Vlasov Perturbation Theory

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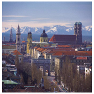


Big data, big questions, Miapbp, 12.05.25

2505.02907, 2502.20451 + 2210.08088, 2210.08089

with Román Scoccimarro, Dominik Laxhuber

$$
\begin{aligned}
\frac{\partial \delta(\tau, \mathbf{x})}{\partial \tau} + \nabla \cdot \{(1+\delta(\tau,\mathbf{x}))\mathbf{v}(\tau,\mathbf{x})\} &= 0 \quad \text{(continuity)} \\
\frac{\partial \mathbf{v}(\tau,\mathbf{x})}{\partial \tau} + \mathcal{H}\mathbf{v} + \mathbf{v}\cdot\nabla\mathbf{v} &= -\nabla\phi - \frac{1}{\rho}\nabla_j(\sigma_{ij}\rho) \quad \text{(Euler)} \\
\nabla^2\phi(\tau,\mathbf{x}) &= \frac{3}{2}\Omega_m \mathcal{H}^2 \delta(\tau,\mathbf{x}) \quad \text{(Poisson)}
\end{aligned}
$$

SPT: pressureless perfect fluid approximation

$$\sigma_{ij}(\tau, \mathbf{x}) \equiv 0$$

EFT: eff. dispersion tensor with free parameters c_a ("counterterms")

$$\sigma_{ij}(\tau, \mathbf{x}) = \sum_a c_a(\tau) \mathcal{O}_a(\tau, \mathbf{x})$$

VPT: solve equation of motion for $\sigma_{ij}(\tau, \mathbf{x})$ (and higher moments)

Why VPT?

- We know pressureless perfect fluid approximation breaks down for collisionless matter due to shell crossing *e.g. Peebles '80, Buchert '97, Pueblas, Scoccimarro '08; ..., Vlasov-Poisson/velocity moments/LPT-extension/... Hahn+ 12+, Colombi 15; Seljak, Vlah 15+; Taruya, Colombi 17; Rampf, Frisch 17; McDonald, Vlah 17, Saga, Taruya, Colombi 18,21+; Rampf, Hahn 20; Rampf, Saga, Taruya, Colombi 23, ...*
- In practice, this reflects in spurious UV sensitivity of SPT loops (e.g. $P_{13}, P_{15}, \ldots$) and prevents convergence

  e.g. 3-loop Blas, MG, Konstandin '13
- Collisionless CDM via N-body; there UV sensitivity is much smaller (UV screening) *Peebles 80, Hogan+ 82, Goroff+ 86, ..., Nichimichi, Bernardeau, Taruya 1411.2970; 1708.08946,...*

  $\Rightarrow$ clustering on BAO-scales less sensitive to small-scale dynamics compared to what it seems when using SPT

Why VPT?

- VPT = perturbation theory for collisionless matter + gravity
- Superposition of many shell crossings on small scales generate (average) velocity dispersion $\langle \sigma_{ij} \rangle$ (non-perturbative)

  Buchert 97, ..., Pueblas, Scoccimarro '08, McDonald '09, ..., Erschfeld '18

- $\Rightarrow$ seeds also fluctuations $\delta\sigma_{ij}(z, \mathbf{k})$ correlated with large-scale modes (perturbative for $k < k_{nl}$), that back-react on δ and θ
- VPT captures the physics of UV screening and decoupling of small-scale modes due to shell crossing in a first principle approach

  $\Rightarrow$ improves over SPT while preserving predictivity
- Phase-space information useful for RSD (..still work in progress)

$$0 = \frac{df}{d\tau} = \left(\frac{\partial}{\partial \tau} + \frac{\mathbf{p}}{am} \frac{\partial}{\partial \mathbf{x}} - am \nabla \phi \frac{\partial}{\partial \mathbf{p}} \right) f(\tau, \mathbf{x}, \mathbf{p}) \quad \text{(Vlasov)}$$

$$\nabla^2 \phi(\tau, \mathbf{x}) \quad = \quad \frac{3}{2} \Omega_m \mathcal{H}^2 \delta(\tau, \mathbf{x}) \quad \text{(Poisson)}$$

$$
\begin{aligned}
1+\delta &= \int d^3p\, f(\tau,\mathbf{x},\mathbf{p}) \\
v_i &= (1+\delta)^{-1}\int d^3p\, \frac{p_i}{am} f(\tau,\mathbf{x},\mathbf{p}) \\
\sigma_{ij} &= (1+\delta)^{-1}\int d^3p\, \frac{p_i p_j}{a^2 m^2} f(\tau,\mathbf{x},\mathbf{p}) - v_i v_j
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{C}(\tau,\mathbf{x},\mathbf{l}) &\equiv \log \int d^3p\, e^{\mathbf{l}\cdot\mathbf{p}/(am)} f(\tau,\mathbf{x},\mathbf{p}) \\
&= \log(1+\delta) + l_i v_i + \frac{1}{2} l_i l_j \sigma_{ij} + \frac{1}{6} l_i l_j l_k \mathcal{C}_{ijk} + \dots
\end{aligned}
$$

Pueblas, Scoccimarro '08; Uhlemann '18; ...

