Title: The speed of sound in the EFTofLSS

Speakers: Caio Nascimento

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

Date: December 10, 2024 - 11:00 AM

URL: https://pirsa.org/24120022

Abstract:

The Effective Field Theory of Large Scale Structure (EFTofLSS) has found tremendous success as a perturbative framework for the evolution of large scale structure, and it is now routinely used to compare theoretical predictions against cosmological observations. The model for the total matter field includes one nuisance parameter at 1-loop order, the effective sound speed, which can be extracted by matching the EFT to full N-body simulations. In this talk we explore two different directions related to the effective sound speed. We first show that its emergence can be understood even without effective field theory ingredients, through a perturbative framework that solves the Vlasov-Poisson system of equations directly in phase space. However, we will argue that the EFT is necessary to ensure self-consistency. We then discuss how one can estimate the effective sound speed, via separate universe techniques, with analytic calculations. The estimate is in good agreement with simulation results, and we show it can be used to extract the cosmology dependence of the effective sound speed and to shed light on what cosmic structures shape its value.

The speed of sound in the EFTofLSS

A semi-analytic estimate for the effective sound speed counterterm in the EFTofLSS (2410.11949)
Cosmological perturbation theory for large scale structure in phase space (2410.05389)

with Marilena Loverde, Matt McQuinn and Drew Jamieson

Caio Nascimento

Perimeter Institute

Dec 10

Outline

1. $\boxed{\text{Motivation}}$

2. A short summary of the EFTofLSS

3. Emergence of the speed of sound in phase-space

4. Extracting the microphysics behind the speed of sound

5. Final remarks

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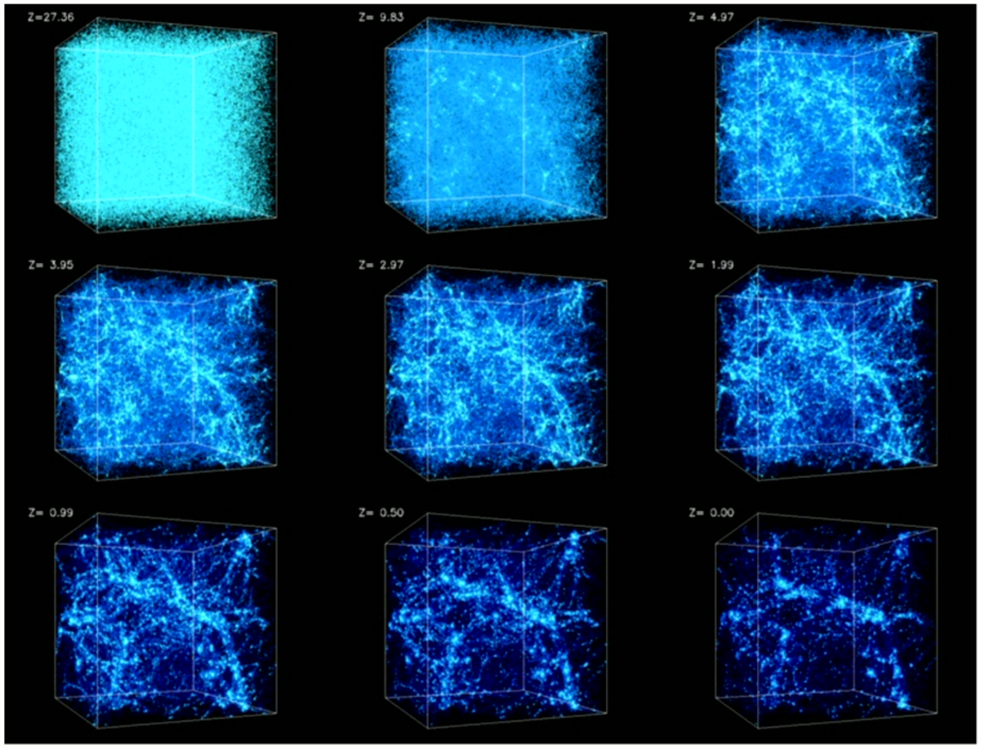
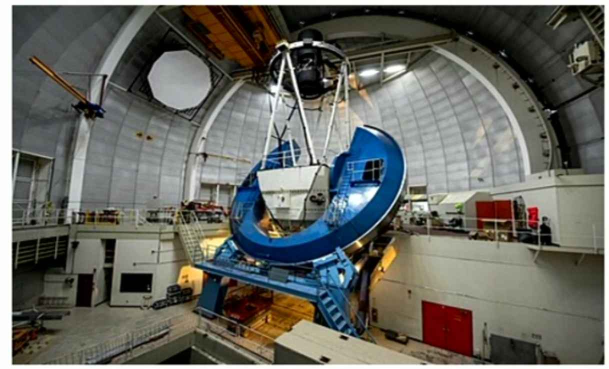
The goal is to learn new physics…

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

Euclid

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… via cosmological parameters!

- Axion mass and coupling to photons

Axion-Induced Patchy Screening of the Cosmic Microwave Background (2405.08059)
Cristina Mondino et al.

- Dynamics of dark energy

DESI 2024 VII: Cosmological Constraints from the Full-Shape Modeling of Clustering Measurements (2411.12022)
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.

Early this year!

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, $k \sim (10^{-3} - 10)\mathrm{Mpc}^{-1}$. 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

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Can't do it without nuisance parameters as well

Familiar example:

$$\frac{\delta n_{\rm g}}{\bar{n}_{\rm g}} = \sum_i b_i \mathcal{O}_i$$

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

Cosmological information

+

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

- Perturbative scales, NO baryonic effects or galaxies

Power spectrum in Standard Perturbation Theory

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

EFT Power spectrum

Speed of sound

Questions we want to answer

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

Valuable intuition

Need to control short-distance fluctuations

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

Cosmology dependence

Short-distance nonlinear evolution

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1. Motivation

2. $\boxed{\text{2. A short summary of the EFTofLSS}}$

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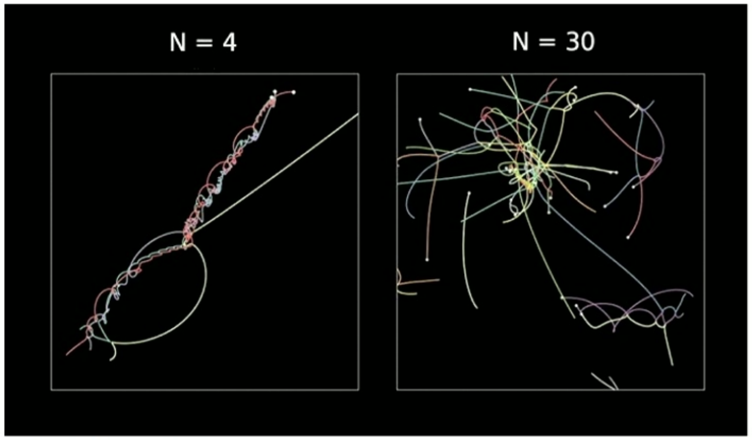
A particle physicist tool: EFT

