THE AMAZING WORLD OF Effective Field Theory of Large Scale Structures & Redshift Space Distortions

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"...to boldly go where no one has gone before..."
...why is this important?

Millenium simulation. Springe et al 2005
...we'll talk about

EFToLSS

RSD

UNIVERSE INFORMATION
**EFTolSS**—Effective Field Theory of Large Scale Structures

Carrasco, Hertzberg, Senatore 2012

- **Large Scale Structures**
  - Most relevant information.
  - Described by the density contrast of dark matter and the matter power spectrum, $P$.
  - Evolve almost linearly

\[
\delta = \frac{\Delta \rho}{\rho_0}
\]

**PERTURBATION THEORY**
Standard Perturbation ✗
- No good agreement with new generation of high precision observational data
- Perfect fluid
- UV divergences → **Unphysical** predictions

EFToLSS ✓
- Much better fit with observations.
- Viscosity, dissipation...
- UV divergences absorbed by **counterterms**!

- Fluid equations in k space

\[
\dot{\delta}_k + \Theta_k = - \int \frac{d^3 \vec{q} d^3 \vec{r}}{(2\pi)^6} (2\pi)^3 \delta(\vec{k} - \vec{q} - \vec{r}) \alpha(\vec{q}, \vec{r}) \Theta(\vec{q}) \delta(\vec{r})
\]

\[
\dot{\Theta}_k + 2H \Theta_k + \frac{3}{2} H^2 \Omega_M(z) \delta_k = - \frac{k^2}{a^2} [Z_\delta \delta_k + Z_\Theta \Theta_k] - \int \frac{d^3 \vec{q} d^3 \vec{r}}{(2\pi)^6} (2\pi)^3 \delta(\vec{k} - \vec{q} - \vec{r}) \beta(\vec{q}, \vec{r}) \Theta(\vec{q}) \Theta(\vec{r})
\]

Theta is the divergence of the velocity field, alpha and beta are kernels.
Kaiser 1987

- Learn about velocities.
- Additional counterterm (CT) contributions to the matter power spectrum involving velocity fields.
EFToLSS & RSD

Senatore, Zaldarriaga 2014

- Power spectrum
  \( < \delta^*(k, z) \delta(k', z) > = (2\pi)^3 \delta_D(\vec{k} + \vec{k}') P(k, z) \)
...1-loop corrections

- Solving equation for density contrast

- Analogously, for $P_{\delta\delta}$ and $P_{\nu\nu}$
...1-loop matter power spectrum in Redshift Space

\[
P_{r,\delta,\delta, ||1\text{-loop}}(k, \mu, t) = P_{\delta,\delta, ||1\text{-loop}}(k, t) + 2\mu^2 P_{\delta,\delta, ||1\text{-loop}}(k, t) \\
+ \mu^4 P_{H, H, ||1\text{-loop}}(k, t) + \left( \frac{k \mu}{aH} \right)^2 P_{\delta, [v^2], \text{tree}}(k, t) \\
- \mu^2 \left( \frac{k \mu}{aH} \right)^2 P_{\delta, [v^2], \text{tree}}(k, t) + \frac{1}{4} \left( \frac{k \mu}{aH} \right)^4 P_{[v^2], [v^2], \text{tree}}(k, t) \\
+ (1 + f \mu^2) \left( \frac{k \mu}{aH} \right)^2 P_{\delta, [v^2], \text{tree}}(k, t) + \frac{i}{3} (1 + f \mu^2) \left( \frac{k \mu}{aH} \right)^2 P_{\delta, [v^2], \text{tree}}(k, t) \\
- (1 + f \mu^2) \left[ (c_1 + c_2) \mu^2 + (c_1 + c_3) \mu^4 \right] \left( \frac{k}{k_{NL}} \right)^2 P_{\delta, \delta, 11}(k, t),
\]
**UV DIVERGENCES AND RENORMALISATION**

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- Local in wave number, \( k \).
- Analytic means polynomial in \( k^2 \).
- Non-analytic, log or fractional powers of \( k^2 \).
Example of loop integrals in momentum space found in $P_{13}$

\[
I_{\alpha\alpha}(\Lambda) = \int_0^\Lambda \frac{d^3q}{(2\pi)^3} \mathcal{P}_R(q) \alpha(k, -q) \alpha(k - q, q)
\]

\[
= \int_0^{k_*} \frac{d^3q}{(2\pi)^3} \mathcal{P}_R(q) \alpha(k', -q) \alpha(k' - q, q) + \int_{k_*}^\Lambda \frac{d^3q}{(2\pi)^3} \mathcal{P}_R(q) \alpha(k, -q) \alpha(k - q, q)
\]

\[
= a_1(\Lambda) \cdot k^2 + b_1 \cdot k^3 + O(k^4).
\]

- Fixed by renormalisation
- Analytic behaviour, UV sensitive
- Low-energy
- Non-analytic

Fit cubic polynomial

COUNTERTERMS
Repeat analysis for $P_{\delta / \pi^{1\text{loop}}} (k, t)$, $P_{\delta / \pi^{1\text{loop}}} (k, t)$ and rest of counterterms
CONCLUSIONS

• The Universe is treated as a fluid. Most of the relevant information in Cosmology is found at large scales.

• At large scales, galaxies are point-like objects. There exist voids, filaments, clusters of galaxies...

• We want to study the backreaction from small scales and the so-called Redshift Space Distortion effect on large scale structures.

• Simulations are very expensive. We would need to run several simulations with different initial conditions.

• Effective Field Theory of Large Scale Structures is a powerful tool
  - This framework solves those theoretical issues present in Standard perturbation theory.
  - Some parameters need to be included in the analytical prediction and need to be measured by matching to numerical data → Renormalisation.
  - It agrees much better with new high precision observational datasets.
& PROSPECTS

- To obtain the renormalisation for the 1 loop matter power spectrum in Redshift Space.
- Compare with observations and N-body simulations.
- To apply this tool to the analysis of the screening mechanism in theories of Modified Gravity.
...1-loop $P_{\delta \delta}$ renormalisation

- $P_{\delta \delta \mid \text{1-loop}} = P_{11} + P_{13} + P_{CT}$
  - Tree level $\Rightarrow$ UV-div

- Low-k behaviour (analytic terms) $\Rightarrow$ Taylor expansion loop integrals
  \[ P_{13}(k, z) \approx P_{11}(k, z) k^2 h(z) \int_0^\Lambda \frac{d^dq}{2\pi^2} \mathcal{P}_R(q) \]

Therefore,

\[ P_{\delta \delta \mid \text{1-loop}} = P_{11} \left( 1 + c_s^2 h(z) k^2 \right) \]

Renormalisation parameter

- Fixed observationally or by simulations
  - Cutoff dependence eliminated by CT in the UV limit (same $k$ & $z$ dependence up to a constant)

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Stochastic term

**RANDOM FORCES**
- Small-scale gravitational interactions (galaxy collisions)
- Friction between the particles of the fluid (galaxies), viscosity and other corrections.

**THERMAL FLUCTUATIONS**
- Fluctuations in the density contrast.
- Stochastic term appears in the effective stress-energy tensor.

**Source of**
- Diffusion/dissipation
- Gravitational energy is turned into heat due to the friction.

**Effect from**
- Random noise
- The fluid is heated up and gravitational contributions appear.

\[ |q_1| < |q_2| > k_{<\{0,1\}} \]