2^n n!} \int \frac{d^3p_1}{(2\pi)^3} \cdots \int \frac{d^3p_n}{(2\pi)^3} F_{r+2n}([\mathbf{k}_1, \mathbf{k}_r], \mathbf{p}_1, -\mathbf{p}_1, \ldots, \mathbf{p}_n, -\mathbf{p}_n) P_\mathrm{L}(p_1) \cdots P_\mathrm{L}(p_n)$$

$$F_{r+2n}([\mathbf{k}_1, \mathbf{k}_r], \mathbf{p}_1, -\mathbf{p}_1, \cdots, \mathbf{p}_n, -\mathbf{p}_n)\Big|_{p_{m+1},\cdots,p_n \to 0}$$
$$\frac{(r+2m)!}{(r+2n)!} (-1)^{n-m} \left(\frac{\mathbf{k}_{[1,r]} \cdot \mathbf{p}_{m+1}}{p_{m+1}}\right)^2 \cdots \left(\frac{\mathbf{k}_{[1,r]} \cdot \mathbf{p}_n}{p_n^2}\right)^2 F_{r+2m}\left([\mathbf{k}_1, \mathbf{k}_r], \mathbf{p}_1, -\mathbf{p}_1, \cdots, \mathbf{p}_m, -\mathbf{p}_m\right)$$

IR resummation

- IR loop summations up to 1-loop

$$\sigma_v^2 \equiv \int dp P_L(p)/6\pi.$$

$$\Gamma^{(r)}_{\text{n-loop}}([\mathbf{k}_1,\mathbf{k}_r])\Big|_{p_2,\cdots,p_n\to 0} = \frac{1}{n!}\left(-\frac{k^2\sigma_v^2}{2}\right)^{n-1}\Gamma^{(r)}_{\text{1-loop}}([\mathbf{k}_1,\mathbf{k}_r]),$$

$$\Gamma^{(r)}_{\text{n-loop}}([\mathbf{k}_1,\mathbf{k}_r])\Big|_{p_1,\cdots,p_n\to 0} = \frac{1}{n!}\left(-\frac{k^2\sigma_v^2}{2}\right)^{n}\Gamma^{(r)}_{\text{tree}}([\mathbf{k}_1,\mathbf{k}_r]).$$

$$\Gamma^{(r)}(z,[\mathbf{k}_1,\mathbf{k}_r]) = \exp\left(-\frac{k^2D^2\sigma_v^2}{2}\right)D^r\left[\Gamma^{(r)}_{\text{tree}}([\mathbf{k}_1,\mathbf{k}_r]) + \left(D^2\Gamma^{(r)}_{\text{1-loop}}[\mathbf{k}_1,\mathbf{k}_r] + \frac{k^2D^2\sigma_v^2}{2}\Gamma^{(r)}_{\text{tree}}([\mathbf{k}_1,\mathbf{k}_r])\right)\right]$$

- Leading order power spectrum

$$P^{(1)}_\Gamma(z,k) = \left[\Gamma^{(1)}(z,k)\right]^2 P_{\rm L}(k) \to e^{-k^2D^2\sigma_v^2}\left[1 + D^2\Gamma^{(1)}_{\text{1-loop}}(k) + \frac{k^2D^2\sigma_v^2}{2}\right]^2 D^2P_{\rm L}(k)$$

RegPT

- Power spectrum (mode-coupling)