Vlasov equation for $f(\tau, \mathbf{x}, \mathbf{p})$

$\Rightarrow$ Coupled hierarchy of non-linear EoM for cumulants $\delta, v_i, \sigma_{ij}, \mathcal{C}_{ijk}, \ldots$

- 0th order: continuity
- 1st order: Euler
- 2nd order:

$$\partial_\tau \sigma_{ij} + 2\mathcal{H}\sigma_{ij} + v_k \nabla_k \sigma_{ij} + \sigma_{jk} \nabla_k v_i + \sigma_{ik} \nabla_k v_j = -\nabla_k \mathcal{C}_{ijk} - \mathcal{C}_{ijk} \nabla_k \ln(1+\delta)$$

- 3rd order:

$$\partial_\tau \mathcal{C}_{ijk} + \ldots = -\nabla_l \mathcal{C}_{ijkl} - \mathcal{C}_{ijkl} \nabla_l \ln(1+\delta)$$

- 4th order: ...

Truncate at some cumulant order c_{max}, assess validity by varying c_{max}

$\rightarrow$ similar for massive neutrino pert. [Ma, Bertschinger], but in VPT we do include non-linearities

- Split cumulants into average and fluctuation part
- Example: 2nd cumulant (= velocity dispersion)

$$\epsilon_{ij}(z, \mathbf{x}) \equiv \frac{\sigma_{ij}(\tau(z), \mathbf{x})}{(\mathcal{H}(z)f(z))^2} = \epsilon(z)\delta_{ij} + \delta\epsilon_{ij}(z, \mathbf{x})$$

- Average velocity dispersion introduces a new scale

$$\boxed{k_\sigma(z) \equiv \epsilon(z)^{-1/2}}$$

(typically not far from non-linear scale $k_{nl}(z)$) *e.g. McDonald 09*

- Generated from average effect of shell-crossing dynamics on small scales; non-perturbative input for VPT
- Fluctuations on large scales, perturbative computation from Vlasov

$\delta\epsilon_{ij}$: 2 scalar, 2 vector, 2 tensor modes (svt)

- Various possibilities for how to determine dispersion scale k_σ
  - (i) self-consistently
  - (ii) halo model
  - (iii) matching $P_{\delta\delta}$ to N-body

MG, Laxhuber, Scoccimarro 25, 22

- Even infinitesimal non-zero initial value of $\epsilon(z_0)$ makes solutions deviate from SPT *Scoccimarro, Pueblas 08; McDonald 09*

- Write all fluctuations into a big vector

$$\psi_a = (\delta, \theta, (\nabla \times v), \delta\epsilon_{ij}, \dots)$$

- EoM has the familiar form

$$\begin{aligned}
&\frac{d}{d\ln D(z)}\psi_a(z,\mathbf{k}) + \Omega_{ab}(z,k)\psi_b(z,\mathbf{k}) \\
&= \sum_{b,c}\int d^3p\,d^3q\,\delta_D(\mathbf{k}-\mathbf{p}-\mathbf{q})\gamma_{abc}(\mathbf{p},\mathbf{q})\psi_b(z,\mathbf{p})\psi_c(z,\mathbf{q})
\end{aligned}$$

- Vertices $\gamma_{abc}(\mathbf{p},\mathbf{q})$
- Evolution matrix $\Omega_{ab}(z,k)$, contains dispersion scale k_σ [and average values of 4th cumulant, etc.]

Linear+non-linear terms obtained from Vlasov eq.

$$u_i = u_i^S + u_i^V = \frac{\nabla_i}{\nabla^2}\theta - \frac{\varepsilon_{ijk}\nabla_j}{\nabla^2} w_k\,,$$

$$\delta\epsilon_{ij}^S = \delta_{ij}\,\delta\epsilon + \frac{\nabla_i\nabla_j}{\nabla^2} g\,,$$
$$\delta\epsilon_{ij}^V = -\frac{\varepsilon_{ilk}\nabla_l\nabla_j}{\nabla^2}\nu_k - \frac{\varepsilon_{jlk}\nabla_l\nabla_i}{\nabla^2}\nu_k\,,$$
$$\delta\epsilon_{ij}^T = t_{ij} \equiv P_{ij,ls}^T \delta\epsilon_{ls}\,,$$

$$\psi \equiv (\delta, \theta, g, \delta\epsilon, A, w_i, \nu_i, t_{ij})\,.$$

$$\Omega = \begin{pmatrix} \Omega^S & & \\ & \Omega^V & \\ & & \Omega^T \end{pmatrix}, \qquad \Omega^S = \begin{pmatrix} & -1 & & & \\ -3/2 & 1/2 & k^2 & k^2 & k^2\epsilon \\ & -2\epsilon & 1 & & \\ & & & 1 & \\ & -1 & & & \end{pmatrix}, \qquad \Omega^V = \begin{pmatrix} 1/2 & k^2 \\ -\epsilon & 1 \end{pmatrix}, \quad \Omega^T = 1\,,$$

$$\gamma_{\delta\theta\delta}(p,q) = \frac{1}{2}\alpha_{pq} = \frac{(p+q)\cdot p}{2p^2}\,,$$
$$\gamma_{\theta\theta\theta}(p,q) = \beta_{pq} = \frac{(p+q)^2 p\cdot q}{2p^2q^2}\,,$$
$$\gamma_{A\theta A}(p,q) = \frac{1}{2}\frac{q\cdot p}{p^2}\,,$$
$$\gamma_{\theta A g}(p,q) = -\frac{1}{2}(p+q)\cdot q\,\frac{q\cdot p}{q^2}\,,$$
$$\gamma_{\theta A\epsilon}(p,q) = -\frac{1}{2}(p+q)\cdot p\,,$$