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



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

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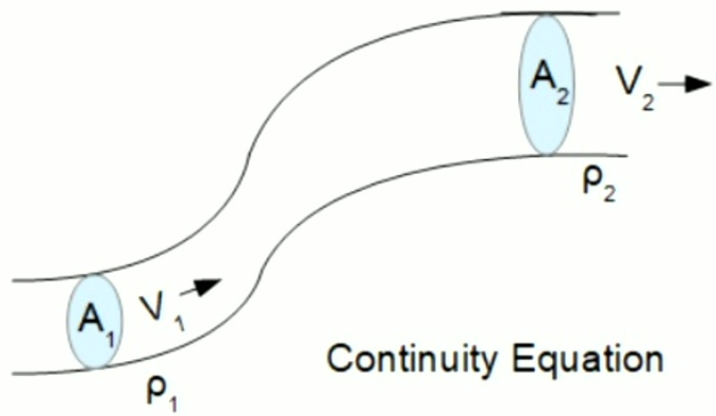
Dynamics of the effective fluid

- 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

Dissipative forces

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Bottom-up effective stress

- SPT: Vanishing by assumption!

$$\tau_{ij}^{\text{eff}} \equiv 0$$

Perturbative expansion in fluctuations:

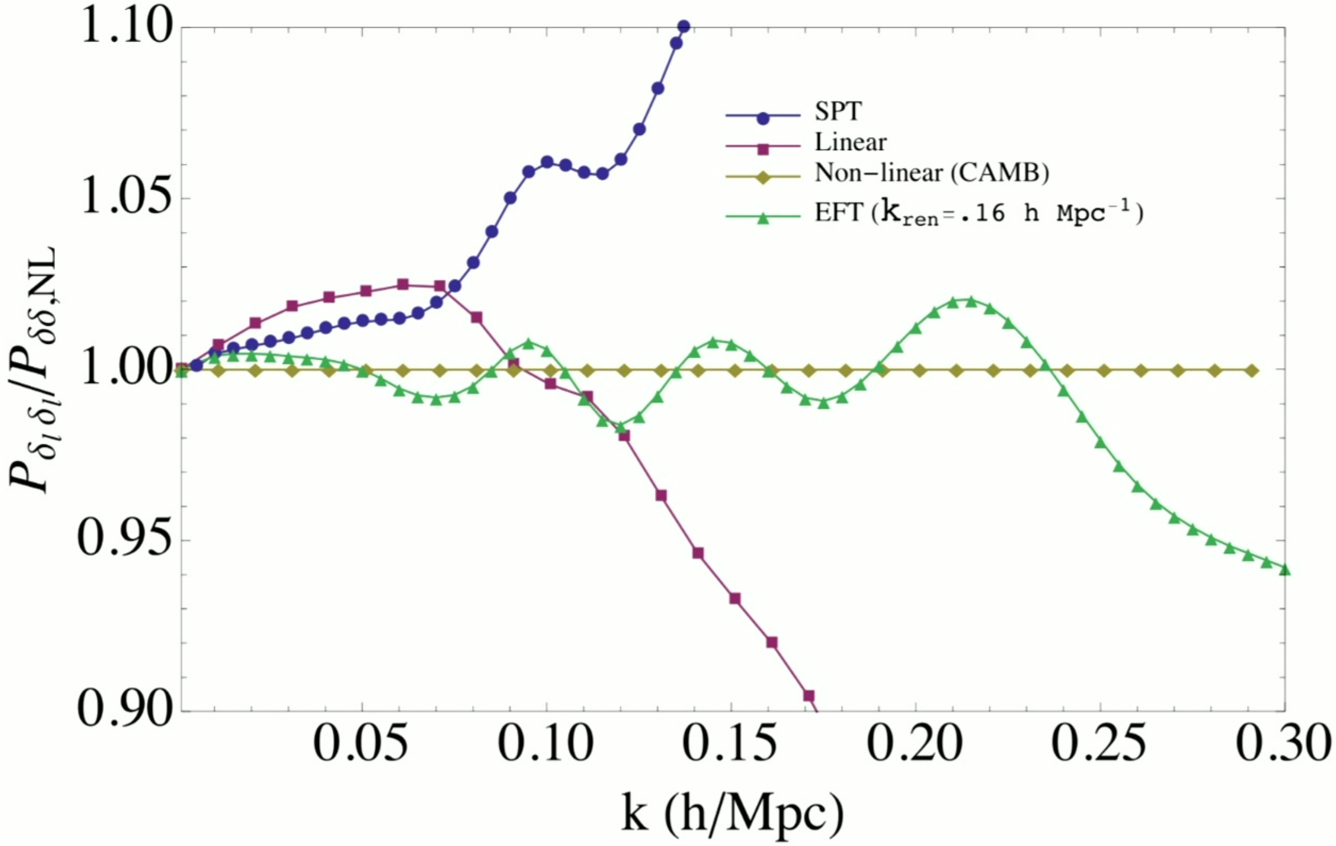
$$\delta_l \, , \, \vec{v}_l$$

- EFT: All terms allowed by symmetries

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

Free nuisance parameter

The success of the EFT approach



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

Outline

1. Motivation
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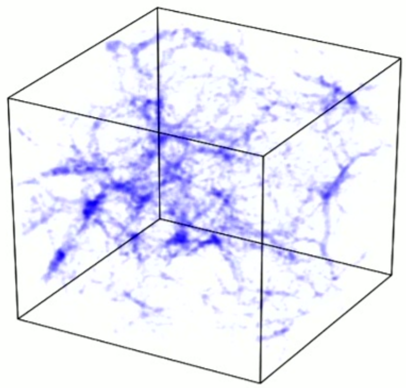
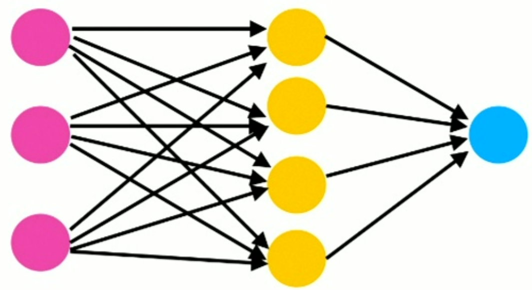
Is the free parameter really necessary?

-  Credit: 1908.05519 +  Credit: https://becominghuman.ai/understanding-the-structure-of-neural-networks-1fa5bd17fef0 = Fast, accurate predictions

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

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People have tried really hard…

[Submitted on 1 Dec 2010 (v1), last revised 20 Oct 2011 (this version, v2)]

The Helmholtz Hierarchy: Phase Space Statistics of Cold Dark Matter

Svetlin Tassev

We present a new formalism to study large-scale structure in the universe. The result is a hierarchy (which we call the "Helmholtz Hierarchy") of equations describing the phase space statistics of cold dark matter (CDM). The hierarchy features a physical ordering parameter which interpolates between the Zel'dovich approximation and fully-fledged gravitational interactions. The results incorporate the effects of stream crossing. We show that the Helmholtz hierarchy is self-consistent and obeys causality to all orders. We present an interpretation of the hierarchy in terms of effective particle trajectories.

