The speed of sound in the EFTofLSS

Based on: 2410.05389 and 2410.11949

with Marilena Loverde, Matt McQuinn and Drew Jamieson

Caio Nascimento

BCCP Cosmology Seminar
Berkeley Oct 29th

Outline

1. Introduction (6 pages)

2. Effective field theory of large scale structure (EFTofLSS) (4 pages)

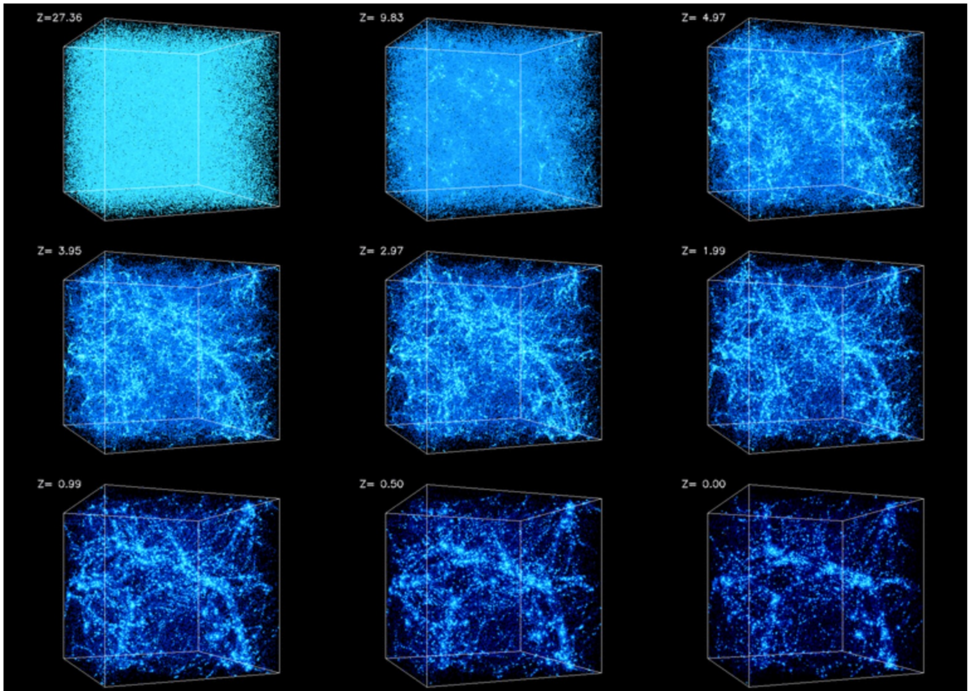
3. Can we get away without the EFT? Yes, but not really… (10 pages)

4. Can we understand the speed of sound from the microphysics of N-body particles? Yes!! (10 pages)

5. Final remarks (1 page)

The goal is to learn new physics…

Nature of dark matter, dark energy and Initial conditions of our Universe!



Credit: Simulations performed at the National Center for Supercomputer Applications by Andrey Kravtsov and Anatoly Klypin.

DESI

Rubin Observatory

….via cosmological parameters!

- Scalar mass and self-interactions

From 100 kpc to 10 Gpc: Dark Matter self-interactions before and after DESI (2407.18252)
Salvatore Bottaro et al.

- Dynamics of dark energy

DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations (2404.03002)
DESI Collaboration

- Amplitude of non-Gaussianity

The imprints of primordial non-gaussianities on large-scale structure: scale dependent bias and abundance of virialized objects (0710.4560)
Neal Dalal et al.

Neutrino mass scale has kept me busy!

[Submitted on 30 Jun 2023 (v1), last revised 14 Aug 2023 (this version, v2)]

Neutrino winds on the sky

Caio Nascimento, Marilena Loverde

We develop a first-principles formalism to compute the distortion to the relic neutrino density field caused by the peculiar motions of large-scale structures. This distortion slows halos down due to dynamical friction, causes a local anisotropy in the neutrino-CDM cross-correlation, and reduces the global cross-correlation between neutrinos and CDM. The local anisotropy in the neutrino-CDM cross-spectrum is imprinted in the three point cross-correlations of matter and galaxies, or the bispectrum in Fourier space, producing a signal peaking at squeezed triangle configurations. This bispectrum signature of neutrino masses is not limited by cosmic variance or potential inaccuracies in the modeling of complicated nonlinear and galaxy formation physics, and it is not degenerate with the optical depth to reionization. We show that future surveys have the potential to detect the distortion bispectrum.

Comments:	36+7 pages, 10 figures. Comments are welcome! Matching JCAP accepted version
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**
Cite as:	arXiv:2307.00049 **[astro-ph.CO]**
	(or arXiv:2307.00049v2 **[astro-ph.CO]** for this version)
	https://doi.org/10.48550/arXiv.2307.00049
Journal reference:	JCAP11(2023)036
Related DOI:	https://doi.org/10.1088/1475-7516/2023/11/036

[Submitted on 1 Apr 2021 (v1), last revised 19 Nov 2021 (this version, v2)]

Generalized Boltzmann hierarchy for massive neutrinos in cosmology

Caio Bastos de Senna Nascimento

Boltzmann solvers are an important tool for the computation of cosmological observables in the linear regime. In the presence of massive neutrinos, they involve solving the Boltzmann equation followed by an integration in momentum space to arrive at the desired fluid properties, a procedure which is known to be computationally slow. In this work we introduce the so-called generalized Boltzmann hierarchy (GBH) for massive neutrinos in cosmology, an alternative to the usual Boltzmann hierarchy, where the momentum dependence is integrated out leaving us with a two-parameter infinite set of ordinary differential equations. Along with the usual expansion in multipoles, there is now also an expansion in higher velocity weight integrals of the distribution function. Using a toy code, we show that the GBH produces the density contrast neutrino transfer function to a $\lesssim 0.5\%$ accuracy at both large and intermediate scales compared to the neutrino free-streaming scale, thus providing a proof-of-principle for the GBH. We comment on the implementation of the GBH in a state of the art Boltzmann solver.

Comments:	12 pages, 10 figures. Matching prd accepted version
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**
Cite as:	arXiv:2104.00703 **[astro-ph.CO]**
	(or arXiv:2104.00703v2 **[astro-ph.CO]** for this version)
	https://doi.org/10.48550/arXiv.2104.00703
Journal reference:	Phys. Rev. D 104, 083535 (2021)
Related DOI:	https://doi.org/10.1103/PhysRevD.104.083535

[Submitted on 16 Mar 2023 (v1), last revised 6 Jul 2023 (this version, v2)]

An accurate fluid approximation for massive neutrinos in cosmology

Caio Nascimento

A measurement of the neutrino mass scale will be achieved with cosmological probes in the upcoming decade. On one hand, the inclusion of massive neutrinos in the linear perturbation theory of cosmological structure formation is well understood and can be done accurately with state of the art Boltzmann solvers. On the other hand, the numerical implementation of the Boltzmann equation is computationally expensive and is a bottleneck in those codes. This has motivated the development of more efficient fluid approximations, despite their limited accuracy over all scales of interest, $k \sim (10^{-3} - 10)\text{Mpc}^{-1}$. In this work we account for the dispersive nature of the neutrino fluid, i.e., the scale dependence in the sound speed, leading to an improved fluid approximation. We show that overall $\lesssim 5\%$ errors can be achieved for the neutrino density and velocity transfer functions at redshift $z \lesssim 5$, which corresponds to an order of magnitude improvement over previous approximation schemes that can be discrepant by as much as a factor of two.