$$\gamma_{\delta w_i\delta}(p,q) = \gamma_{Aw_iA}(p,q) = \frac{1}{2}\frac{(p\times q)_i}{p^2}\,,$$
$$\gamma_{\theta w_i\theta}(p,q) = \frac{1}{2}\left(1+\frac{2p\cdot q}{q^2}\right)\frac{(p\times q)_i}{p^2}\,,$$
$$\gamma_{\theta A\nu_i}(p,q) = \frac{1}{2}\left(1+\frac{2p\cdot q}{q^2}\right)(p\times q)_i\,,$$
$$\gamma_{\theta At_{ij}}(p,q) = -\frac{1}{2}p_ip_j\,,$$

$$\gamma_{g\theta g}(p,q) = \frac{1}{2}\frac{p\cdot q}{q^2}\left(\frac{k^2}{p^2}+\frac{1}{2}-\frac{3}{2}\frac{(k\cdot p)^2}{k^2p^2}\right),$$
$$\gamma_{g\theta\epsilon}(p,q) = \frac{1}{2}\left(3\frac{(k\cdot p)^2}{k^2p^2}-1\right),$$
$$\gamma_{\epsilon\theta g}(p,q) = \frac{1}{2}\frac{p\cdot q}{2p^2q^2k^2}((k\cdot p)^2-p^2k^2)\,,$$
$$\gamma_{\epsilon\theta\epsilon}(p,q) = \frac{1}{2}\frac{k\cdot pk\cdot q}{k^2p^2}\,.$$

$$\gamma_{gw_ig}(p,q) = \frac{1}{2}\frac{1}{p^2}\left(\frac{3}{2}\frac{(k\cdot q)^2}{k^2q^2}+3\frac{k\cdot qp\cdot q}{k^2q^2}-\frac{p\cdot q}{q^2}-\frac{1}{2}\right)(p\times q)_i\,,$$
$$\gamma_{gw_i\epsilon}(p,q) = \frac{1}{2}3\frac{k\cdot p}{p^2k^2}(p\times q)_i\,,$$
$$\gamma_{g\theta\nu_i}(p,q) = -\frac{1}{2}\frac{1}{k^2p^2q^2}\left(p\cdot qk^2+3k\cdot pk\cdot q\right)(p\times q)_i\,,$$
$$\gamma_{g\theta t_{ij}}(p,q) = -\frac{1}{2}\frac{2k^2-3p\cdot q-6k\cdot p}{2k^2p^2}p_ip_j\,,$$

Example: 2nd cumulant truncation *a bit tedious ... but straightforward*

5 scalar + 2*2 vector [+ 1*2 tensor modes], 33 [+15] vertices

- Perturbative solution in initial density δ_0 as usual

$$\psi_a(z, \mathbf{k}) = \sum_n \int d^3k_1 \cdots d^3k_n \, \delta_D(\mathbf{k} - \mathbf{k}_1 - \cdots - \mathbf{k}_n) \times F_{n,a\ldots}(\mathbf{k}_1, \ldots, \mathbf{k}_n; z)\delta_0(\mathbf{k}_1) \cdots \delta_0(\mathbf{k}_n)$$

$\Rightarrow$ boils down to using F_n kernels different from SPT in loop integrals

- Example: UV limit of F_3 kernel $q \gg k_\sigma \gg k$

$$F_3^{\mathrm{SPT}}(\mathbf{k},\mathbf{q},-\mathbf{q}) \quad \to \quad -\frac{61}{1890} \times \frac{k^2}{q^2}$$

$$F_{3,a=\delta}^{\mathrm{VPT}}(\mathbf{k},\mathbf{q},-\mathbf{q};z) \quad \to \quad -\mathrm{const} \times \frac{k^2}{q^2} \times \left(\frac{k_\sigma(z)}{q}\right)^{4/\alpha}$$

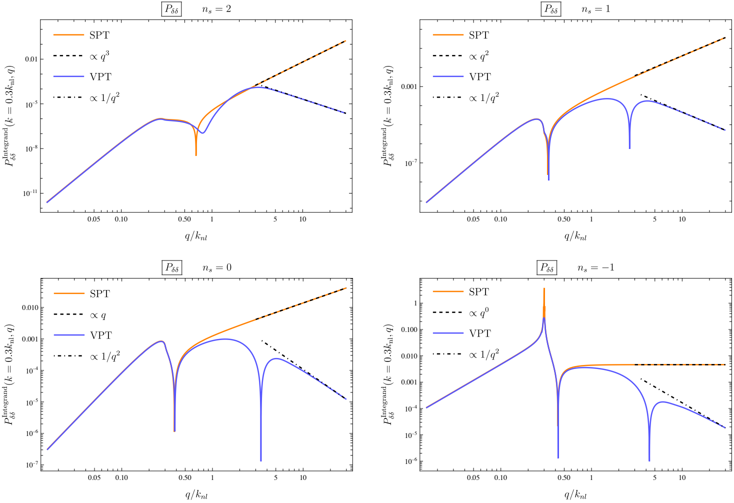
for average dispersion $\epsilon(z) \propto D(z)^\alpha$, i.e. $k_\sigma(z) \propto D(z)^{-\alpha/2}$ $\quad (^*)$