[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 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 14 Oct 2022]

Perturbation theory with dispersion and higher cumulants: non-linear regime

Mathias Garny, Dominik Laxhuber, Roman Scoccimarro

We present non-linear solutions of Vlasov Perturbation Theory (VPT), describing gravitational clustering of collisionless dark matter with dispersion and higher cumulants induced by orbit crossing. We show that VPT can be cast into a form that is formally analogous to standard perturbation theory (SPT), but including additional perturbation variables, non-linear interactions, and a more complex propagation. VPT non-linear kernels have a crucial decoupling property: for fixed total momentum, the kernels becomes strongly suppressed when any of the individual momenta cross the dispersion scale into the non-linear regime. This screening of UV modes allows us to compute non-linear corrections to power spectra even for cosmologies with very blue power-law input spectra, for which SPT diverges. We compare predictions for the density and velocity divergence power spectra as well as the bispectrum at one-loop order to N-body results in a scaling universe with spectral indices $-1 \leq n_s \leq +2$. We find a good agreement up to the non-linear scale for all cases, with a reach that increases with the spectral index n_s. We discuss the generation of vorticity as well as vector and tensor modes of the velocity dispersion, showing that neglecting vorticity when including dispersion would lead to a violation of momentum conservation. We verify momentum conservation when including vorticity, and compute the vorticity power spectrum at two-loop order, necessary to recover the correct large-scale limit with slope $n_w = 2$. Comparing to our N-body measurements confirms the cross-over from k^4 to k^2 scaling on large scales. Our results provide a proof-of-principle that perturbative techniques for dark matter clustering can be systematically improved based on the known underlying collisionless dynamics.

[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.

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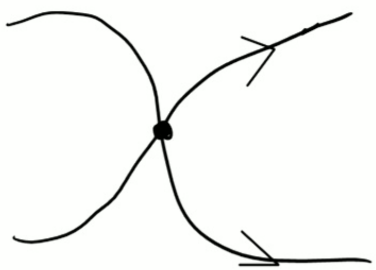
… with partial success!

Common theme: Accommodate a nonzero average velocity dispersion

↓

Improvement over SPT



Shell-crossing

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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

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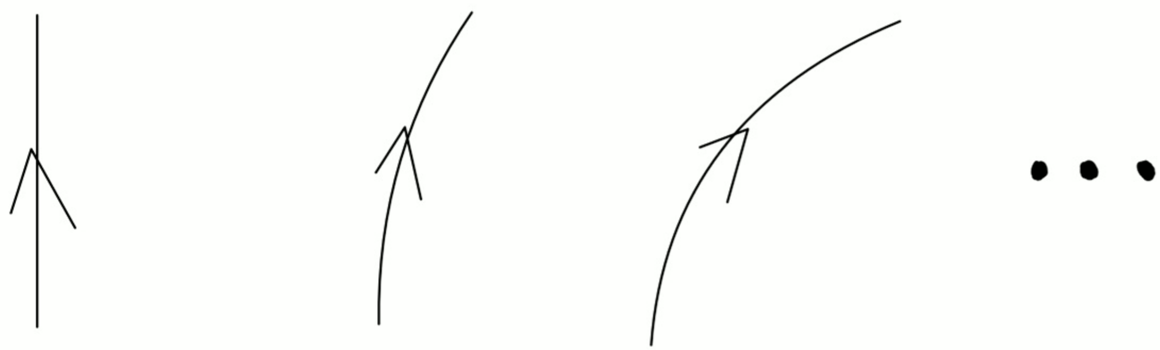
Physical interpretation

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



0-th order

1st order

2nd order

$$\sim \left(\frac{dg}{dx}\right)^0 \quad \sim \left(\frac{dg}{dx}\right)^1$$

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Application #1: Deriving the fluid description

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

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

$\rightarrow$ SPT

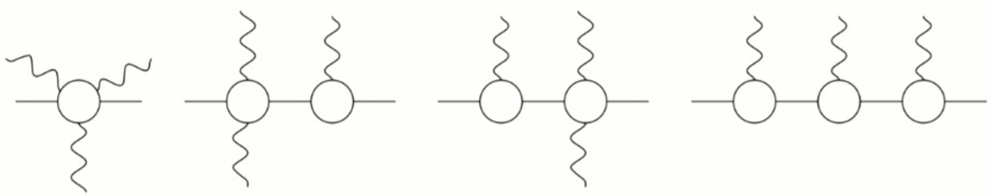


Figure 7. Four diagrams contribute to the distribution function fluctuation at third order in perturbation theory.

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

with new source terms:

$$s_1^{(3)} = \frac{fD_\mathrm{L}}{a}\frac{dc_1^{(2)}}{da} + \frac{fD_\mathrm{L}}{a^2}\left(2 + f + \frac{d\log H}{d\log a} + \frac{d\log f}{d\log a}\right)c_1^{(2)}$$

$$s_2^{(3)} = \frac{fD_\mathrm{L}}{a}\frac{dc_2^{(2)}}{da} + \frac{fD_\mathrm{L}}{a^2}\left(2 + f + \frac{d\log H}{d\log a} + \frac{d\log f}{d\log a}\right)c_2^{(2)}$$

$$s_3^{(3)} = \frac{3}{2}\Omega_{\mathrm{m},0}H_0^2\frac{D_\mathrm{L}c_1^{(2)}}{a^5H^2} + \frac{fD_\mathrm{L}}{a}\frac{dc_1^{(2)}}{da} - \frac{f^2D_\mathrm{L}^3}{a^2}$$

$$s_4^{(3)} = \frac{3}{2}\Omega_{\mathrm{m},0}H_0^2\frac{D_\mathrm{L}c_2^{(2)}}{a^5H^2} + \frac{fD_\mathrm{L}}{a}\frac{dc_2^{(2)}}{da} + \frac{f^2D_\mathrm{L}^3}{a^2}$$

$$s_5^{(3)} = 2\frac{fD_\mathrm{L}}{a}\frac{dc_1^{(2)}}{da} - 2\frac{f^2D_\mathrm{L}^3}{a^2}$$

$$s_6^{(3)} = 2\frac{fD_\mathrm{L}}{a}\frac{dc_2^{(2)}}{da}\,.$$

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

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

$$P_{22}(a,k) = \sum_{i=1}^{2}\sum_{j=1}^{2} c_i^{(2)}(a)c_j^{(2)}(a)\langle h_i^{(2)}(\vec{k})h_j^{(2)}(-\vec{k})\rangle' \equiv \sum_{i=1}^{2}\sum_{j=1}^{2} c_i^{(2)}(a)c_j^{(2)}(a)\Sigma_{ij}(k)\,, \qquad \text{(D.6)}$$

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.(3.33) and (3.34). We obtain from Eq.(3.31):

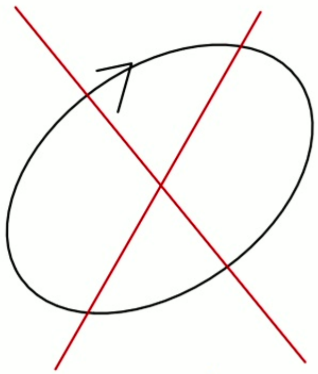
$$\Sigma_{11}(k) = \frac{1}{2}k^3\int_0^\infty \frac{dx}{2\pi^2}\int_{-1}^1 \frac{dt}{2}\frac{(t+x-2xt^2)^2}{(1-2xt+x^2)^2}P_\mathrm{L}(kx)P_\mathrm{L}\left(k\sqrt{1-2xt+x^2}\right)$$

$$\Sigma_{12}(k) = \Sigma_{21}(k) = \frac{1}{2}k^3\int_0^\infty \frac{dx}{2\pi^2}\int_{-1}^1 \frac{dt}{2}\frac{(t+x-2xt^2)(t-x)}{(1-2xt+x^2)^2}P_\mathrm{L}(kx)P_\mathrm{L}\left(k\sqrt{1-2xt+x^2}\right) \qquad \text{(D.7)}$$

