# The Effective Field Theory of Large Scale Structure

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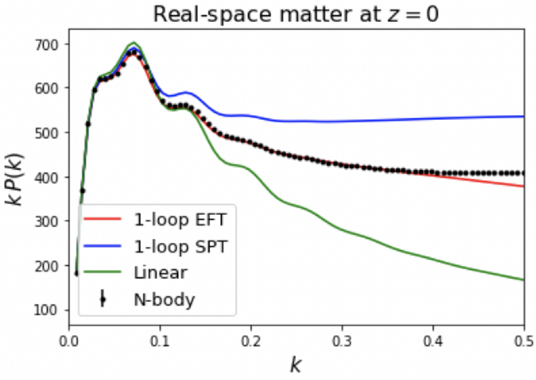
# Outline

# The Era of Precision Cosmology

- **Success of Linear Theory:** On very large scales ($k \to 0$), standard linear perturbation theory describes the universe remarkably well (e.g., CMB).
- **The Frontier:** Upcoming surveys (DESI, Euclid, LSST) will probe smaller scales with unprecedented precision.
- **The Challenge:** Linear theory breaks down at the non-linear scale:

$$k_{NL} \sim 0.1 - 0.3\, h/\text{Mpc}$$

Here, $\delta \sim \mathcal{O}(1)$, and loop corrections become divergent.



# Why not just use N-body Simulations?

Simulations are powerful, but they have limitations (Senatore):

- **Computational Cost:** Running high-resolution simulations for every point in parameter space is prohibitive.
- **Systematic Errors:** Simulations have their own percent-level inaccuracies.
- **Baryonic Physics:** We cannot reliably simulate complex baryonic effects (star formation, feedback) from first principles on cosmological scales.
- **Understanding:** We want an analytical *theory*, not just a numerical black box.

# Standard Perturbation Theory (SPT)

SPT treats dark matter as a **perfect pressureless fluid** at all scales.

## The Equations (Euler & Continuity)

$$\dot{\delta} + \nabla \cdot [(1+\delta)\vec{v}] = 0$$

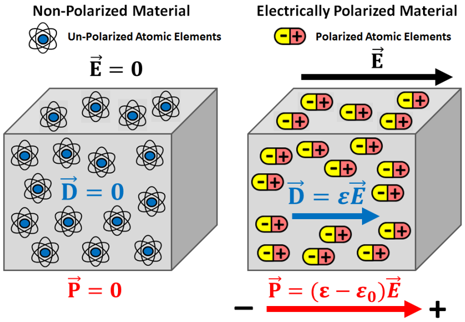
$$\dot{\vec{v}} + \mathcal{H}\vec{v} + (\vec{v} \cdot \nabla)\vec{v} = -\nabla\Phi$$

- Expanded iteratively: $\delta = \delta^{(1)} + \delta^{(2)} + \delta^{(3)} + \dots$
- **The Problem:** Loop integrals integrate over *all* momenta, including $k \to \infty$.
- This assumes the fluid is perfect even at the scale of galaxies and stars, which is physically incorrect (shell crossing, virialization).

# The Dielectric Analogy

How do we describe light propagating through a material?

- **Microscopic View:** Trillions of atoms, electrons, complex QM interactions.
- **Macroscopic View:** We don't solve the Schrödinger equation for every atom!
- We use **Effective Parameters**: Polarizability $\rightarrow$ Dielectric constant $\epsilon$.




**The Lesson:** We can describe large-scale physics without knowing the details of small-scale non-linearities (galaxy formation), provided we introduce effective coefficients.

# Formalism: Smoothing the Universe (Baumann)

We split the fields into long-wavelength (IR) and short-wavelength (UV) modes using a smoothing scale $\Lambda$:

$$\delta_L(\vec{x}) = \int d^3y \, W_\Lambda(|\vec{x} - \vec{y}|)\delta(\vec{y})$$

Applying this to the Euler equation generates a new term due to non-linearity:

$$[\rho v_i v_j]_\Lambda \neq \rho_L v_{Li} v_{Lj}$$

## The Effective Stress Tensor

$$\dot{v}_{Li} + \mathcal{H} v_{Li} + \cdots = -\nabla \Phi_L - \frac{1}{\rho_L} \partial^j [\tau_{ij}]_\Lambda$$

$\tau_{ij}$ encodes the backreaction of small-scale physics (velocity dispersion, virialization) on large scales.