- UV screening captured by VPT; obtained from collisionless dynamics (1st principle)
- Power-law index $4/\alpha$ independent of truncation order

  [only important that incoming linear modes stop growing at $z = z_q$ when $k_\sigma(z) \sim q$]
- For scaling universe $\alpha = 4/(3+n_s)$

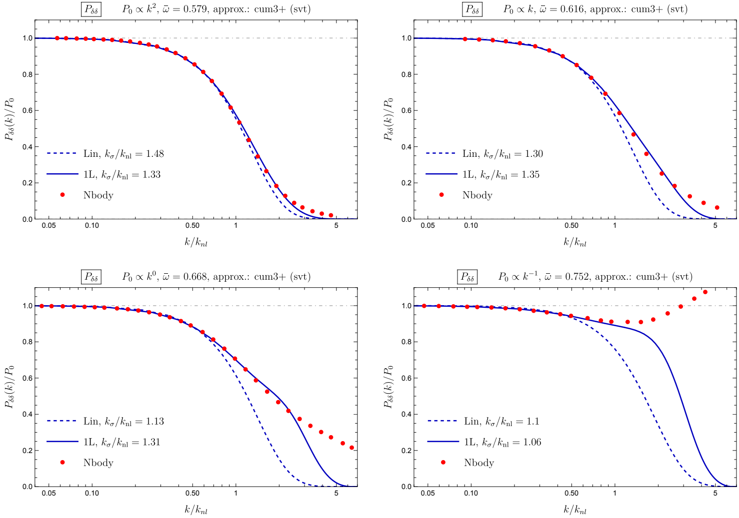
$(^*)$: For arbitrary $\epsilon(z)$ replace $(k_\sigma(z)/q)^{4/\alpha}$ by $(D(z_q)/D(z))^2$

One-loop integrand for power law spectra $P_0 \propto k^{n_s}$



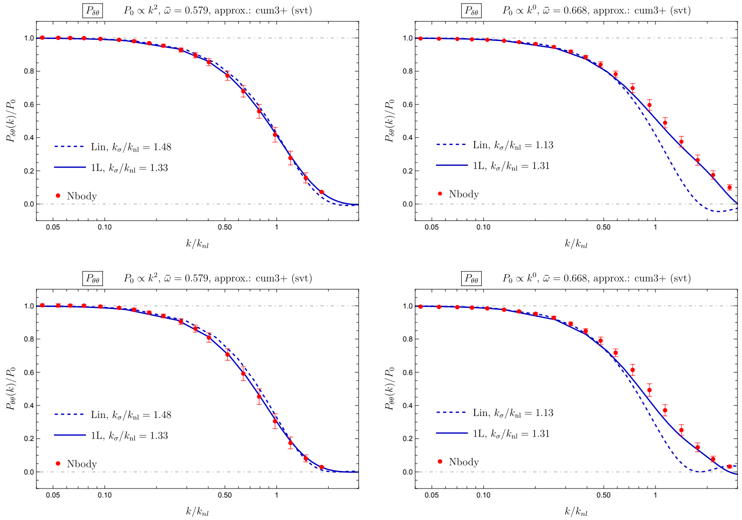
L-loop: SPT $\propto q^{(n_s+3)L-2}$; VPT $\propto q^{-2}$ indep. of n_s and L *MG, Laxhuber, Scoccimarro 2210.08089*

$P_{\delta\delta}$ for power law spectra $P_0 \propto k^{n_s}$



VPT with 1-param ($=k_\sigma/k_{nl}$) matched to N-body *MG, DL, Scoccimarro 2210.08089*

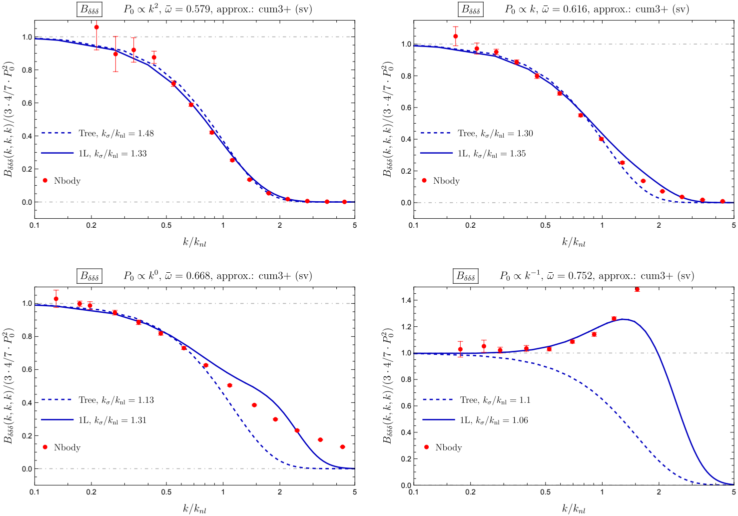
$P_{\delta\theta}$ and $P_{\theta\theta}$



$P_{\delta\theta}$ and $P_{\theta\theta}$ VPT with 0 free parameters [k_σ/k_{nl} already fixed from $P_{\delta\delta}$]