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

Cosmological perturbation theory for large scale structure in phase space
2410.05389

Physical interpretation



Beyond convergence radius

Need large gravitational field gradients

- No bound structures
- No shell-crossing

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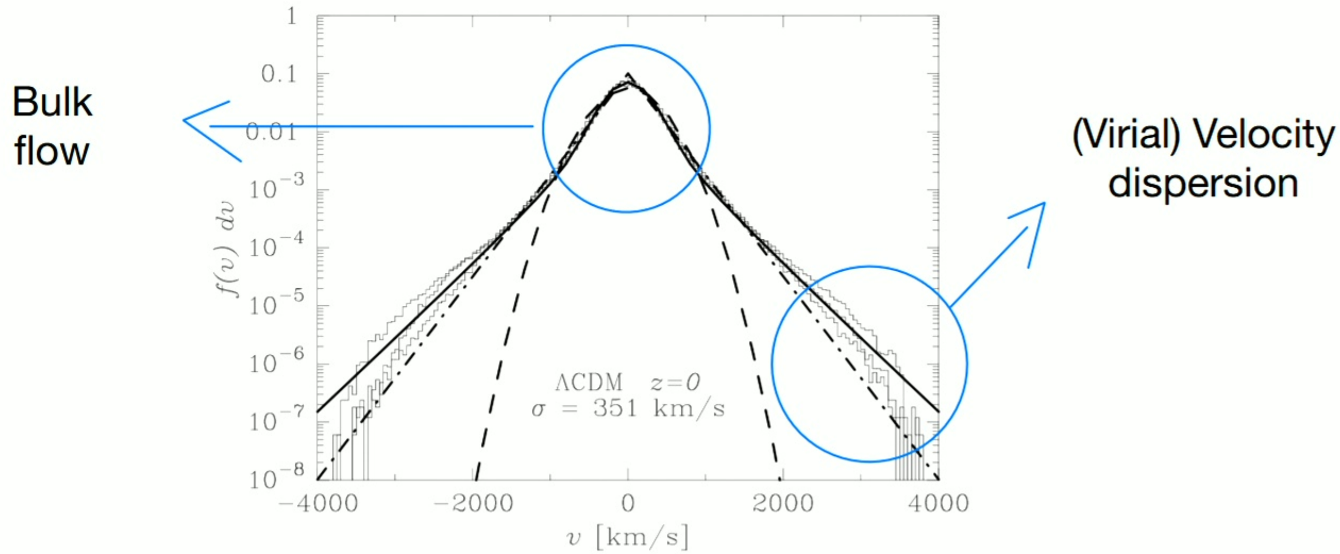
But maybe we can do better?



Credit: astro-ph/0009166 - Ravi Sheth and Antonaldo Diaferio

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

$\propto \delta_D^{(3)}(\vec{q})$

Perturbative backreactions

Non-perturbative backreactions

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Application #2: Emergence of the counterterm

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

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

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

Same as EFT methods!

Mathias Garny, Dominik Laxhuber and Roman Scoccimaro
2210.08089

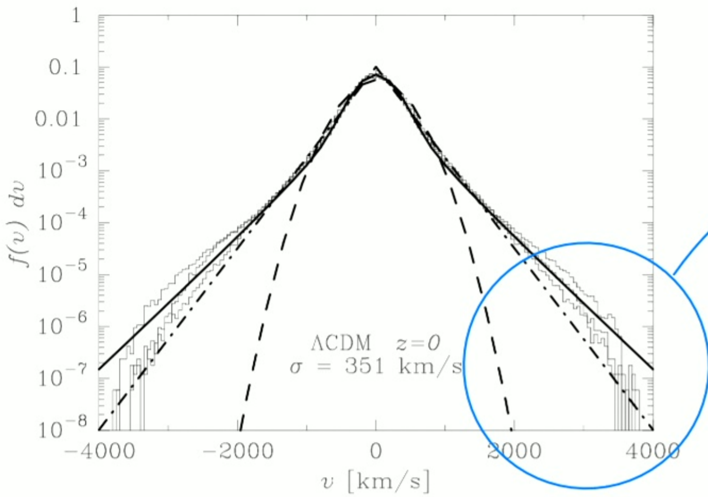
Alejandro Aviles
1512.07198

Patrick McDonald and Zvonimir Vlah
1709.02834

- Right way of thinking about it, BUT…

This cannot be the full story

Credit: astro-ph/0009166 - Ravi Sheth and Antonaldo Diaferio



Mostly from virialized halos

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

Decoupling of virialized scales??

The Large-scale Structure of the Universe
P.J.E. Peebles

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First recap

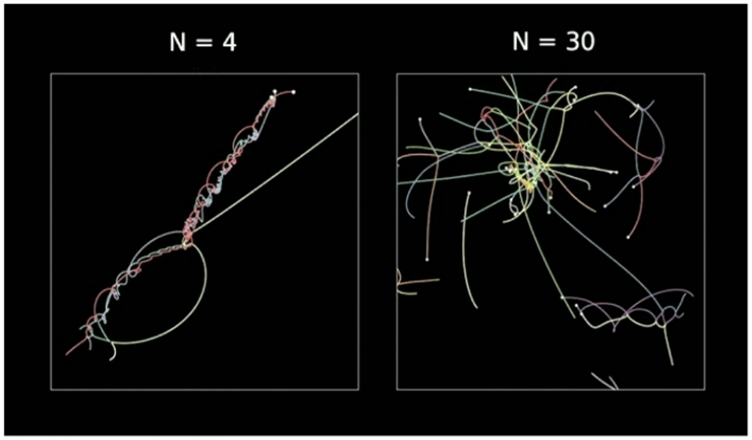
- Cosmological SPT can be formulated entirely at the phase-space level. Vanishing stress is a consequence of the perturbative expansion.

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

Outline

1. Motivation
2. A short summary of the EFTofLSS
3. Emergence of the speed of sound in phase-space
4. Extracting the microphysics behind the speed of sound
5. Final remarks

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

$$\rho_s = \rho - \rho_l \Longrightarrow \tau_{ij}^{\text{eff}} \Longrightarrow c_{\text{eff}}^2$$

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In practice can be avoided

- A bottom-up estimator:

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

$$\Big\downarrow$$

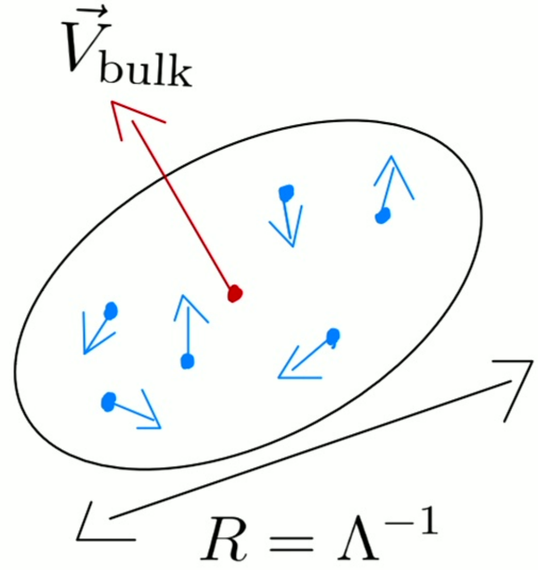
$$\hat{c}^2_{\rm eff}(z) \sim -\lim_{k\to 0} \frac{P^{\rm NL}(z,k) - P^{\rm SPT}_{\text{1-loop}}(z,k)}{k^2 P_{\rm L}(k)}$$

- Very efficient, but also very uninformative!