$$
\begin{aligned}
P_\Gamma^{(2)}(z,k) &= 2! \int \frac{d^3k_1}{(2\pi)^3} \int \frac{d^3k_2}{(2\pi)^3} (2\pi)^3 \delta_D(\mathbf{k}-\mathbf{k}_{[1,r]}) \left[\Gamma^{(2)}(z,\mathbf{k}_1,\mathbf{k}_2)\right]^2 P_{\rm L}(k_1) P_{\rm L}(k_2) \\
&\to e^{-k^2D^2\sigma_v^2} 2! \int \frac{d^3k_1}{(2\pi)^3} \frac{d^3k_2}{(2\pi)^3} (2\pi)^3 \delta_D(\mathbf{k}-\mathbf{k}_{[1,2]}) D^2 P_{\rm L}(k_1) D^2 P_{\rm L}(k_2) \\
&\quad \times \Bigg[\left(\Gamma^{(2)}_{\rm tree}(\mathbf{k}_1,\mathbf{k}_2)\right)^2 + 2\Gamma^{(2)}_{\rm tree}(\mathbf{k}_1,\mathbf{k}_2) \left(D^2\Gamma^{(2)}_{\text{1-loop}}(\mathbf{k}_1,\mathbf{k}_2) + \frac{k^2D^2\sigma_v^2}{2}\Gamma^{(2)}_{\rm tree}(\mathbf{k}_1,\mathbf{k}_2)\right) \\
&\qquad + \left(D^2\Gamma^{(2)}_{\text{1-loop}}(\mathbf{k}_1,\mathbf{k}_2) + \frac{k^2D^2\sigma_v^2}{2}\Gamma^{(2)}_{\rm tree}(\mathbf{k}_1,\mathbf{k}_2)\right)^2 \Bigg]
\end{aligned}
$$

$$e^{-k^2D^2\sigma_v^2} D^4 P_{22}(k)$$

- 1-loop RegpT   Taruya et.al. 1208.1191

$$P_{\text{Reg,1-loop}}(z,k) = e^{-k^2D^2\sigma_v^2}\left[1 + D^2\Gamma^{(1)}_{\text{1-loop}}(k) + \frac{k^2D^2\sigma_v^2}{2}\right]^2 D^2 P_{\rm L}(k) + e^{-k^2D^2\sigma_v^2} D^4 P_{22}(k).$$

Exponential dumping

- Extra terms that are treated perturbatively in RegPT

$$P_\Gamma^{(2)}(z,k) \quad = \quad e^{-k^2D^2\sigma_v^2}\left(\frac{k^2D^2\sigma_v^2}{2}\right)\left[\left(1+D^2\Gamma^{(1)}_{\text{1-loop}}(k)+\frac{k^2D^2\sigma_v^2}{2}\right)^2 D^2P_\mathrm{L}(k)-D^2P_\mathrm{L}(k)\right]$$

$$\begin{aligned}P_\Gamma^{(2)}(z,k) \quad &\to \quad e^{-k^2D^2\sigma_v^2}D^4\left(P_{22}(k)-k^2\sigma_v^2P_\mathrm{L}(k)\right)\\ &+e^{-k^2D^2\sigma_v^2}(k^2D^2\sigma_v^2)\left(1+D^2\Gamma^{(1)}_{\text{1-loop}}(k)+\frac{k^2D^2\sigma_v^2}{2}\right)^2 D^2P_\mathrm{L}(k).\end{aligned}$$

- All orders

$$\begin{aligned}P_\Gamma^{(r)}(z,k) \quad &\to \quad e^{-k^2D^2\sigma_v^2}\frac{(k^2D^2\sigma_v^2)^{r-1}}{(r-1)!}\left(1+D^2\Gamma^{(1)}_{\text{1-loop}}(k)+\frac{k^2D^2\sigma_v^2}{2}\right)^2 D^2P_\mathrm{L}(k)\\ &+e^{-k^2D^2\sigma_v^2}\frac{(k^2D^2\sigma_v^2)^{r-2}}{(r-2)!}D^4\left(P_{22}(k)-k^2\sigma_v^2P_\mathrm{L}(k)\right).\end{aligned}$$

$$P(z,k)=\sum_{r=1}^{\infty}P_\Gamma^{(r)}(z,k)=D^2P_\mathrm{L}(k)+D^4P_{\text{1-loop}}(k)+\left(D^2\Gamma^{(1)}_{\text{1-loop}}(k)+\frac{k^2D^2\sigma_v^2}{2}\right)^2 D^2P_\mathrm{L}(k),$$

no exponential damping

Consistency relation

Peloso and Pietroni 1609.06624

- Response function   cf. Nishimichi , Bernardeau, Taruya 1411.2970

$$K_{ab}(k, q; \eta, \eta') \equiv q^3 \int d\Omega_{\mathbf{q}} \, \frac{\delta P_{ab}[P^0](\mathbf{k}; \eta, \eta')}{\delta P^0(\mathbf{q})}\bigg|_{P^0=\bar{P}^0}$$