Comments:	10+8 pages, 7 figures. Matching prd accepted version
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**
Cite as:	arXiv:2303.09580 **[astro-ph.CO]**
	(or arXiv:2303.09580v2 **[astro-ph.CO]** for this version)
	https://doi.org/10.48550/arXiv.2303.09580
Related DOI:	https://doi.org/10.1103/PhysRevD.108.023505

[Submitted on 10 Feb 2021 (v1), last revised 27 Aug 2021 (this version, v2)]

Neutrinos in N-body simulations

Caio Bastos de Senna Nascimento, Marilena Loverde

In the next decade, cosmological surveys will have the statistical power to detect the absolute neutrino mass scale. N-body simulations of large-scale structure formation play a central role in interpreting data from such surveys. Yet these simulations are Newtonian in nature. We provide a quantitative study of the limitations to treating neutrinos, implemented as N-body particles, in N-body codes, focusing on the error introduced by neglecting special relativistic effects. Special relativistic effects are potentially important due to the large thermal velocities of neutrino particles in the simulation box. We derive a self-consistent theory of linear perturbations in Newtonian and non-relativistic neutrinos and use this to demonstrate that N-body simulations overestimate the neutrino free-streaming scale, and cause errors in the matter power spectrum that depend on the initial redshift of the simulations. For $z_i \lesssim 100$, and neutrino masses within the currently allowed range, this error is $\lesssim 0.5\%$, though represents an up to $\sim 10\%$ correction to the shape of the neutrino-induced suppression to the cold dark matter power spectrum. We argue that the simulations accurately model non-linear clustering of neutrinos so that the error is confined to linear scales.

Comments:	15 pages, 7 figures. Matching prd accepted version
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**
Report number:	YITP-SB-2021-02
Cite as:	arXiv:2102.05690 **[astro-ph.CO]**
	(or arXiv:2102.05690v2 **[astro-ph.CO]** for this version)
	https://doi.org/10.48550/arXiv.2102.05690
Journal reference:	Phys. Rev. D 104, 043512 (2021)
Related DOI:	https://doi.org/10.1103/PhysRevD.104.043512

Can’t do it without nuisance parameters as well

Ex: $$\frac{\delta n_g}{\bar{n}_g} = \sum_i b_i \mathcal{O}_i$$

$$\mathcal{O}_i = \delta, \delta^2, [(\partial_i \partial_j - \nabla^2 \delta_{ij})\phi]^2, \ldots$$

In principle contains cosmological information

+

Information about galaxy formation physics

Improved extraction of cosmological parameters!

Full-shape analysis with simulation-based priors: cosmological parameters and the structure growth anomaly (2409.10609)
Mikhail Ivanov et al.

HOD-informed prior for EFT-based full-shape analyses of LSS (2409.12937)
Hanyu Zhang et al.

Focus on the effective sound speed

Power spectrum in Standard Perturbation Theory

Linear power spectrum

$$P^{\mathrm{EFT}}_{\text{1-loop}}(z,k) - P^{\mathrm{SPT}}_{\text{1-loop}}(z,k) \sim c^2_{\mathrm{eff}}(z)k^2 P_{\mathrm{L}}(k)$$

EFT Matter power spectrum

Encapsulates well-understood short-scale nonlinear gravitational evolution!

Questions we want to answer

- Can we arrive at this structure without any EFT ingredients? Yes, but not entirely self-consistent!

New way of thinking about it

Need to control short-distance fluctuations

- Can we understand the microphysics underlying the sound speed? Yes!!

Cosmology dependence

Info on short-distance nonlinear evolution

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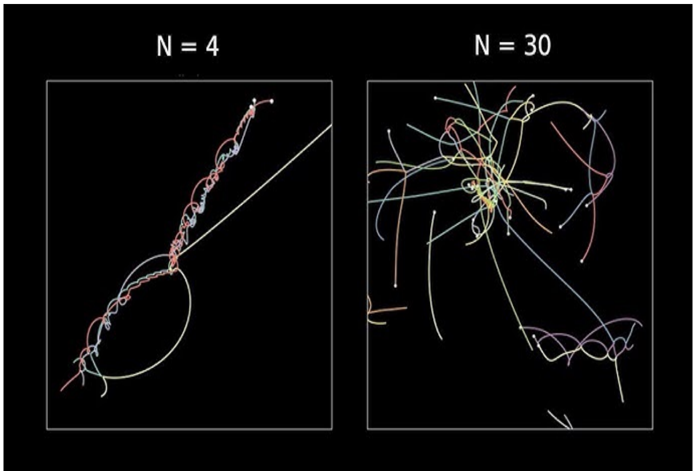
A particle physicist tool: EFT



Credit: Snapshot from https://www.youtube.com/watch?v=ijxwdV_ZWnc

$$R = \Lambda^{-1}$$

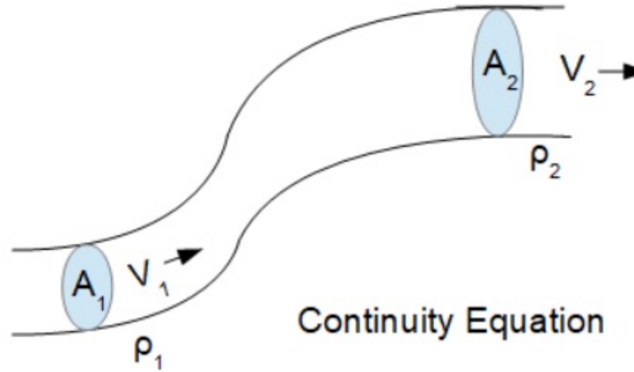
Smoothing

$$\rho = \rho_l + \cancel{\rho_s}$$

Credit: https://www.thoughtco.com/what-is-fluid-dynamics-4019111

The effective fluid

- Conservation of mass



Credit: https://www.vcalc.com/wiki/vCalc/Continuity+Equation

- Momentum balance

$$\frac{D\vec{v}_l}{dt} \sim \vec{\nabla}\phi_l + \vec{\nabla}\cdot\tau^{\mathrm{eff}}$$

Gravitational field

Dissipation

Bottom-up effective stress

- SPT: Vanishing by assumption!