"Taking the rocky road": Top-down effective stress

$$\tau^{\text{eff}} = 2K + U$$

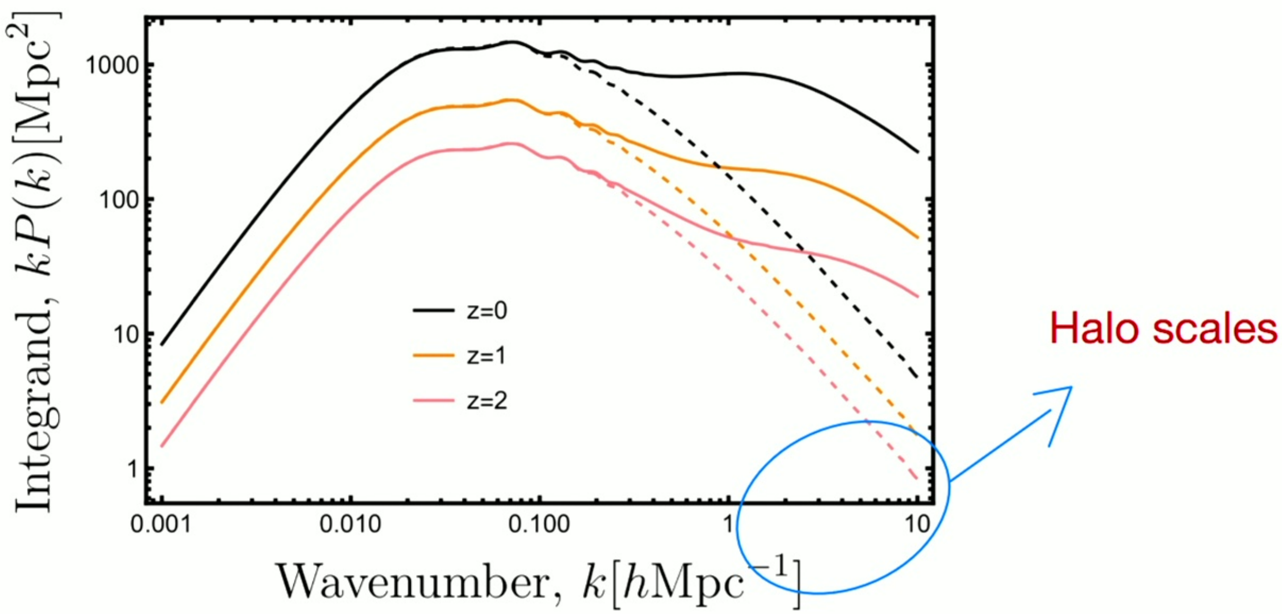
J.J Carrasco, M.P. Hertzberg and L.Senatore
The Effective Field Theory of Cosmological Large Scale Structures
(1206.2926)



OBS: Virialized structures decouple!

Average gravitational energy: Easy to compute

$$\langle U \rangle = \frac{1}{2}\langle \phi_s \delta_s \rangle$$ = Integrate nonlinear power spectrum over short scales!



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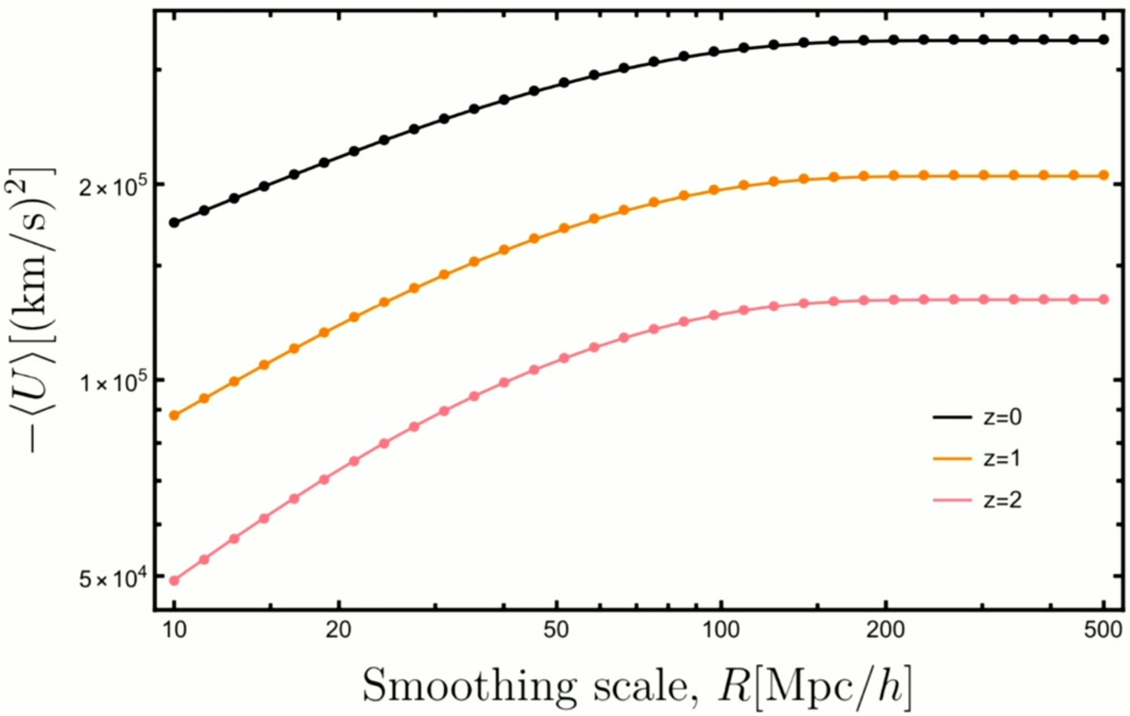
Comparison to simulations



- Round data points extracted from MillenniumTNG simulations!