# Parameterizing the Unknown: The Stress Tensor

Since we cannot compute $\tau_{ij}$ from first principles (UV physics is non-linear), we expand it in terms of long-wavelength operators allowed by symmetries (Equivalence Principle):

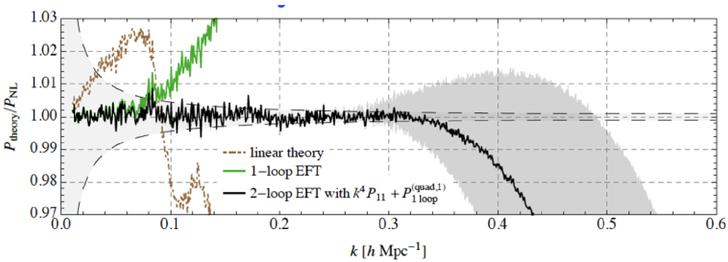
$$\langle \tau_{ij} \rangle \sim \underbrace{p_b \delta_{ij}}_{\text{Background Pressure}} + \underbrace{c_s^2 \delta_L \delta_{ij}}_{\text{Sound Speed}} - \underbrace{\frac{c_{vis}^2}{H} \partial_i v_{Lj}}_{\text{Viscosity}} + \dots$$

- $c_s^2$ **(Effective Sound Speed):** Represents the resistance of small-scale structures to gravitational collapse.
- **Renormalization:** This term leads to a counterterm in the power spectrum:

$$P_{EFT}(k) = P_{linear} + P_{1-loop}^{SPT} - 2c_s^2 k^2 P_{linear}$$

- $c_s^2$ is a **free parameter** measured from data or simulations.

# EFT vs. SPT vs. N-body Simulations




**Key Findings:**

- SPT fails at $k \sim 0.1\, h/$Mpc.
- **1-loop EFT** extends reach to $k \sim 0.3$.
- **2-loop EFT** reaches $k \sim 0.6$ with $\sim 1\%$ precision.
- We gain access to $\sim 100\times$ more modes than linear theory!

# IR-Resummation: Handling Bulk Flows

- **The Problem:** Large-scale bulk flows displace matter by $\sim 10\,\mathrm{Mpc}$. This "smears" the Baryon Acoustic Oscillations (BAO) peak.
- Standard Eulerian perturbation theory cannot handle these large displacements (convergence issues).
- **EFT Solution:** We can resum these infrared (IR) modes non-perturbatively.
- **Result:** The EFT correctly predicts the damping of the BAO oscillations, matching observations without ad-hoc smoothing.

# Summary & Outlook

- **A Rigorous Theory:** EFTofLSS is not a model; it is a rigorous perturbation theory based on the hierarchy of scales ($k \ll k_{NL}$).
- **UV Physics Encapsulated:** The complex formation of halos and galaxies (and baryonic physics) is encapsulated in effective coefficients (like $c_s^2$), which we fit to data.
- **High Precision:** It allows us to analytically compute the power spectrum to much higher $k$, unlocking vast amounts of cosmological information from future surveys.
- **Outlook:**
  - Application to Redshift Space Distortions (RSD).
  - Biased tracers (Galaxies/Halos).
  - Constraining Primordial Non-Gaussianity.

# Reading Material

**Core References for this Presentation:**

The theoretical framework discussed today relies heavily on the foundational lectures by Leonardo Senatore, which introduce the effective fluid description derived from the Boltzmann equation (Senatore n.d.).

For practical applications, including IR-resummation and data comparison, we follow the comprehensive introduction provided by Oliver Philcox (Philcox n.d.).


- Philcox, Oliver H. E. (n.d.). *An Introduction to the EFTofLSS*. Lecture Notes. Available at https://oliverphilcox.github.io/files/eft_intro.pdf.
- Senatore, Leonardo (n.d.). *Lectures on the Effective Field Theory of Large-Scale Structure*. Lecture Notes. Available at https://indico.ictp.it/event/8317/session/15/contribution/61/material/2/0.pdf.

# Thank You!