MG, Laxhuber, Scoccimarro 2210.08089

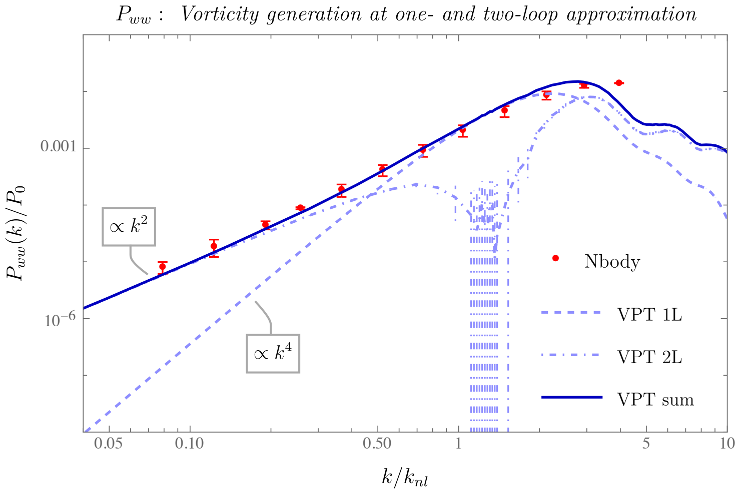
One-loop equilateral bispectrum



$B(k,k,k)$ VPT with 0 free parameters [k_σ/k_{nl} already fixed from $P_{\delta\delta}$]

MG, Laxhuber, Scoccimarro 2210.08089

Two-loop vorticity power spectrum



P_{ww} VPT with 0 free parameters [k_σ/k_{nl} already fixed from $P_{\delta\delta}$]

MG, Laxhuber, Scoccimarro 2210.08089

Dependence on truncation?

- Hierarchy of evolution equations for cumulants $\mathcal{C}_{i_1 i_2 \cdots i_c}$
- Evolution of cth cumulant depends on $c' \leq c + 1$
- Truncation at c_{max}

Dependence on truncation?

- VPT including all cumulants up to order $c_{\rm max}$
- Use spherical harmonic basis *cf. Seljak, McDonald,... '11; MG Scoccimarro '25*

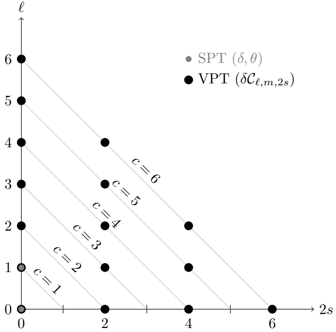
$$
\begin{aligned}
\mathcal{C}(z,\mathbf{k},\mathbf{L}) &\equiv \log\int d^3p\, e^{\mathbf{L}\cdot\mathbf{p}/(am)}\, f(z,\mathbf{k},\mathbf{p}) \\
&= \log(1+\delta) + L_i v_i + \frac{1}{2}L_iL_j\sigma_{ij} + \frac{1}{6}L_iL_jL_k\mathcal{C}_{ijk} + \ldots \\
&= \sum_{\ell,m,s} |\mathbf{L}|^{2s+\ell}\, Y_{\ell m}(\hat{\mathbf{L}})\, \mathcal{C}_{\ell,m,2s}(z,\mathbf{k})
\end{aligned}
$$

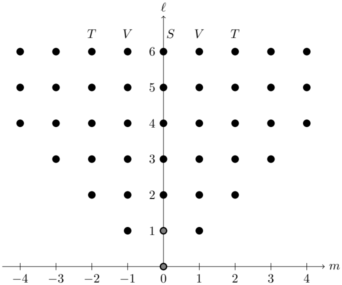
- Cumulants at order c:

$$\mathcal{C}_{\ell,m,2s}(z,\mathbf{k})$$

with $c = \ell + 2s$

Dependence on truncation?





- e.g first cumulant v_i: $\ell = 1, 2s = 0$; $m = 0, \pm 1$ (θ, vorticity)
- e.g. second cumulant σ_{ij}:
  $\ell = 0, 2s = 2$; (one scalar mode)
  $\ell = 2, 2s = 0, m = 0, \pm 1, \pm 2$ (1S+2V+2T modes)

Linear+non-linear terms obtained from Vlasov eq.

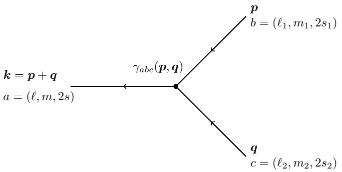
$$
\begin{aligned}
\psi_a \;=\; & \big(\delta(\eta,\boldsymbol{k}), \delta C_{000}(\eta,\boldsymbol{k}), \delta C_{1m0}(\eta,\boldsymbol{k})|_{m=0,\pm1},\\
& \delta C_{002}(\eta,\boldsymbol{k}), \delta C_{2m0}(\eta,\boldsymbol{k})|_{m=0,\pm1,\pm2},\\
& \delta C_{1m2}(\eta,\boldsymbol{k})|_{m=0,\pm1}, \delta C_{3m0}(\eta,\boldsymbol{k})|_{m=0,\pm1,\pm2,\pm3},\\
& \delta C_{004}(\eta,\boldsymbol{k}), \delta C_{2m2}(\eta,\boldsymbol{k})|_{m=0,\pm1,\pm2},\\
& \qquad \delta C_{4m0}(\eta,\boldsymbol{k})|_{m=0,\pm1,\pm2,\pm3,\pm4}, \ldots\big)\,,
\end{aligned}
$$