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

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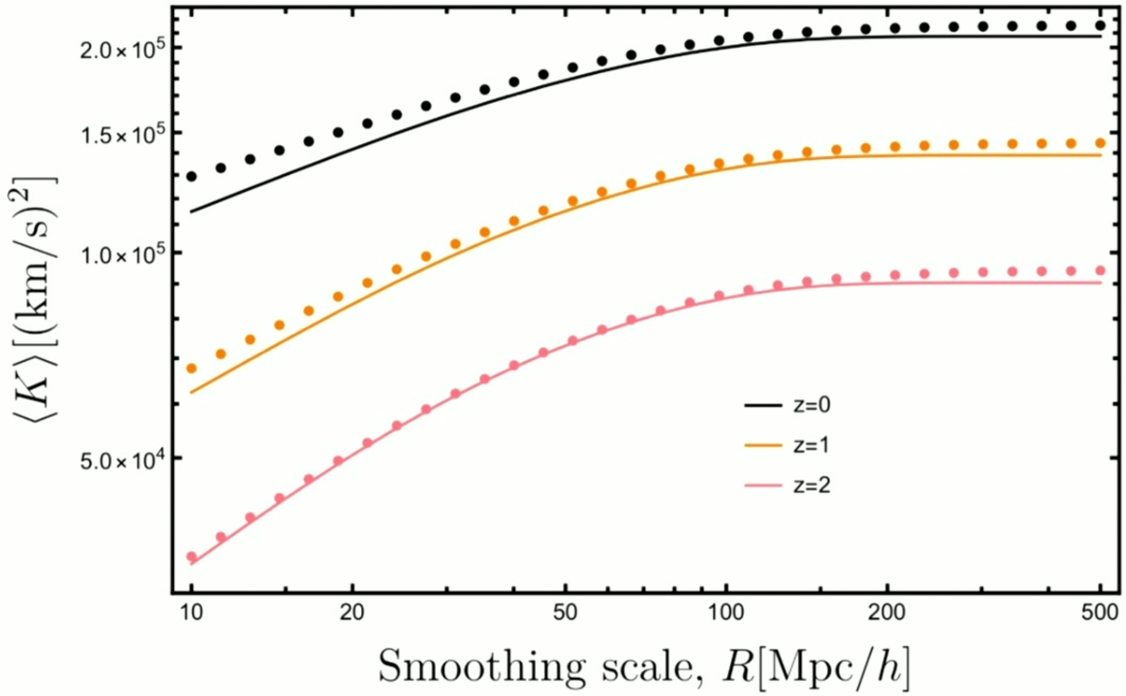
Average kinetic energy

$$\frac{d}{dt}\left[\langle K\rangle + \langle U\rangle\right] + H\left[2\langle K\rangle + \langle U\rangle\right] = 0 \longrightarrow \text{Reconstruct } \langle K\rangle$$

Layzer-Irvine (1960's)



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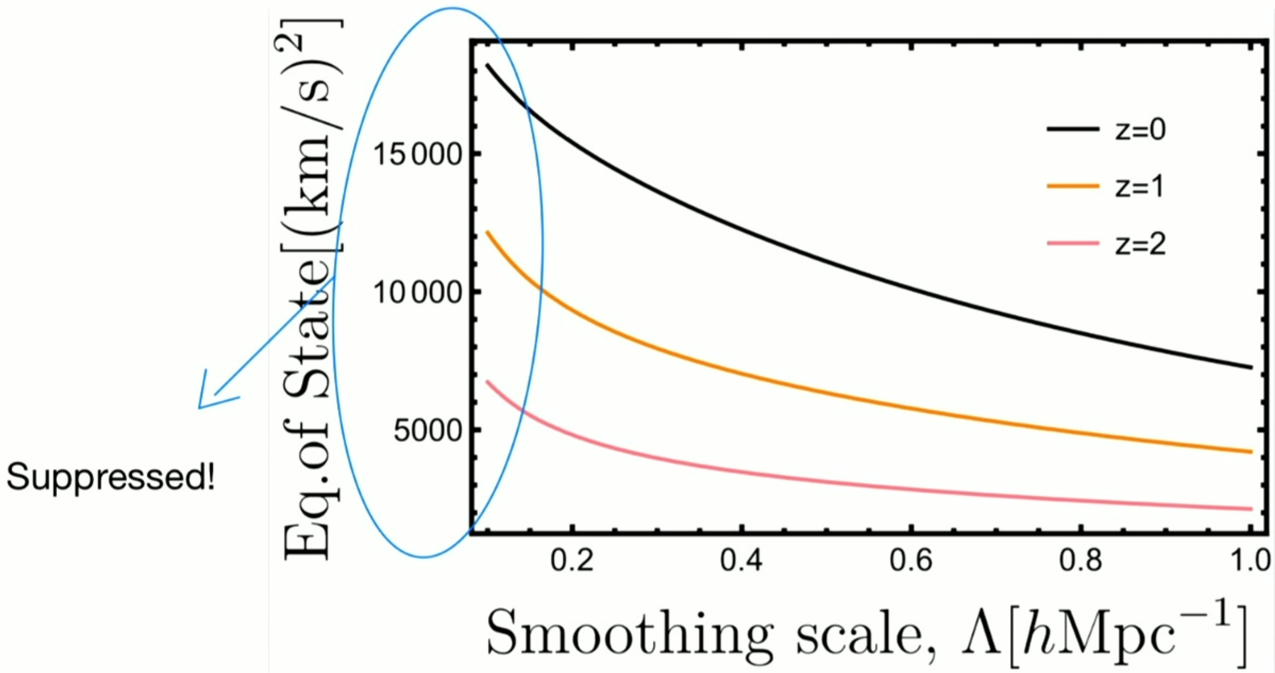
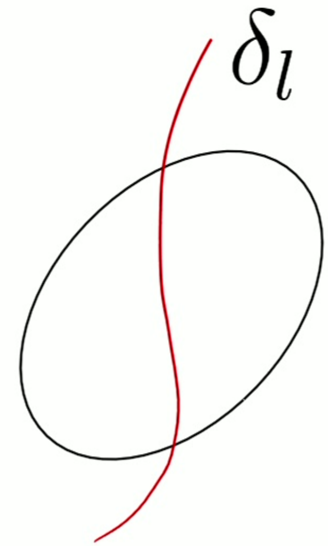
Equation of state: $\omega = \dfrac{\langle \tau^{\mathrm{eff}} \rangle}{3\bar{\rho}}$



Effective sound speed

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



Tidal effects: Coupling of short and long modes

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

Separate universe methods

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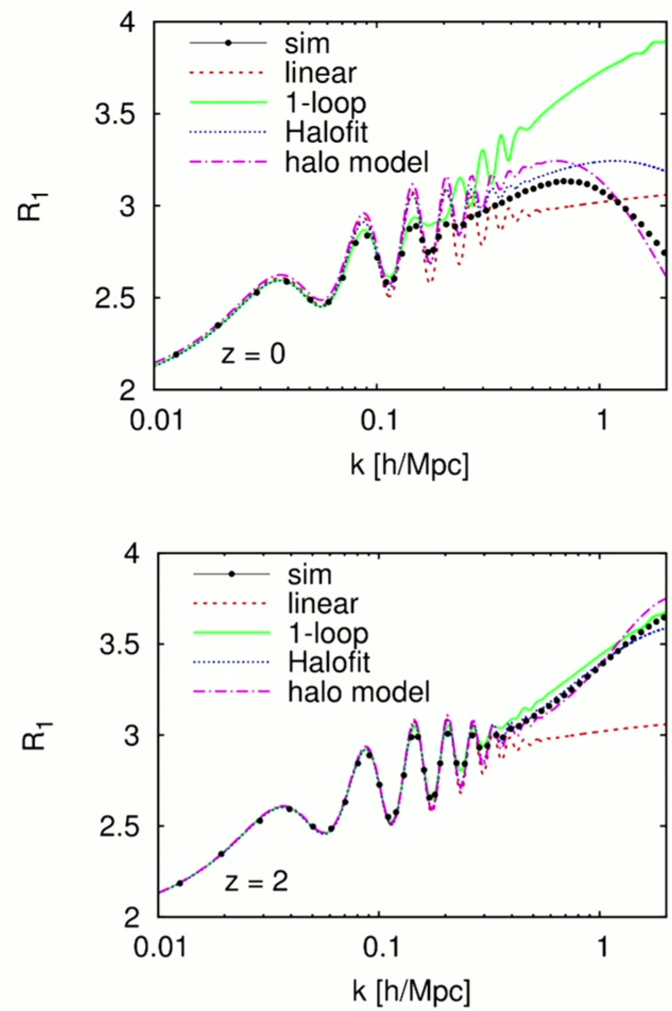
The separate universe