- IR limit of the response function is determined by Galiean invariance at full order

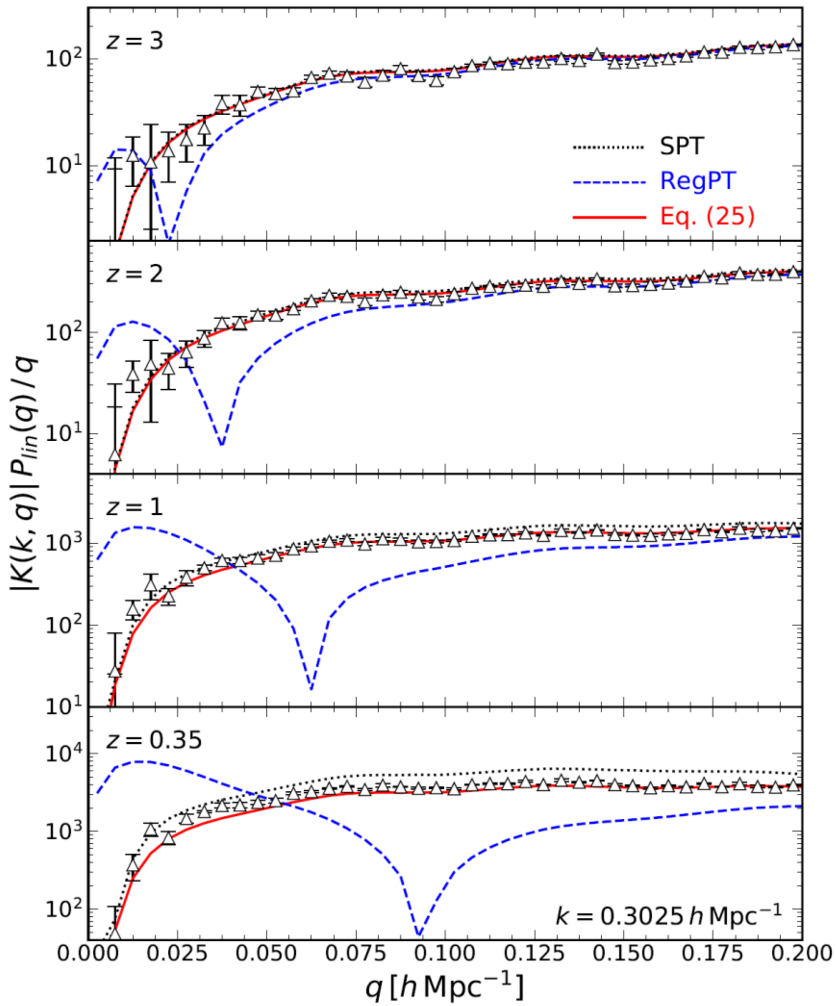
$$K_{ab}(k, q; \eta, \eta') \to -\frac{1}{3}\frac{1}{(2\pi)^2}k^2 q \left(e^{\eta} - e^{\eta'}\right)^2 P_{ab}(k; \eta, \eta') + O(q^3)$$

- SPT satisfies this relation order by order

$$K_{11}^{PT}(k, q; \eta, \eta') \to -\frac{1}{3}\frac{1}{(2\pi)^2}k^2 q \left(e^{\eta} - e^{\eta'}\right)^2 P^0(k)$$