$$
\begin{aligned}
\partial_\eta \psi_a(\eta,\boldsymbol{k}) \;+\; & \Omega_{ab}(\eta,k)\psi_b(\eta,\boldsymbol{k})\\
& = \int_{\boldsymbol{pq}} \gamma_{abc}(\boldsymbol{p},\boldsymbol{q})\psi_b(\eta,\boldsymbol{p})\psi_c(\eta,\boldsymbol{q})\,, \quad (41)
\end{aligned}
$$

$$
\Omega_{ab} = \left(\delta^K_{\ell\ell'} A^{ss'}_{\ell m} + \delta^K_{\ell-1,\ell'} B^{ss'}_{\ell m} + \delta^K_{\ell+1,\ell'} C^{ss'}_{\ell m}\right)\delta^K_{mm'}\,, \quad (44)
$$

with

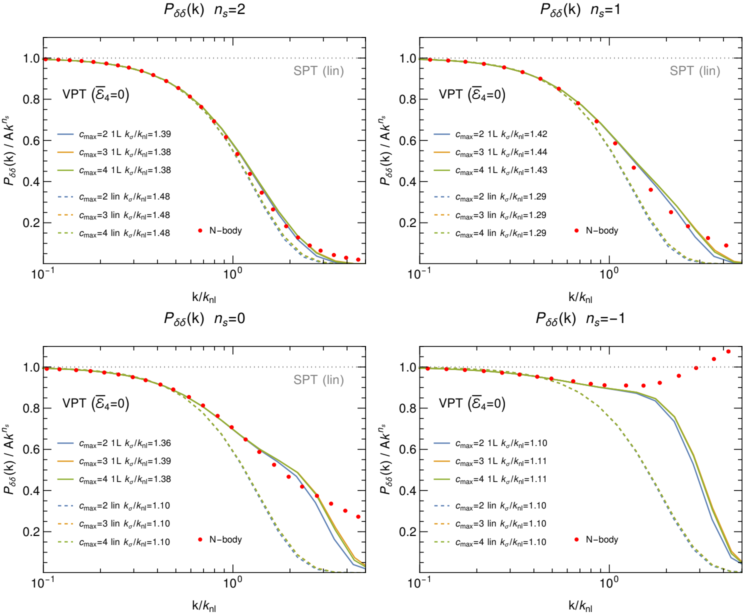
$$
\begin{aligned}
A^{ss'}_{\ell m} &= \left(\frac{3}{2}\frac{\Omega_m}{f^2} - 1\right)(\ell+2s)\delta^K_{ss'}\,,\\
B^{ss'}_{\ell m} &= \frac{\{1,k^2\}}{2\ell+1}\sqrt{\ell^2-m^2}\left(\frac{\delta^K_{s+1,s'}}{(2s+1)}\right.\\
&\qquad \left. + \frac{(2s)!\,\mathcal{E}_{2s-2s'+2}(\eta)}{(2(s-s')+1)!(2s')!}\Theta_{s-s'}\right),\\
C^{ss'}_{\ell m} &= -\frac{\{1,k^2\}}{2\ell+1}\sqrt{(\ell+1)^2-m^2}\left((2\ell+3+2s)\,\delta^K_{ss'}\right.\\
&\qquad \left. + \frac{(2s)!\,\mathcal{E}_{2s-2s'}(\eta)}{(2(s-s')-1)!(2s')!}\Theta_{s-1-s'}\right), \qquad (45)
\end{aligned}
$$



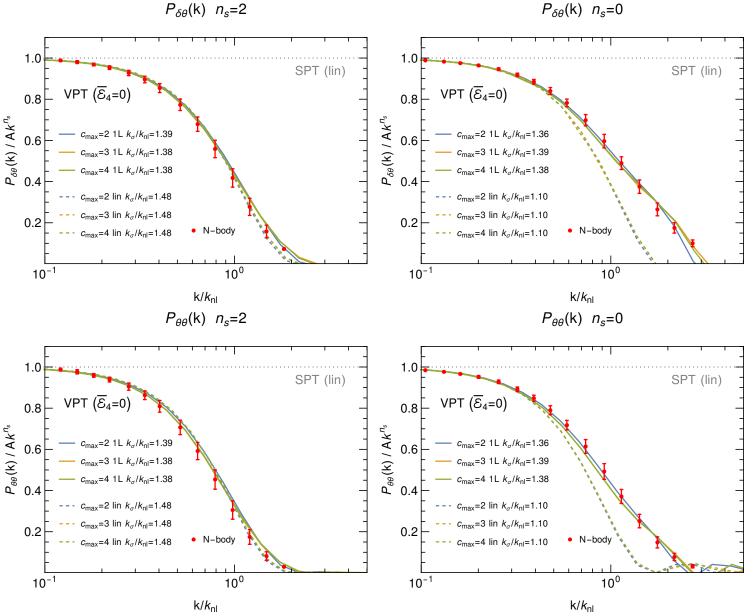
$$
\begin{aligned}
\tilde\gamma_{abc}(\boldsymbol{p},\boldsymbol{q}) \;=\; & (-1)^{\frac{\ell_1+\ell_2-1-\ell}{2}}\frac{(2s)!}{(2s_1)!(2s_2)!}\delta^K_{\ell_1+2s_1+\ell_2+2s_2,\ell+2s+1}\\
& \times \frac{pk^{a_\ell}}{p^{a_{\ell_1}}q^{a_{\ell_2}}}(2\ell_1+1)(-1)^{m'}[D^{m'}_{\ell m}((R^{\boldsymbol{p}})^{-1}R^{\boldsymbol{k}})]^* D^{m'_2}_{\ell_2 m_2}((R^{\boldsymbol{p}})^{-1}R^{\boldsymbol{q}})\\
& \times \left[(2\ell_2+1+2s_2)\begin{pmatrix}\ell & \ell_1 & \ell_2-1\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\ell & \ell_1 & \ell_2-1\\ -m' & m_1 & m'_2\end{pmatrix}\sqrt{\ell_2^2-(m'_2)^2}\right.\\
& \left. + 2s_2\begin{pmatrix}\ell & \ell_1 & \ell_2+1\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\ell & \ell_1 & \ell_2+1\\ -m' & m_1 & m'_2\end{pmatrix}\sqrt{(\ell_2+1)^2-(m'_2)^2}\right].
\end{aligned}
$$