$$\tau_{ij}^{\mathrm{eff}} \equiv 0 \longrightarrow$$

Perturbative expansion in fluctuations

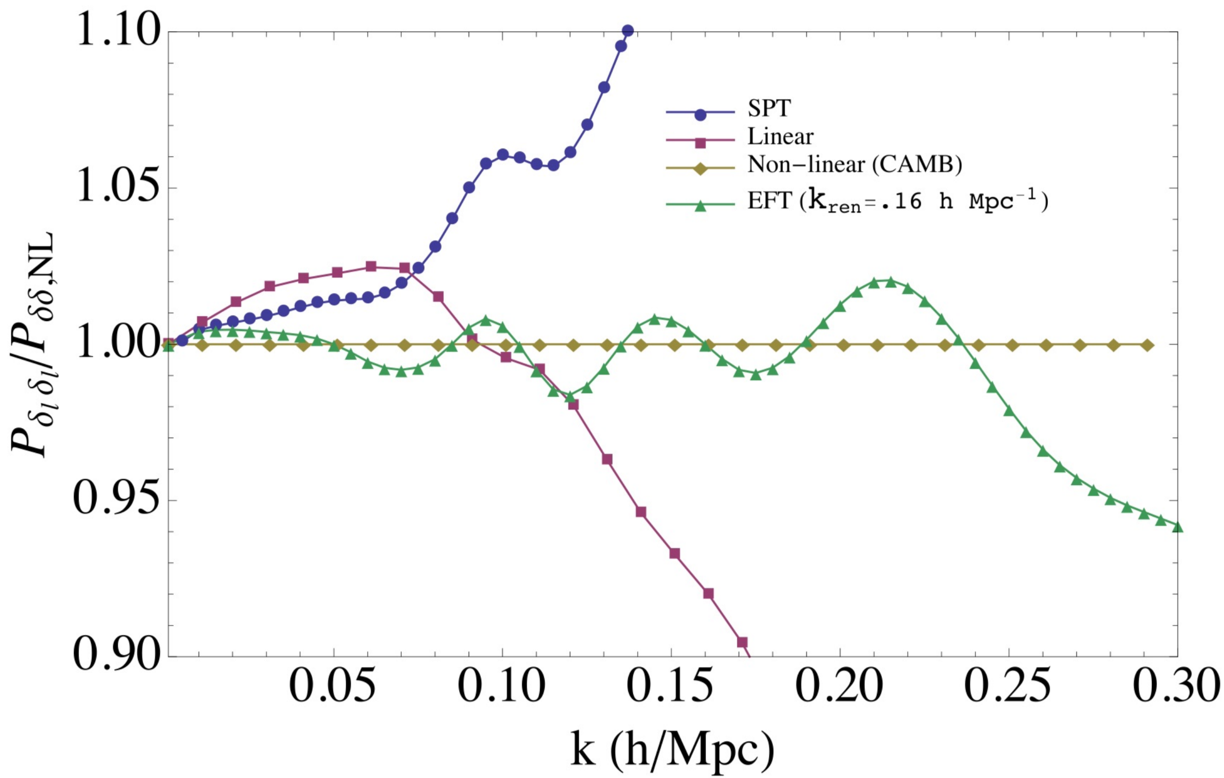
$$\delta_l\,,\ \vec{v}_l$$

- EFT: All terms allowed by symmetries

$$\partial^i \left(\frac{1}{\rho_l} \partial^j \tau_{ij}^{\mathrm{eff}} \right) = c_{\mathrm{eff}}^2(a) \nabla^2 \delta_l + \ldots$$

Free nuisance parameter

The success of the EFT approach



Credit: J.J. Carrasco, M.P. Hertzberg and L.Senatore. 1206.2926

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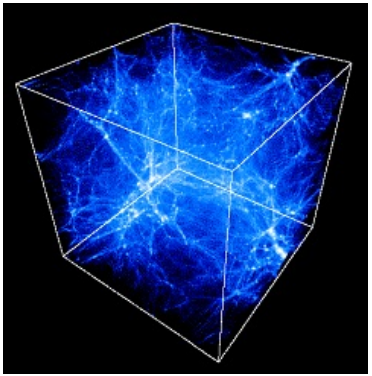
Is the free parameter really necessary?

- 

  Credit: Chandrajit Bajaj

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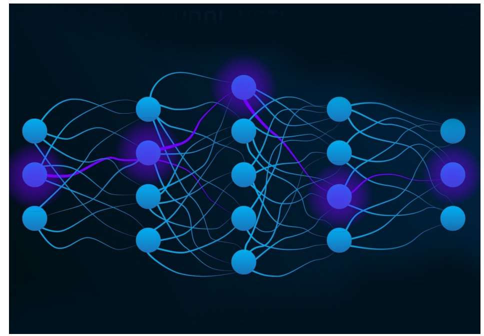
  

  Credit: https://www.the-scientist.com/artificial-neural-networks-learning-by-doing-71687

  $=$ Fast accurate observables in the nonlinear regime

- $$\tau_{ij}^{\text{eff}} \equiv 0 \longrightarrow$$ Theoretical framework that avoids this assumption?

People have tried really hard…

[Submitted on 8 Sep 2017 (v1), last revised 6 Jan 2018 (this version, v3)]

Large-scale structure perturbation theory without losing stream crossing

Patrick McDonald, Zvonimir Vlah

We suggest an approach to perturbative calculations of large-scale clustering in the Universe that includes from the start the stream crossing (multiple velocities for mass elements at a single position) that is lost in traditional calculations. Starting from a functional integral over displacement, the perturbative series expansion is in deviations from (truncated) Zel'dovich evolution, with terms that can be computed exactly even for stream-crossed displacements. We evaluate the one-loop formulas for displacement and density power spectra numerically in 1D, finding dramatic improvement in agreement with N-body simulations compared to the Zel'dovich power spectrum (which is exact in 1D up to stream crossing). Beyond 1D, our approach could represent an improvement over previous expansions even aside from the inclusion of stream crossing, but we have not investigated this numerically. In the process we show how to achieve effective-theory-like regulation of small-scale fluctuations without free parameters.

[Submitted on 17 Dec 2018 (v1), last revised 3 Jul 2019 (this version, v2)]

Evolution of dark matter velocity dispersion

Alaric Erschfeld, Stefan Floerchinger

Cosmological perturbation theory for the late Universe dominated by dark matter is extended beyond the perfect fluid approximation by taking the dark matter velocity dispersion tensor as an additional field into account. A proper tensor decomposition of the latter leads to two additional scalar fields, as well as a vector and a tensor field. Most importantly, the trace of the velocity dispersion tensor can have a spatially homogeneous and isotropic expectation value. While it decays at early times, we show that a back-reaction effect quadratic in perturbations makes it grow strongly at late times. We compare sterile neutrinos as a candidate for comparatively warm dark matter to weakly interacting massive particles as a rather cold dark matter candidate and show that the late time growth of velocity dispersion is stronger for the latter. Another feature of a non-vanishing velocity dispersion expectation value is that it destroys the apparent self-consistency of the single-stream approximation and allows thereby to treat times and scales beyond shell-crossing.

[Submitted on 22 Dec 2015 (v1), last revised 7 Mar 2016 (this version, v2)]

The dark matter dispersion tensor in perturbation theory

Alejandro Aviles

We compute the dark matter velocity dispersion tensor up to third order in perturbation theory using the Lagrangian formalism, revealing growing solutions at the third and higher orders. Our results are general and can be used for any other perturbative formalism. As an application, corrections to the matter power spectrum are calculated, and we find that some of them have the same structure as those in the effective field theory of large-scale structure, with "EFT-like" coefficients that grow quadratically with the linear growth function and are further suppressed by powers of the logarithmic linear growth factor f; other corrections present additional k dependence. Due to the velocity dispersions, there exists a free-streaming scale that suppresses the whole 1-loop power spectrum. Furthermore, we find that as a consequence of the nonlinear evolution, the free-streaming length is shifted towards larger scales, wiping out more structure than that expected in linear theory. Therefore, we argue that the formalism developed here is better suited for a perturbation treatment of warm dark matter or neutrino clustering, where the velocity dispersion effects are well known to be important. We discuss implications related to the nature of dark matter.

[Submitted on 14 Oct 2022]

Perturbation theory with dispersion and higher cumulants: framework and linear theory

Mathias Garny, Dominik Laxhuber, Roman Scoccimarro

The standard perturbation theory (SPT) approach to gravitational clustering is based on a fluid approximation of the underlying Vlasov-Poisson dynamics, taking only the zeroth and first cumulant of the phase-space distribution function into account (density and velocity fields). This assumption breaks down when dark matter particle orbits cross and leads to well-known problems, e.g. an anomalously large backreaction of small-scale modes onto larger scales that compromises predictivity. We extend SPT by incorporating second and higher cumulants generated by orbit crossing. For collisionless matter, their equations of motion are completely fixed by the Vlasov-Poisson system, and thus we refer to this approach as Vlasov Perturbation Theory (VPT). Even cumulants develop a background value, and they enter the hierarchy of coupled equations for the fluctuations. The background values are in turn sourced by power spectra of the fluctuations. The latter can be brought into a form that is formally analogous to SPT, but with an extended set of variables and linear as well as non-linear terms, that we derive explicitly. In this paper, we focus on linear solutions, which are far richer than in SPT, showing that modes that cross the dispersion scale set by the second cumulant are highly suppressed. We derive stability conditions on the background values of even cumulants from the requirement that exponential instabilities be absent. We also compute the expected magnitude of averaged higher cumulants for various halo models and show that they satisfy the stability conditions. Finally, we derive self-consistent solutions of perturbations and background values for a scaling universe and study the convergence of the cumulant expansion. The VPT framework provides a conceptually straightforward and deterministic extension of SPT that accounts for the decoupling of small-scale modes.