but RPT-like summations break this consistency relation

Response function from simulations

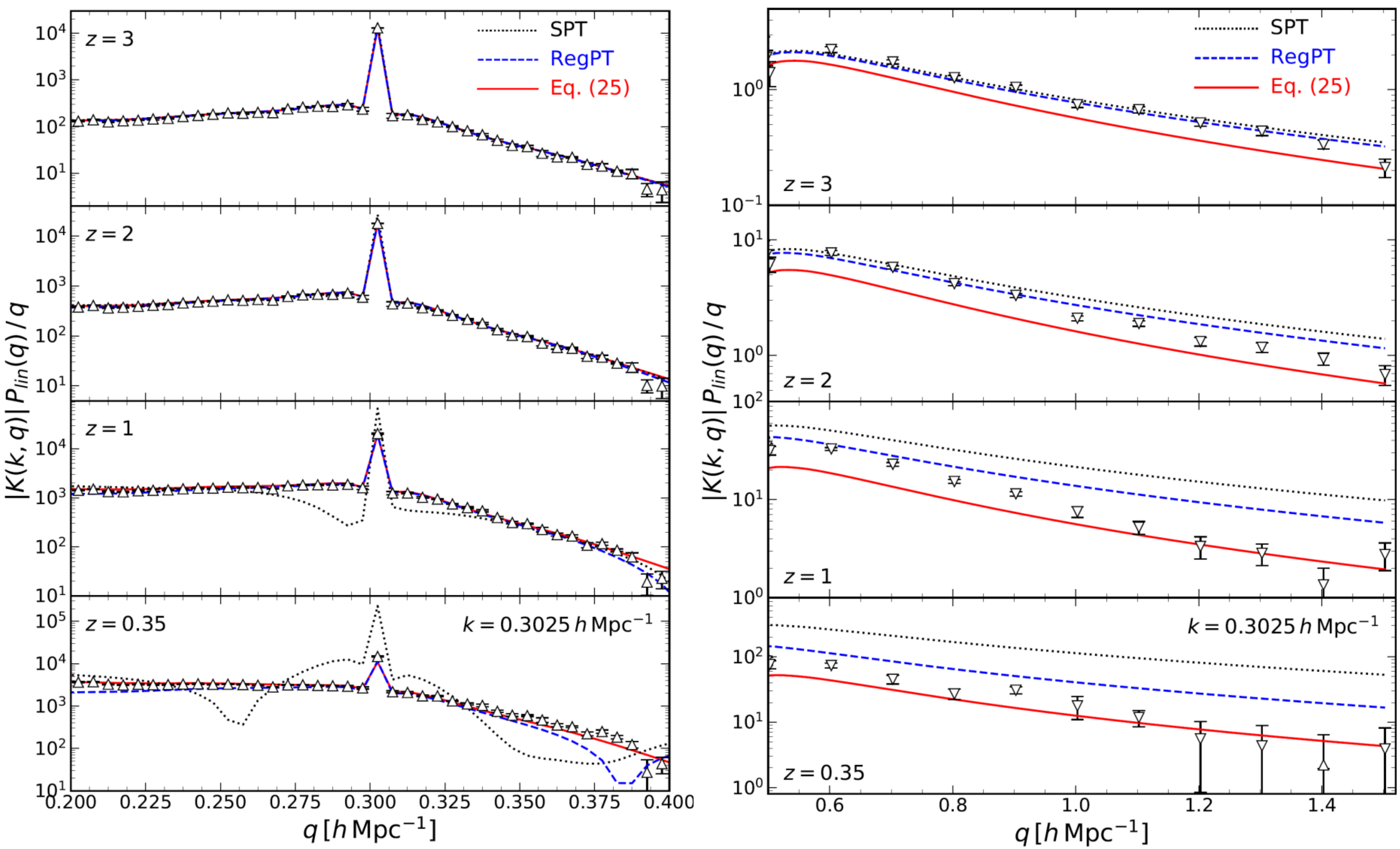


Nishimichi, , Bernardeau Taruya
1708.08946

$$q \ll k$$

Nishimichi, Taruya, Bernardeau 1708.08946

$q \approx k$ $\qquad$ $q \gg k$



Baryon acoustic oscillations

- Long modes can affect the local physics if there is a physical feature of the size k_{BAO}^{-1} and $q \approx k_{BAO}$

cf. SPT

$$P_{13} + P_{22} \to \int \frac{d^3q}{(2\pi)^3} \left(\frac{\boldsymbol{k}\cdot\boldsymbol{q}}{q^2}\right)^2 P_0(q) \Big[P_0(|\boldsymbol{k}-\boldsymbol{q}|) - P_0(k)\Big] \qquad q \to 0$$