- $\rho_{\rm SU}(t) = \rho(t)\,[1+\delta_l(t)]$

- $R(k) = \dfrac{1}{P(k)} \dfrac{dP(k|\delta_l)}{d\delta_l}\Big|_{\delta_l=0}$

$\Downarrow$

Halo model



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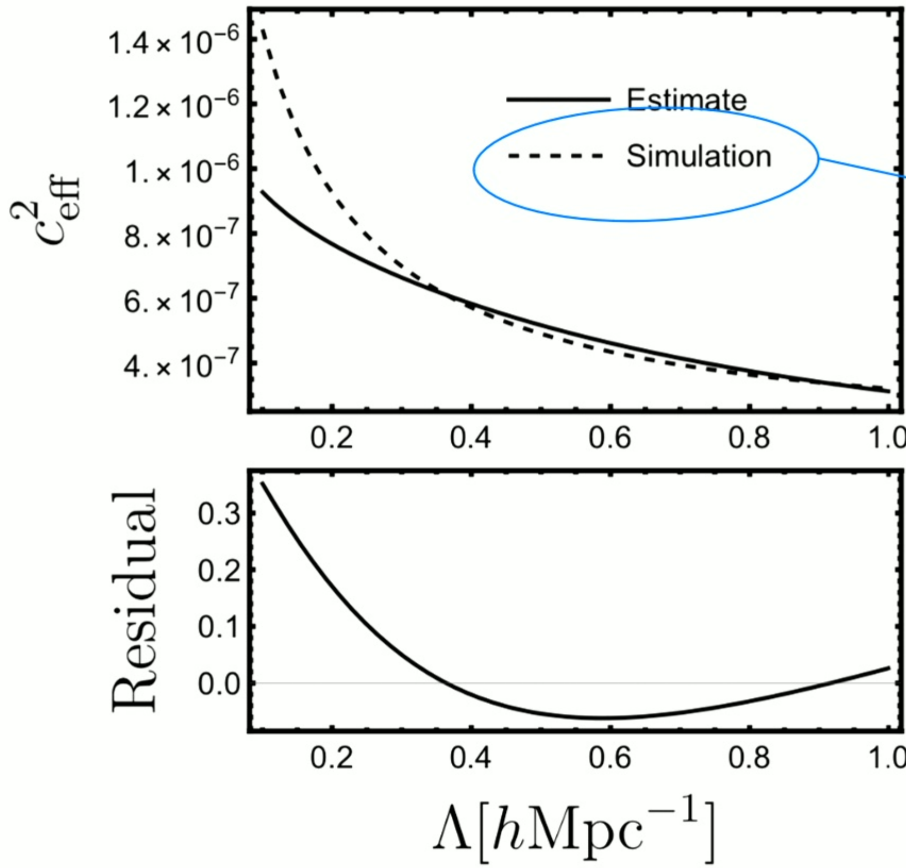
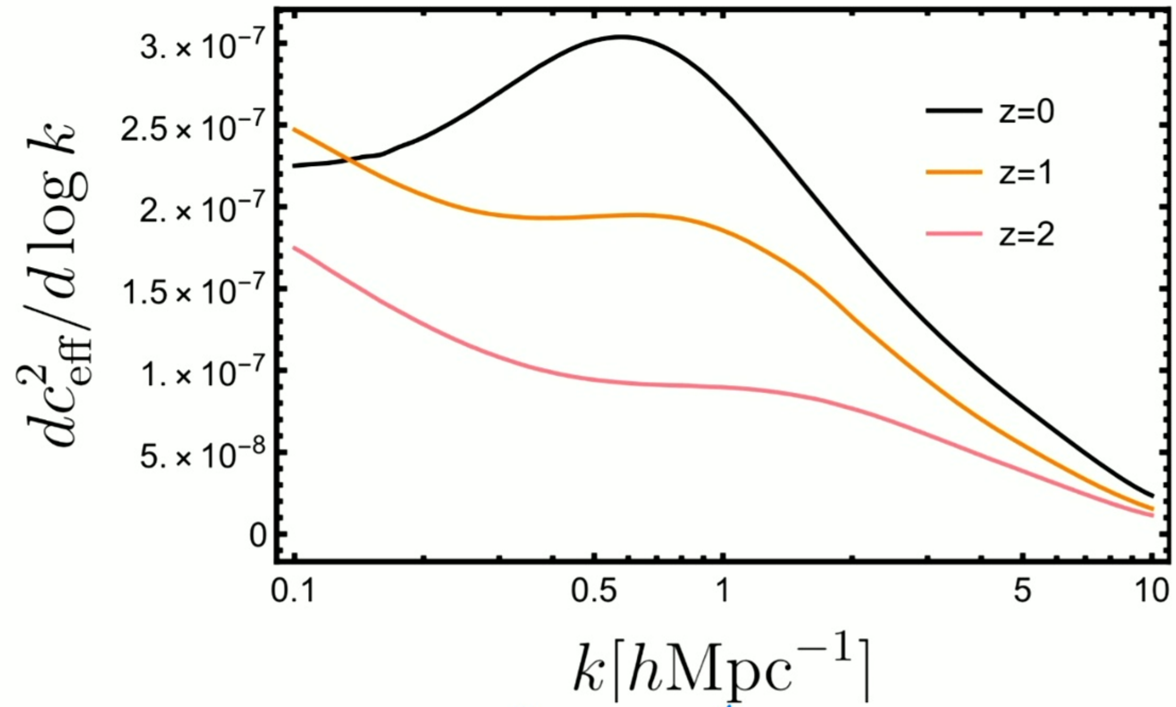
Credit: Wagner, Schmidt, Chiand and Komatsu (1503.03487)

Comparison to simulation results



Precision Comparison of the Power Spectrum in the EFTofLSS with Simulations
Foreman, Perrier and Senatore
(1507.05326)

What cosmic structures contribute the most?