[Submitted on 6 Oct 2009]

How to generate a significant effective temperature for cold dark matter, from first principles

Patrick McDonald

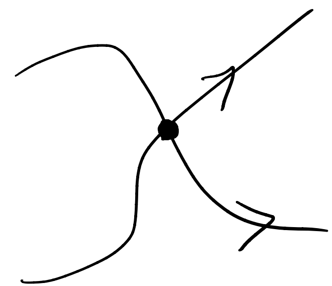
I show how to reintroduce velocity dispersion into perturbation theory (PT) calculations of structure in the Universe, i.e., how to go beyond the pressureless fluid approximation, starting from first principles. This addresses a possible deficiency in uses of PT to compute clustering on the weakly non-linear scales that will be critical for probing dark energy. Specifically, I show how to derive a non-negligible value for the (initially tiny) velocity dispersion of dark matter particles, <\delta v^2>, where \delta v is the deviation of particle velocities from the local bulk flow. The calculation is essentially a renormalization of the homogeneous (zero order) dispersion by fluctuations 1st order in the initial power spectrum. For power law power spectra with n>-3, the small-scale fluctuations diverge and significant dispersion can be generated from an arbitrarily small starting value -- the dispersion level is set by an equilibrium between fluctuations generating more dispersion and dispersion suppressing fluctuations. For an n=-1.4 power law normalized to match the present non-linear scale, the dispersion would be ~100 km/s. This n corresponds roughly to the slope on the non-linear scale in the real \LambdaCDM Universe, but \LambdaCDM contains much less initial small-scale power -- not enough to bootstrap the small starting dispersion up to a significant value within linear theory (viewed very broadly, structure formation has actually taken place rather suddenly and recently, in spite of the usual "hierarchical" description). The next order PT calculation, which I carry out only at an order of magnitude level, should drive the dispersion up into balance with the growing structure, accounting for small dispersion effects seen recently in simulations.

… with partial success!

Common theme: Accommodate a nonzero average velocity dispersion

$\Downarrow$

Improvement over SPT



Shell-crossing

Our phase-space approach

- $$f(t,\vec{x},\vec{p}) = \bar{f}(t,p) + \delta f(t,\vec{x},\vec{p})$$

- $$\frac{\partial f}{\partial t} + \vec{p}\cdot\frac{\partial \phi}{\partial \vec{x}} = \frac{\partial \phi}{\partial \vec{x}}\cdot\frac{\partial f}{\partial \vec{q}}$$

$$\frac{\partial \bar{f}}{\partial t} = \left\langle \frac{\partial \phi}{\partial \vec{x}}\cdot\frac{\partial f}{\partial \vec{q}} \right\rangle$$

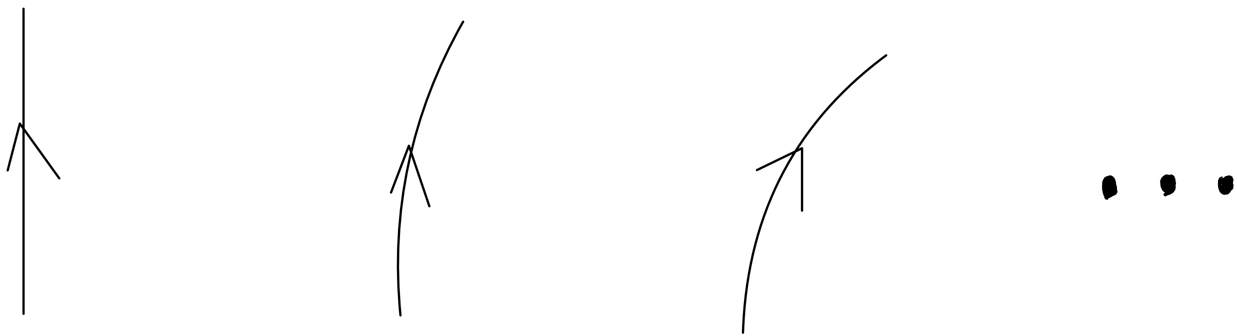
$$\frac{\partial \delta f}{\partial t} + \vec{q}\cdot\frac{\partial \delta f}{\partial \vec{x}} = :\frac{\partial \phi}{\partial \vec{x}}\cdot\frac{\partial f}{\partial \vec{q}}:$$

Normal ordering = Average subtraction

- Iterative solution: NO apriori assumptions about stress

Physical interpretation

$$\ddot{x}(t) = g(x(t)) \quad \longrightarrow \quad x(t) = x_0 + v_0 t + \int_0^t dt' \int_0^{t'} dt'' g(x(t''))$$



0-th order

1st order

$$\sim \left(\frac{dg}{dx}\right)^0$$

2nd order

$$\sim \left(\frac{dg}{dx}\right)^1$$

First step

- $$\frac{\partial \bar{f}}{\partial t} = \left\langle \frac{\partial \phi}{\partial \vec{x}} \cdot \frac{\partial f}{\partial \vec{q}} \right\rangle$$

$$\frac{\partial \delta f}{\partial t} + \vec{q} \cdot \frac{\partial \delta f}{\partial \vec{x}} = \, : \frac{\partial \phi}{\partial \vec{x}} \cdot \frac{\partial f}{\partial \vec{q}} :$$

SPT

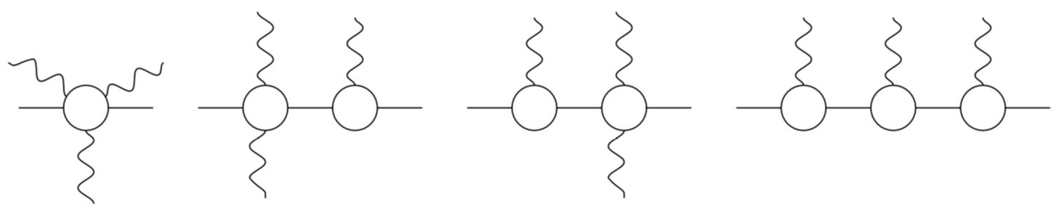


Figure 7. Four diagrams contribute to the distribution function fluctuation at third order in perturbation theory.

FYI: Our paper is a good reference for numerical calculations in SPT beyond EdS kernels!

$$s_1^{(3)} = \frac{fD_{\rm L}}{a}\frac{dc_1^{(2)}}{da} + \frac{fD_{\rm L}}{a^2}\left(2+f+\frac{d\log H}{d\log a}+\frac{d\log f}{d\log a}\right)c_1^{(2)}$$
$$s_2^{(3)} = \frac{fD_{\rm L}}{a}\frac{dc_2^{(2)}}{da} + \frac{fD_{\rm L}}{a^2}\left(2+f+\frac{d\log H}{d\log a}+\frac{d\log f}{d\log a}\right)c_2^{(2)}$$
$$s_3^{(3)} = \frac{3}{2}\Omega_{\rm m,0}H_0^2\frac{D_{\rm L}c_1^{(2)}}{a^5H^2} + \frac{fD_{\rm L}}{a}\frac{dc_1^{(2)}}{da} - \frac{f^2D_{\rm L}^3}{a^2}$$
$$s_4^{(3)} = \frac{3}{2}\Omega_{\rm m,0}H_0^2\frac{D_{\rm L}c_2^{(2)}}{a^5H^2} + \frac{fD_{\rm L}}{a}\frac{dc_2^{(2)}}{da} + \frac{f^2D_{\rm L}^3}{a^2}$$
$$s_5^{(3)} = 2\frac{fD_{\rm L}}{a}\frac{dc_1^{(2)}}{da} - 2\frac{f^2D_{\rm L}^3}{a^2}$$
$$s_6^{(3)} = 2\frac{fD_{\rm L}}{a}\frac{dc_2^{(2)}}{da}\,.$$

Cosmological perturbation theory for large-scale structure in phase space
2410.05389

Eq.(3.38) admits a simple analytic solution (derived in Appendix A)