$$= \int \frac{d^3q}{(2\pi)^3} \left(\frac{\boldsymbol{k}\cdot\boldsymbol{q}}{q^2}\right)^2 P_0(q) \Big[P_0^w(|\boldsymbol{k}-\boldsymbol{q}|) - P_0^w(k)\Big]$$

the smooth part cancels but the wiggle part remains

cf Gamma expansion Sugiyama & Spergel 1306.6660

$$P(z,k) = \Big[\Gamma^{(1)}(z,k)\Big]^2 P_{\rm lin}^{\rm nw}(k) + \sum_{n=2}^{\infty} P_\Gamma^{(n)}(z,k) + \Big[\Gamma^{(1)}(z,k)\Big]^2 \left[P_{\rm lin}(k) - P_{\rm lin}^{\rm nw}(k)\right]$$

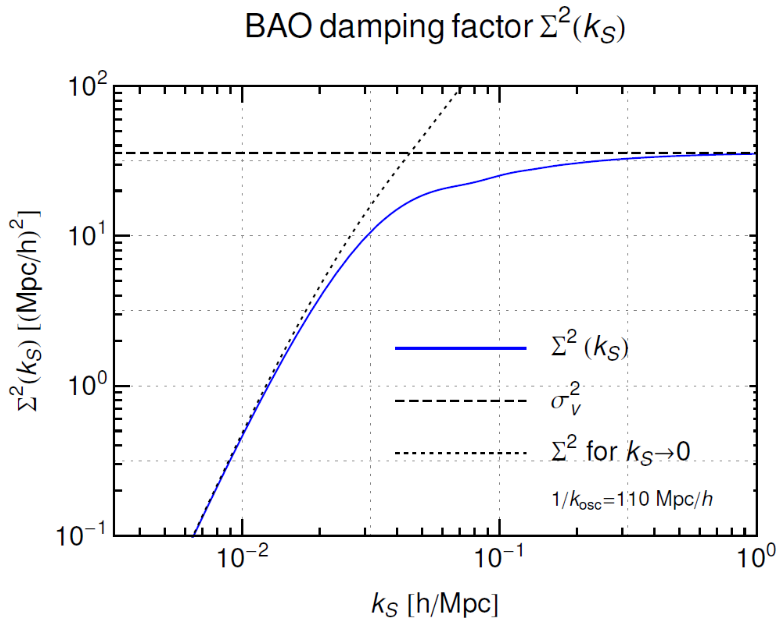
no BAO oscillation

$$\exp\left(-\frac{k^2\bar{\Sigma}_{\rm v}^2(z)}{2}\right) D^2 \left[P_{\rm lin}(k) - P_{\rm lin}^{\rm nw}(k)\right]$$

BAO damping factor

- If $k < k_{osc}$, the BAO oscillations can be ignored so the damping should vanish