Sheets and filaments

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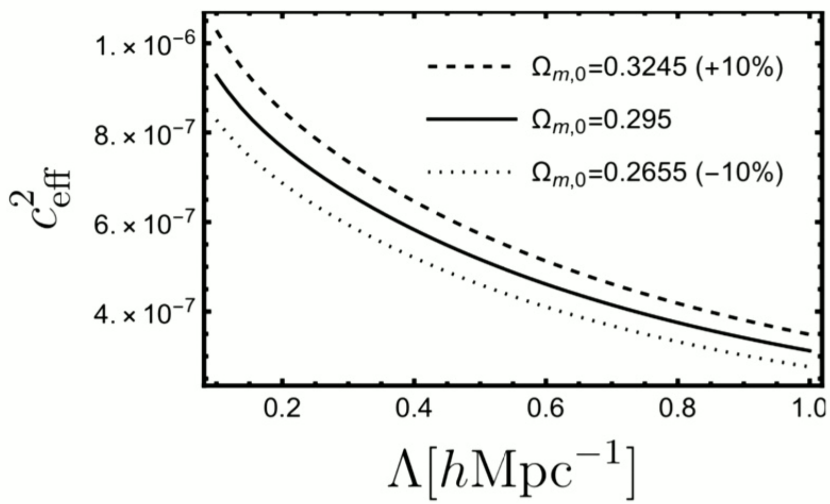
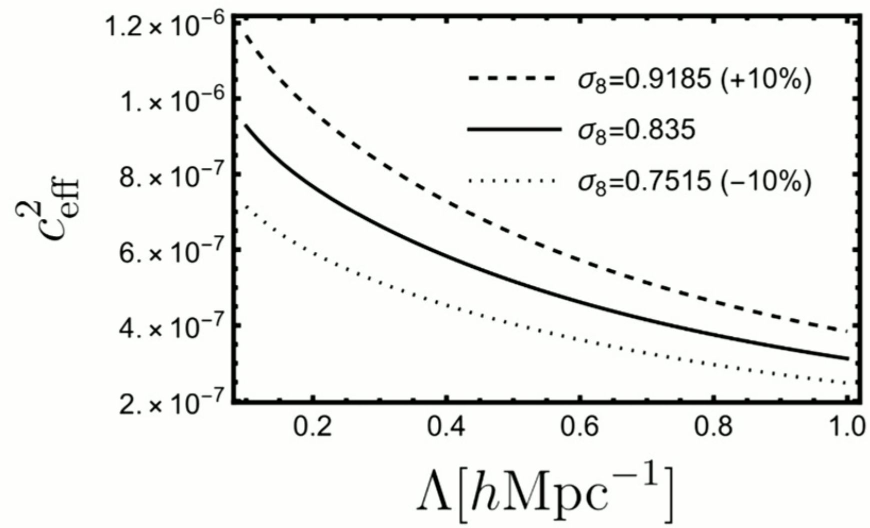
Cosmological information?

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



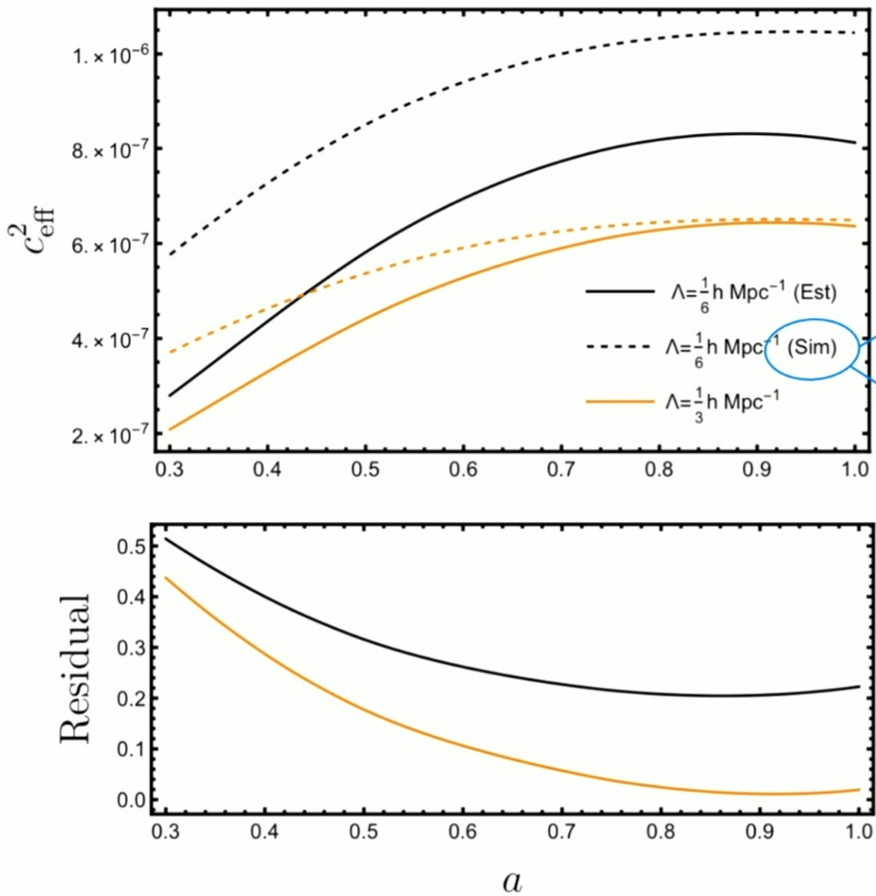
$$c^2_{\rm eff} \sim \sigma_8^{2.2-2.5}$$



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

$\rightarrow$ Strong dependence on amplitude of fluctuations from simulations!

Can extract the time dependence



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

+

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

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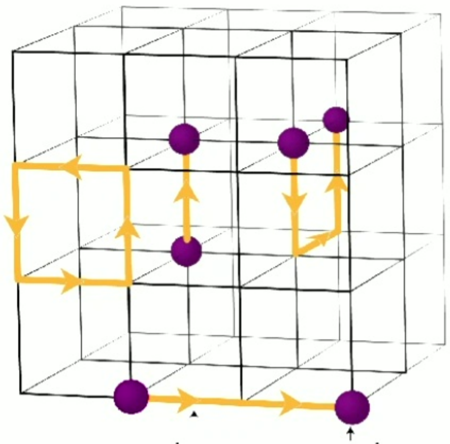
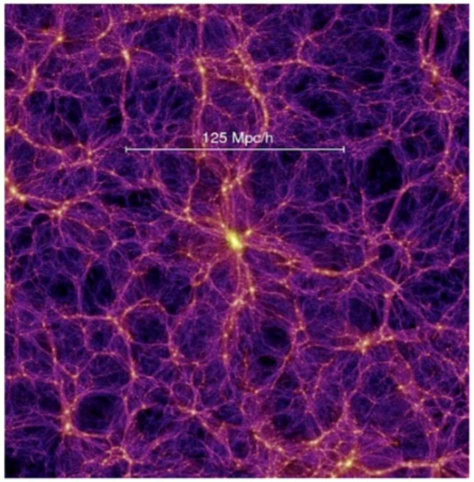
The EFTofLSS is similar to Chiral PT in QCD



Credit: https://doi.org/10.1051/epjconf/202024509008



Credit: http://portillo.ca/nbody/the-n-body-problem/

Low energy limit

ChPT

EFTofLSS

QCD phase transition
vs
Gravitational collapse

Chiral symmetry
vs
Isotropy

Quark condensate
vs
Stress tensor

Second recap

- The cosmic energy equation is 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!

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

Outline

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Final remarks

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

- Accounting for backreactions 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!!