MG, Scoccimarro 2502.20451

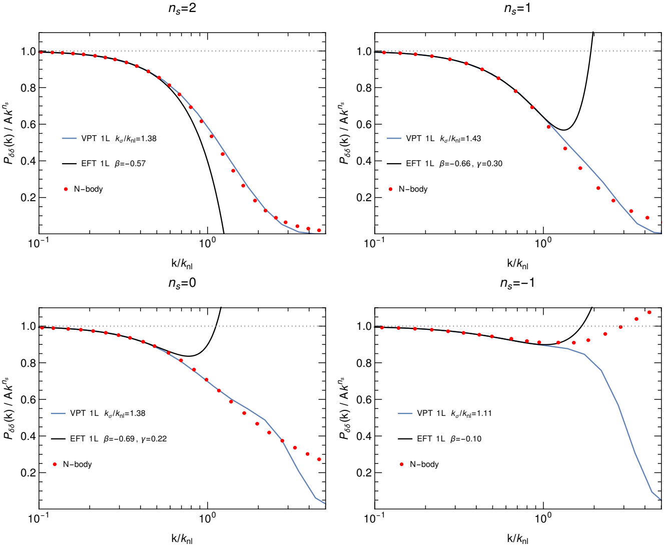
Dependence on truncation?



Dependence on truncation?



Comparison to (leading corr. terms in) EFT?



black = 2-param EFT fit to N-body *Pajer, Zaldarriaga '13*

blue = VPT with 1-param ($=k_\sigma/k_{nl}$) matched to N-body *MG, Scoccimarro '25*

Application to ΛCDM cosmology

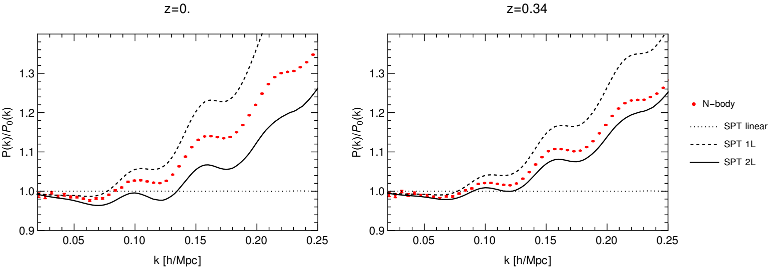
VPT input: average dispersion $\epsilon(z) = \langle\sigma_{ii}\rangle/3(f\mathcal{H})^2$

We consider two possibilities:

- (1) Estimated from simulation (using halo finder and estimate of dispersion in and around halos based on NFW); yields $k_\sigma(z) = \epsilon(z)^{-1/2}$ comparable to nonlinear scale
  $\Rightarrow$ 0 free parameters
- (2) Treating $k_\sigma(z) = \epsilon(z)^{-1/2}$ as free parameter
  $\Rightarrow$ 1 free parameter

Application to ΛCDM cosmology: case (1)

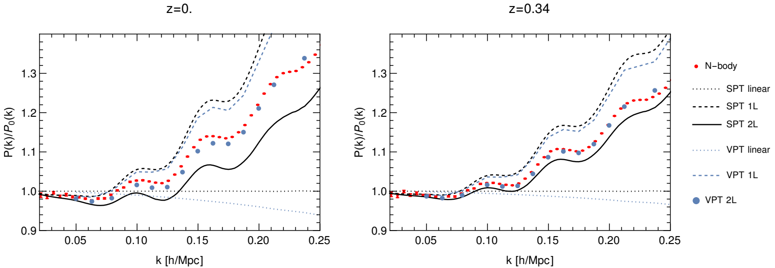
$$P_{\delta\delta}(z, k)$$



red = N-body, black = SPT,

Application to ΛCDM cosmology: case (1)