  the dumping factor is not $e^{-k^2 D^2 \sigma_v^2}$



- Various IR reusmmations to reproduce this behaviour

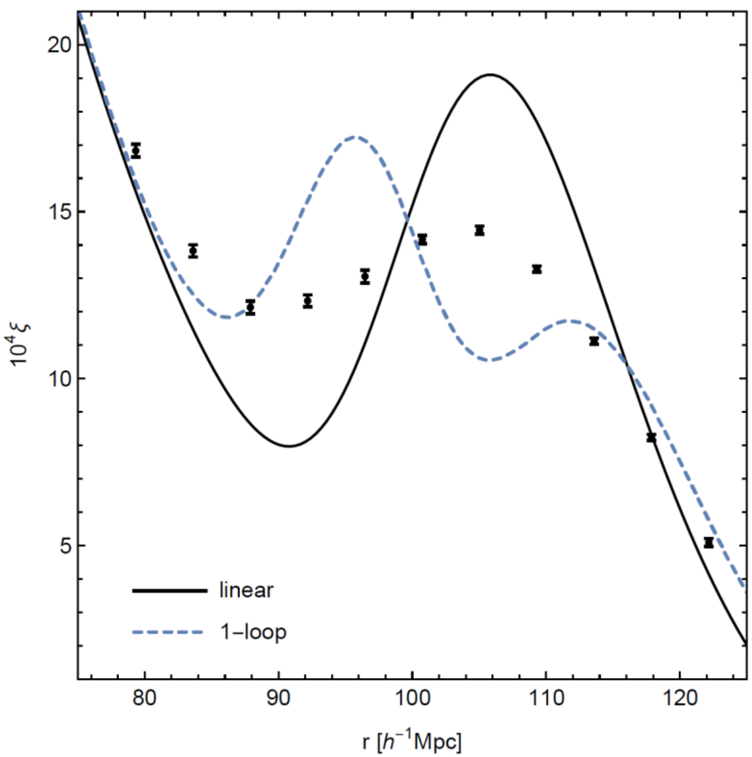
cf. Lagrangian PT based approach

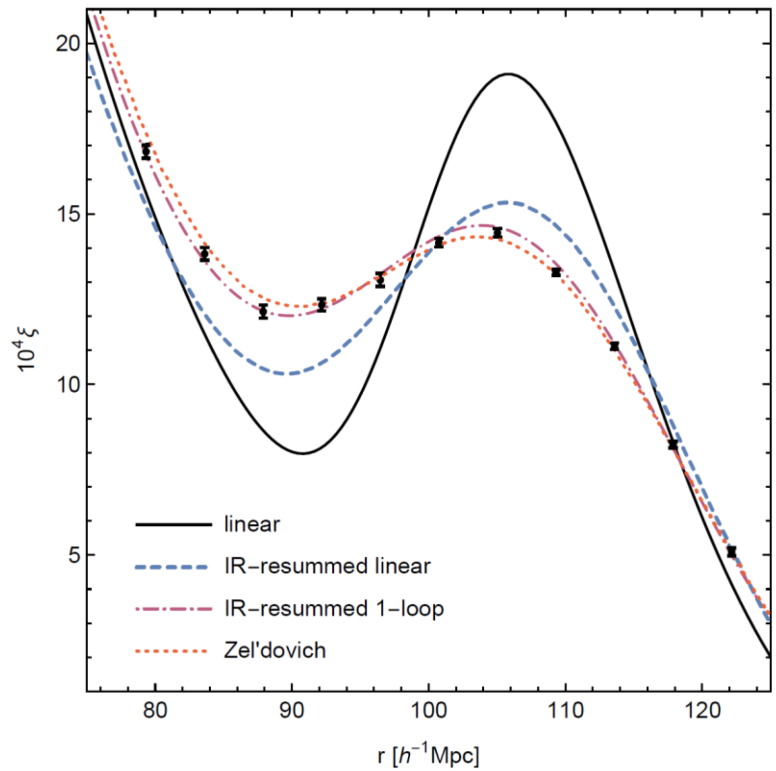
Vlah, Seljak, Chu, Feng 1509.02120

$$\langle\langle A^{\mathrm{nw},=0\ell} \rangle\rangle \equiv \frac{D(z)^2}{\pi^2} \frac{1}{q_{\mathrm{max}}^3 - q_{\mathrm{min}}^3} \int_{q_{\mathrm{min}}}^{q_{\mathrm{max}}} \mathrm{d}q\, q^2 \int_0^\infty \mathrm{d}k\, P_{\mathrm{nw}}^*(k) [1 - j_0(kq)]$$

Correlation function Baldauf et.al. 1504.04366

- The damping of wiggles due to IR modes is enough to explain the failure of SPT and this is nothing to do with UV physics