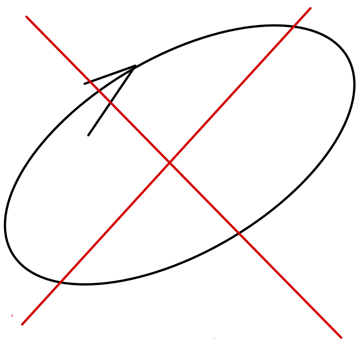
$$c_i^{(3)}(a) = H(a)\int_0^a \frac{da'}{(a')^3H^3(a')}\int_0^{a'} da''(a'')^3H^2(a'')s_i^{(3)}(a'')\,.$$

$$P_{22}(a,k) = \sum_{i=1}^{2}\sum_{j=1}^{2} c_i^{(2)}(a)c_j^{(2)}(a)\langle h_i^{(2)}(\vec{k})h_j^{(2)}(-\vec{k})\rangle' \equiv \sum_{i=1}^{2}\sum_{j=1}^{2} c_i^{(2)}(a)c_j^{(2)}(a)\Sigma_{ij}(k)\,,$$

where $\Sigma_{ij}(k) = \langle h_i^{(2)}(\vec{k})h_j^{(2)}(-\vec{k})\rangle'$ and the time-dependent coefficients $c_i^{(2)}(a)$ follow from Eqs.(and (3.34). We obtain from Eq.(3.31):

$$\Sigma_{11}(k) = \frac{1}{2}k^3\int_0^\infty \frac{dx}{2\pi^2}\int_{-1}^1\frac{dt}{2}\frac{(t+x-2xt^2)^2}{(1-2xt+x^2)^2}P_{\rm L}(kx)P_{\rm L}\left(k\sqrt{1-2xt+x^2}\right)$$
$$\Sigma_{12}(k) = \Sigma_{21}(k) = \frac{1}{2}k^3\int_0^\infty \frac{dx}{2\pi^2}\int_{-1}^1\frac{dt}{2}\frac{(t+x-2xt^2)(t-x)}{(1-2xt+x^2)^2}P_{\rm L}(kx)P_{\rm L}\left(k\sqrt{1-2xt+x^2}\right)$$
$$\Sigma_{22}(k) = \frac{1}{2}k^3\int_0^\infty \frac{dx}{2\pi^2}\int_{-1}^1\frac{dt}{2}\frac{(t-x)^2}{(1-2xt+x^2)^2}P_{\rm L}(kx)P_{\rm L}\left(k\sqrt{1-2xt+x^2}\right)\,.$$

Physical interpretation



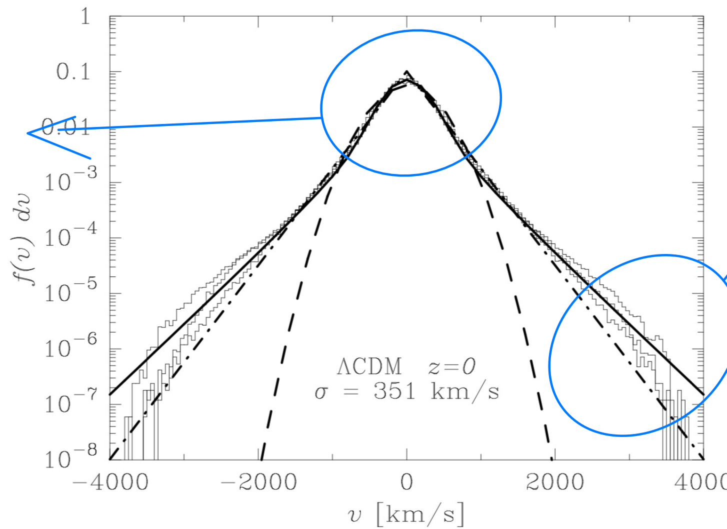
Beyond convergence radius
of iterative solution

Need strong
gravitational fields

- No bound structures
- No shell-crossing

But maybe we can do better?

Bulk flow



Velocity dispersion

EFT-like counterterm.
Does not quite work!

From astro-ph/0009166 - Ravi Sheth and Antonaldo Diaferio

$$\bar{f}(t,q) = \bar{f}^{(0)}(q) + \bar{f}^{(2)}(t,q) + \ldots \quad + \bar{f}^{(\text{ad-hoc})}(t,q)$$

$\propto \delta_{\mathrm{D}}^{(3)}(\vec{q})$

CDM

Perturbative backreactions

Nonperturbative backreactions

First recap

- Cosmological SPT can be formulated entirely at the phase-space level. Vanishing stress is a consequence of the perturbative expansion.

- An EFT-like counterterm naturally emerges when incorporating an ad-hoc nonzero average velocity dispersion. Need the EFT to get it right!

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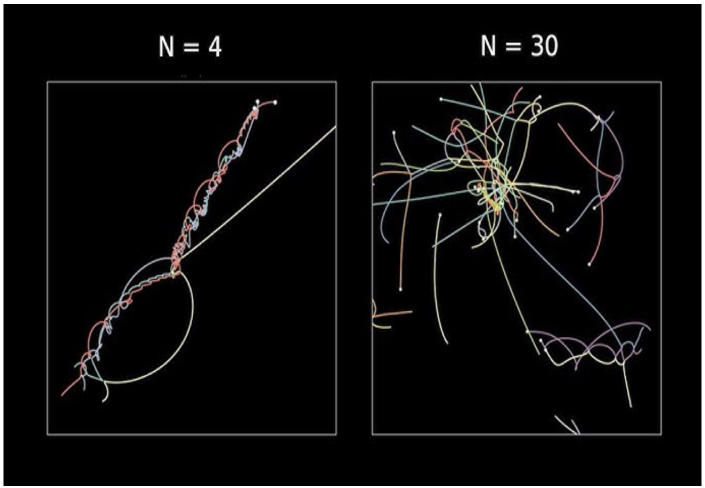
Back to the EFTofLSS