$P_{\delta\delta}(z,k)$

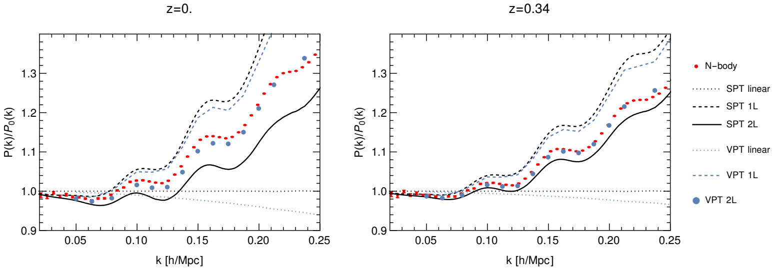


red = N-body, black = SPT, blue = VPT

MG, Laxhuber, Scoccimarro 2505.02907

Application to ΛCDM cosmology: case (1)

$P_{\delta\delta}(z, k)$



red = N-body, black = SPT, blue = VPT

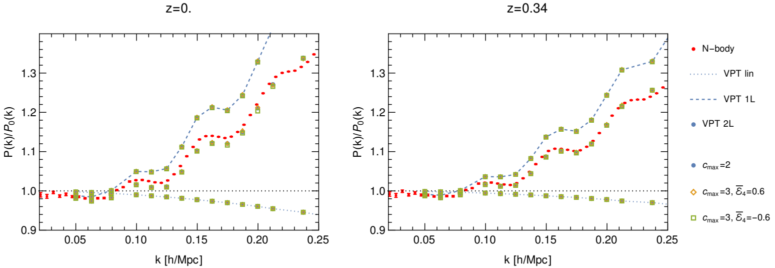
MG, Laxhuber, Scoccimarro 2505.02907

Residual difference at $z = 0$ consistent with missing 3-loop contributions

$k_\sigma(z = 0) = 0.36h/\mathrm{Mpc}$, $k_\sigma(z = 0.34) = 0.47h/\mathrm{Mpc}$

$k_{\mathrm{nl}}(z = 0) = 0.27h/\mathrm{Mpc}$, $k_{\mathrm{nl}}(z = 0.34) = 0.37h/\mathrm{Mpc}$

Application to ΛCDM cosmology: case (1)



Truncation $c_{\max} = 2$ (circles) versus $c_{\max} = 3$ (diamonds, boxes)

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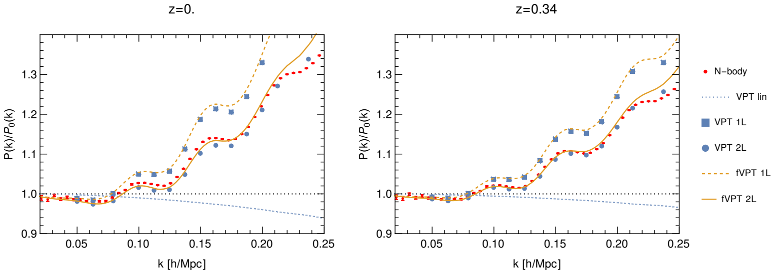
Application to ΛCDM cosmology: case (1)



Full VPT versus simplified scheme fVPT (includes main features of VPT; computational effort equal to SPT)

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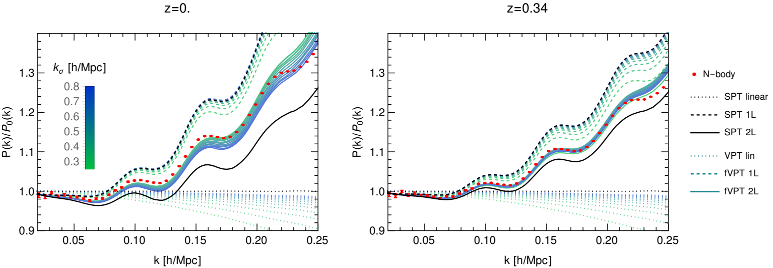
Application to ΛCDM cosmology: case (2)



Variation with k_σ; partial cancellation in 2-loop result

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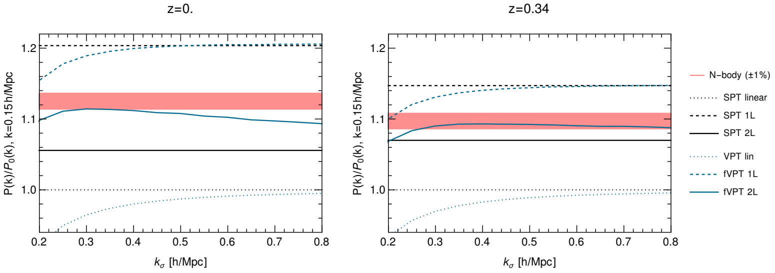
Application to ΛCDM cosmology



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Conclusion

- Conceptually simple idea:
  VPT = perturbation theory for collisionless matter
  SPT = pert. theory for perfect fluid
- based on first principles
- physical new scale $k_\sigma(z)$ related to average value of velocity dispersion generated by shell crossing / halo formation on small scales
- includes known features of structure formation that SPT misses (velocity dispersion and higher cumulants; UV screening = decoupling of small modes; vorticity generation; ....)
- so far demonstrated for $P_{\delta\delta}$ for ΛCDM; and for scaling universes with $n_s = -1, .., 2$, $P_{\delta\delta}, P_{\delta\theta}, P_{\theta\theta}, B(k,k,k), P_{ww}$
- future: RSD; could be used in EFT pipeline instead of SPT (better motivated priors on EFT corrections)