EFT of LSS

Baunmann et.al.1004.2488, Carrasco et.al. 1206.2926

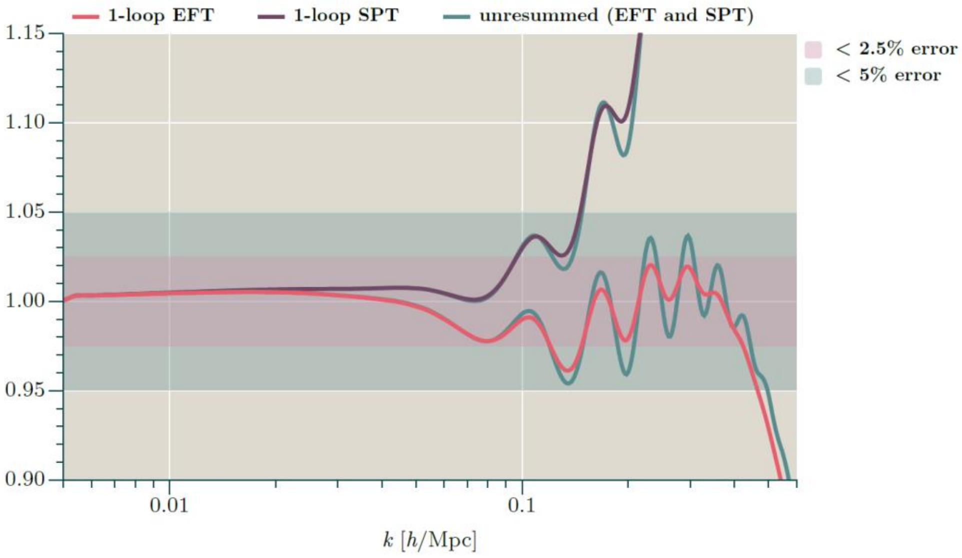
- UV contributions

  They cannot be computed within PT. Introduce a counter term to accounting for unknown UV physics

$$P(k) = P^{SPT}(k) - 2c_s^2 \frac{k^2}{k_{NL}^2} P_L(k)$$

- IR resummation

  IR resummation suppresses the wiggles in the fitting of the sound speed



Fonseca et.al. 1704.05309

RPT v EFF of LSS

- RPT (RegPT,…)
  - no free parameter (though there is a UV cut-off dependence in $\sigma_v^2 \equiv \int dp P_L(p)/6\pi.$)
  - The damping plays two roles (suppression of wiggles due to IR modes and suppression of non-wiggle part due to UV physics)
  - Theoretical justifications for the damping is questionable (i.e. violation of the equivalence principle)

- EFT of LSS
  - Theoretical foundation is solid (a clear separation of IR and UV physics)
  - BAO physics is predicable
  - No predictability for non-linear corrections

Redshift distortions

- EFT of LSS has been extended to RSD

The strategy is the same

Step 1: SPT prediction in redshift space

Step 2: IR resummation cf. Vlah, Seljak, Chu, Feng 1509.02120

$$\langle\langle k_i k_j A^{\mathrm{nw},=0\ell}_{s,ij} \rangle\rangle = k^2 \left[1 + f(f+2)\mu^2\right] \langle\langle A^{\mathrm{nw},=0\ell} \rangle\rangle$$

Step 3: Introduce counter terms

$$P_\ell(k) = P_\ell^{SPT}(k) - 2c_\ell^2 \frac{k^2}{k_{NL}^2} P_{L\ell}(k)$$

a free parameter for each multipole

TNS v EFT of LSS

- 1-loop SPT

$$P^{(\mathrm{S})}_{\mathrm{SPT}}(k,\mu) = \left\{1-(k\mu f\sigma_{\mathrm{v,lin}})^2\right\}\left\{P_{\delta\delta}(k)+2f\,\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)\right\} + A(k,\mu) + B(k,\mu) + C(k,\mu).$$

- TNS

  a partial summation and introduction of a FoG parameter σ_{v}

$$P^{(\mathrm{S})}(k,\mu) = D_{\mathrm{FoG}}[k\mu\, f\,\sigma_{\mathrm{v}}]\left\{P_{\delta\delta}(k) + 2\,f\,\mu^2\,P_{\delta\theta}(k) + f^2\,\mu^4\,P_{\theta\theta}(k) + A(k,\mu) + B(k,\mu)\right\}.$$

- EFT of LSS

  no resummation (only IR resummation)

  For monopole and quadrupole, there are two free parameters

Summary

- Perturbative approach to RSD

  It is possible to include modified gravity effects consistently in the templates

  So far all the tests have been done only for dark matter
  It is necessary to extend the tests to dark matter halos and galaxy mocks
  (cf. MG-PICOLA Winther et.al. 1703.00879)

- New approaches to RSD

  EFT of LSS approach is gaining popularity
  Reconstruction reduces non-linearity

  It remains to see whether these approaches are useful phenomenologically