Credit: Snapshot from https://www.youtube.com/watch?v=ijxwdV_ZWnc

$$R = \Lambda^{-1}$$

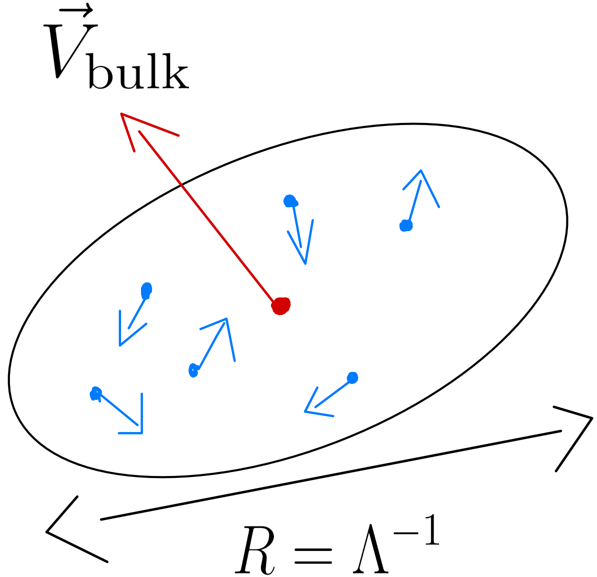
Smoothing

Credit: https://www.thoughtco.com/what-is-fluid-dynamics-4019111

$$\phi_s = \phi - \phi_l \implies \tau_{ij}^{\text{eff}}$$

Top-down effective stress: $\tau^{\rm eff} = 2K + U$

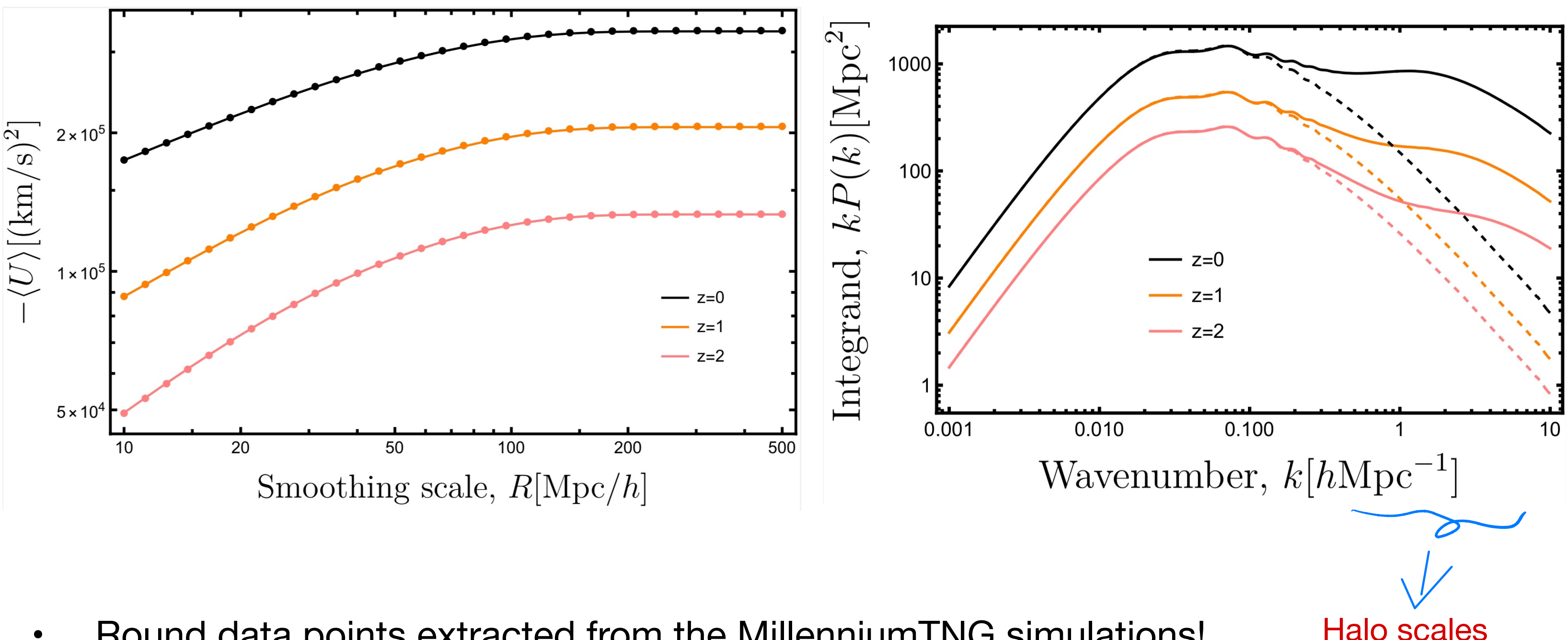
J.J. Carrasco, M.P. Hertzberg and L.Senatore. 1206.2926



OBS: Virialized structures decouple!

The Large-scale Structure of the Universe
Peebles, arxiv:0910/5142

Average gravitational energy



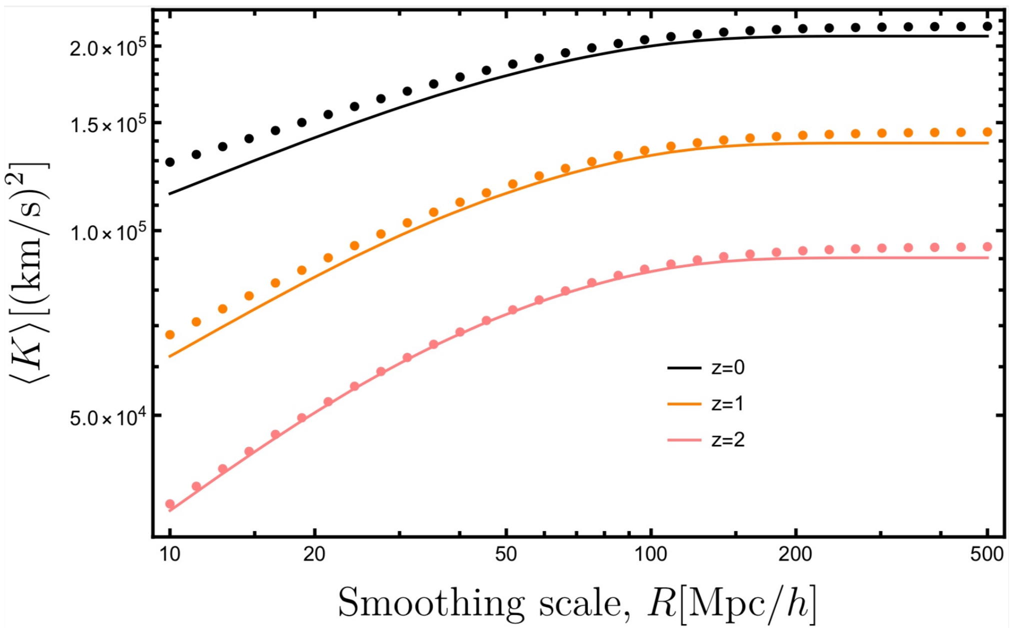
- Round data points extracted from the MillenniumTNG simulations!

The MillenniumTNG Project: High-precision predictions for matter clustering and halo statistics
arxiv: 2210.10059

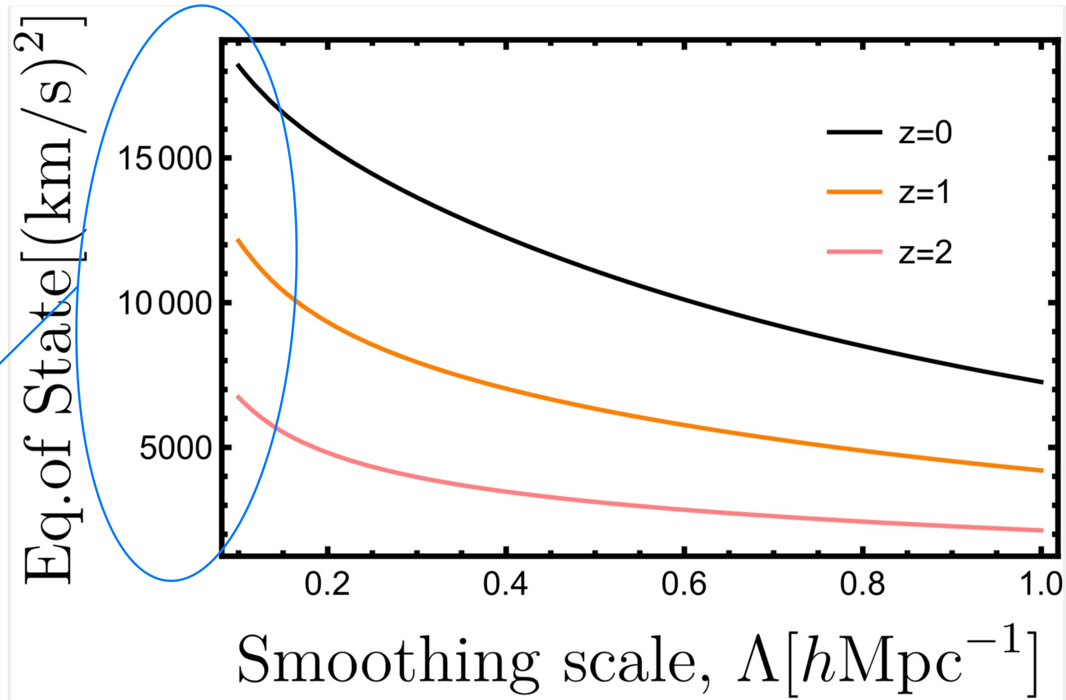
Average kinetic energy

- $$\frac{d}{dt}(\langle K\rangle + \langle U\rangle) + H(2\langle K\rangle + \langle U\rangle) = 0 \longrightarrow$$ Reconstruct $\langle K\rangle$

Layzer-Irvine (1960's)



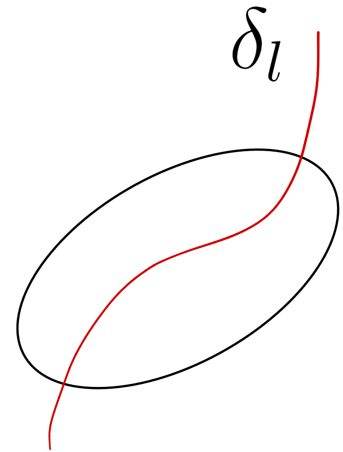
Equation of state



Suppressed!

Effective sound speed

- $$\partial^i \left(\frac{1}{\rho_l} \partial^j \tau^{\mathrm{eff}}_{ij} \right) = c^2_{\mathrm{eff}}(a) \nabla^2 \delta_l + \ldots$$

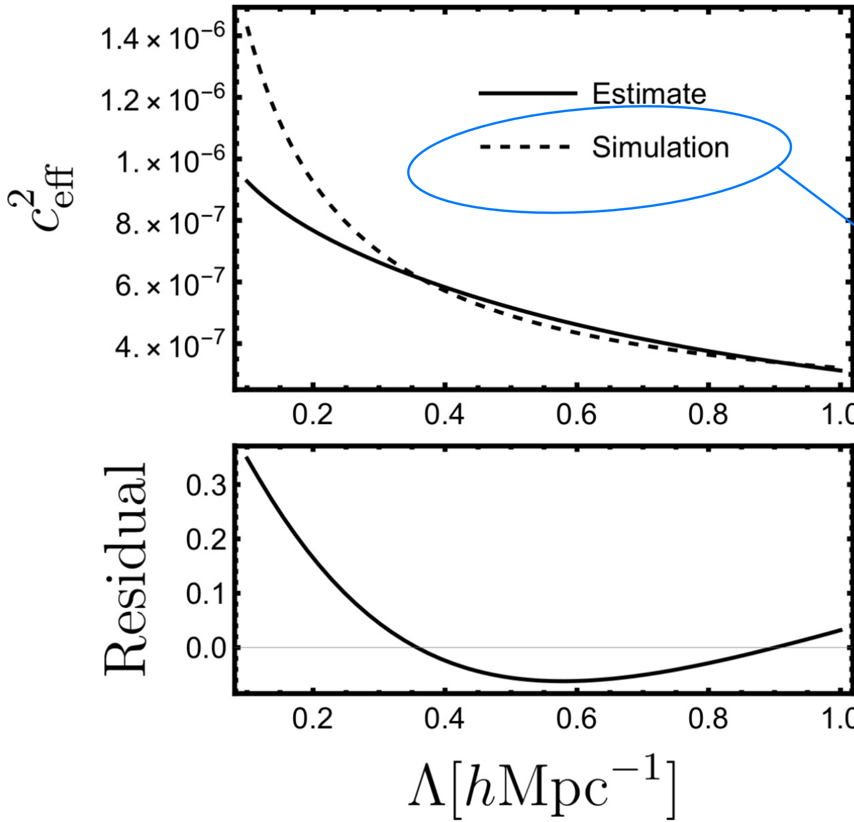


Tidal effects: Coupling of short and long modes

- $$\langle \tau^{\mathrm{eff}} \rangle_{\delta_l} = \langle \tau^{\mathrm{eff}} \rangle_{\delta_l = 0} + \left. \frac{\partial \langle \tau^{\mathrm{eff}} \rangle_{\delta_l}}{\partial \delta_l} \right|_{\delta_l = 0} \delta_l + \mathcal{O}(\delta_l^2)$$

Separate universe methods

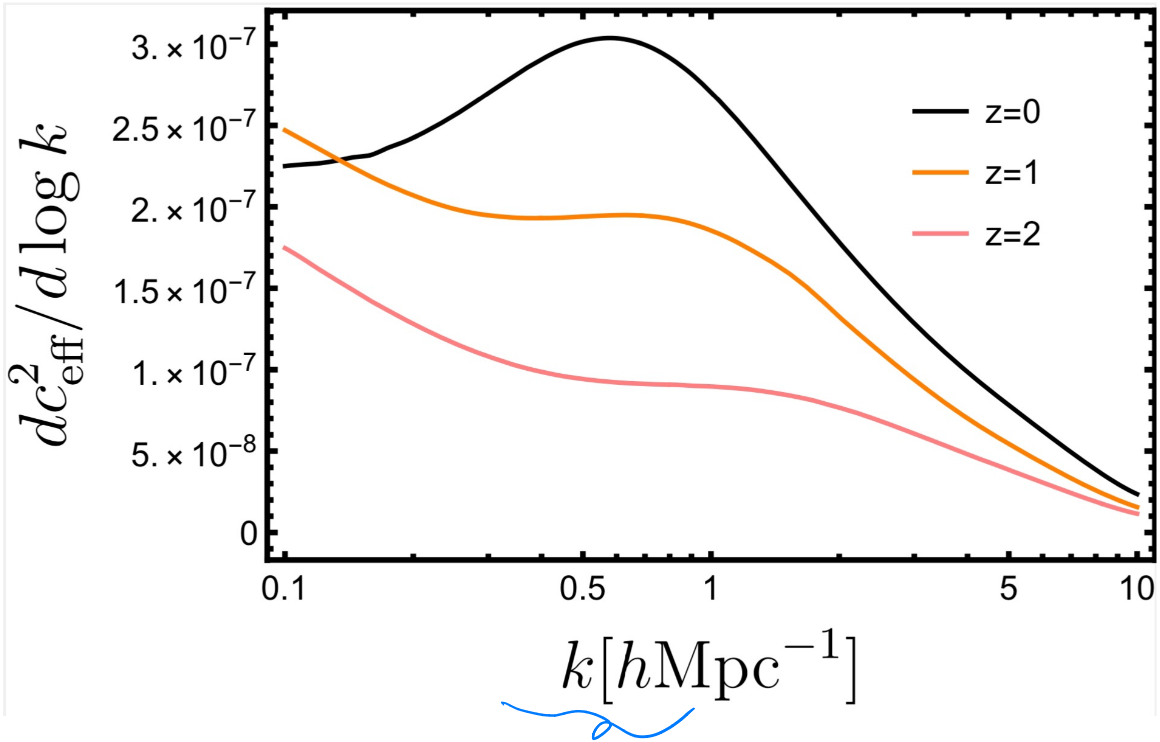
Comparison to simulation results



Precision Comparison of the Power Spectrum in the EFTofLSS with Simulations
Simon Foreman, Hideki Perrier, Leonardo Senatore
arxiv: 1507.05326

- Can also extract the time dependence

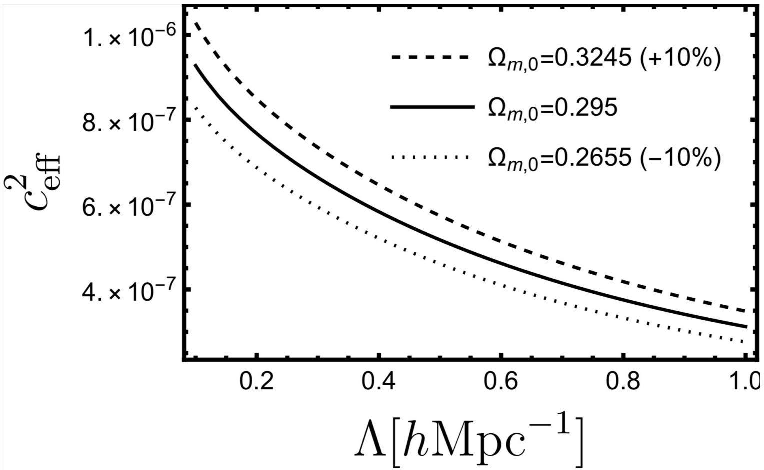
What cosmic structures contribute the most?



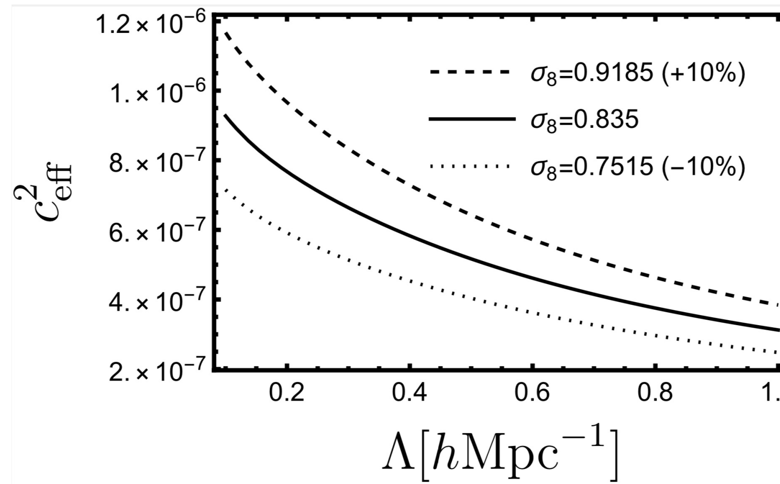
Sheets and filaments

Cosmological information?

$$c^2_{\text{eff}} \sim \Omega_{\text{m},0}^{1.1-1.2}$$



$$c^2_{\text{eff}} \sim \sigma_8^{2.2-2.5}$$



The EFT of Large Scale Structures at All Redshifts: Analytical Predictions for Lensing
Simon Foreman and Leonardo Senatore
arxiv:1503.01775

→ Strong dependence on amplitude of fluctuations from simulations!

Second recap

- The cosmic energy equation is very powerful, and connects the kinetic and potential contributions to the effective stress tensor

- The EFT counterterm can be estimated from short-distance fluctuations using simple analytical methods. The agreement to simulations is remarkable!

- The approach can be used to interpret both the cosmological and short-scale informations encoded in the counterterm.

Outline

1. Introduction (5 pages)

2. Effective field theory of large scale structure (EFTofLSS) (4 pages)

3. Can we get away without the EFT? Yes, but not really… (11 pages)

4. Can we understand the speed of sound from the microphysics of short scale fluctuations? Yes!! (12 pages)

5. Final remarks (1 page)

Conclusion

- Large-scale structure SPT can be formulated directly at the phase-space level. Vanishing stress is a consequence of the perturbative expansion.

- Accounting for backreations from nonperturbative short-distance scales into the background distribution function produces an EFT-like counterterm, but the full EFTofLSS framework is still necessary.

- Separate universe methods open a new window into the effective sound speed counterterm, one that enables interpretability.

- Future developments? Anisotropic separate universe, field level investigation, thorough comparisons to existing methods…

Thank you!!

Bonus…

Can improve upon SPT

$$\cancel{\frac{\partial \bar{f}}{\partial t} = \left\langle \frac{\partial \phi}{\partial \vec{x}} \cdot \frac{\partial f}{\partial \vec{q}} \right\rangle}$$

- $$\frac{\partial \delta f}{\partial t} + \vec{q} \cdot \frac{\partial \delta f}{\partial \vec{x}} = : \frac{\partial \phi}{\partial \vec{x}} \cdot \frac{\partial f}{\partial \vec{q}} :$$

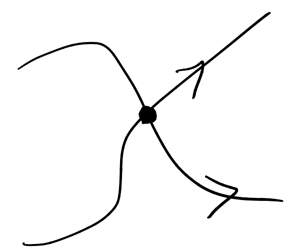
$$\longrightarrow \Delta P_{\text{1-loop}}(z,k) \sim -\sigma^2_{\text{dis}}(z) k^2 P_{\text{L}}(k)$$

Same as EFT Methods!

Mathias Garny et al (2210.08089)

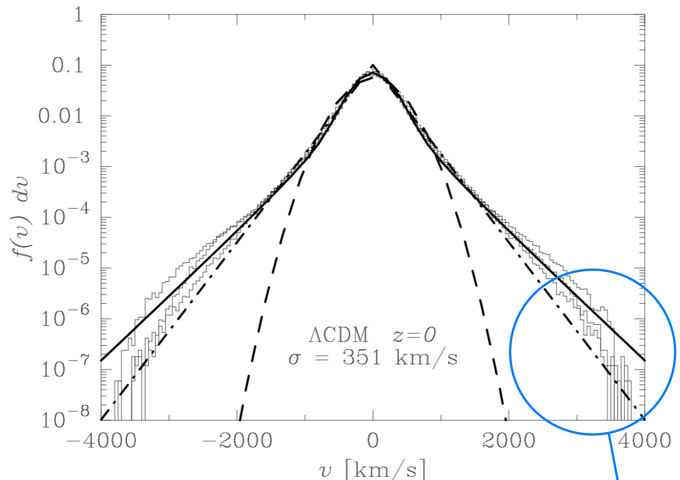
Alejandro Aviles (1512.07198)

Patrick McDonald (1709.02834)



Shell-crossing

Things are not so simple…



From astro-ph/0009166 - Ravi Sheth and Antonaldo Diaferio

Mostly from virialized halos

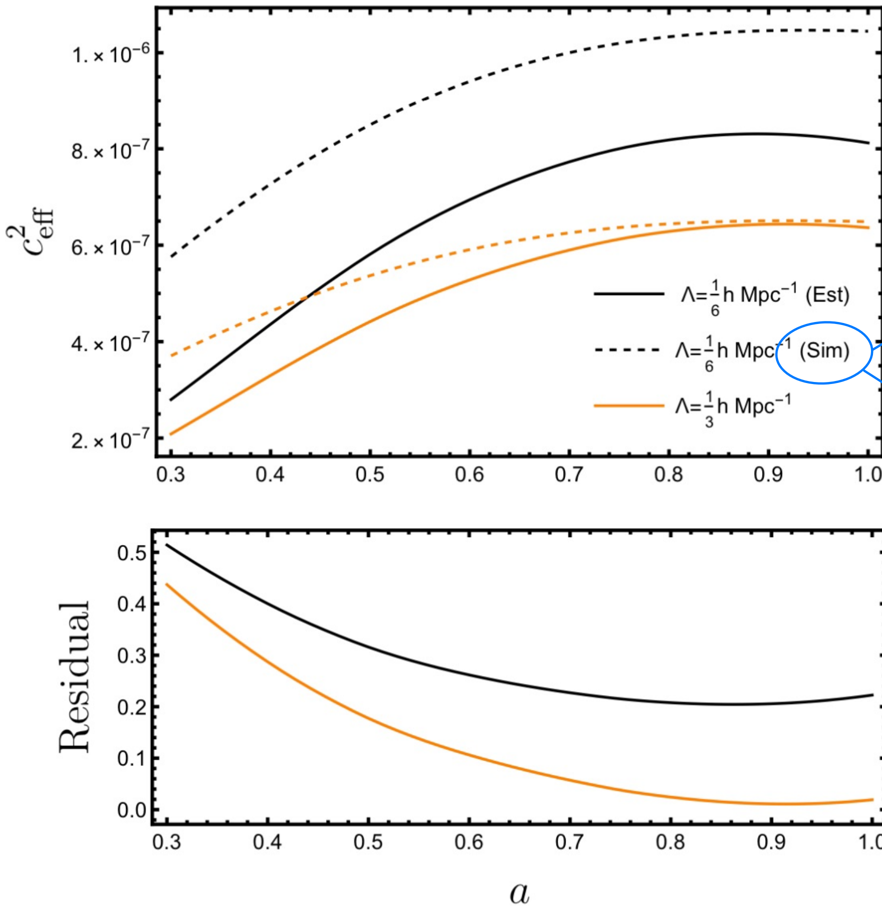
$$\sigma^2_{\rm dis}$$

Decoupling of virialized scales??

Inconsistency!

The Large-scale Structure of the Universe
Peebles, arxiv:0910/5142

Time dependence



Precision Comparison of the Power Spectrum in the EFTofLSS with Simulations
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arxiv: 1507.05326

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On the Renormalization of the Effective Field Theory of Large Scale Structures
Enrico Pajer and Matias Zaldarriaga
arxiv: 1301.7182