The amazing world of

# *EFFECTIVE FIELD THEORY of LARGE SCALE STRUCTURES in REDSHIFT SPACE*

*Lucía Fonseca de la Bella*

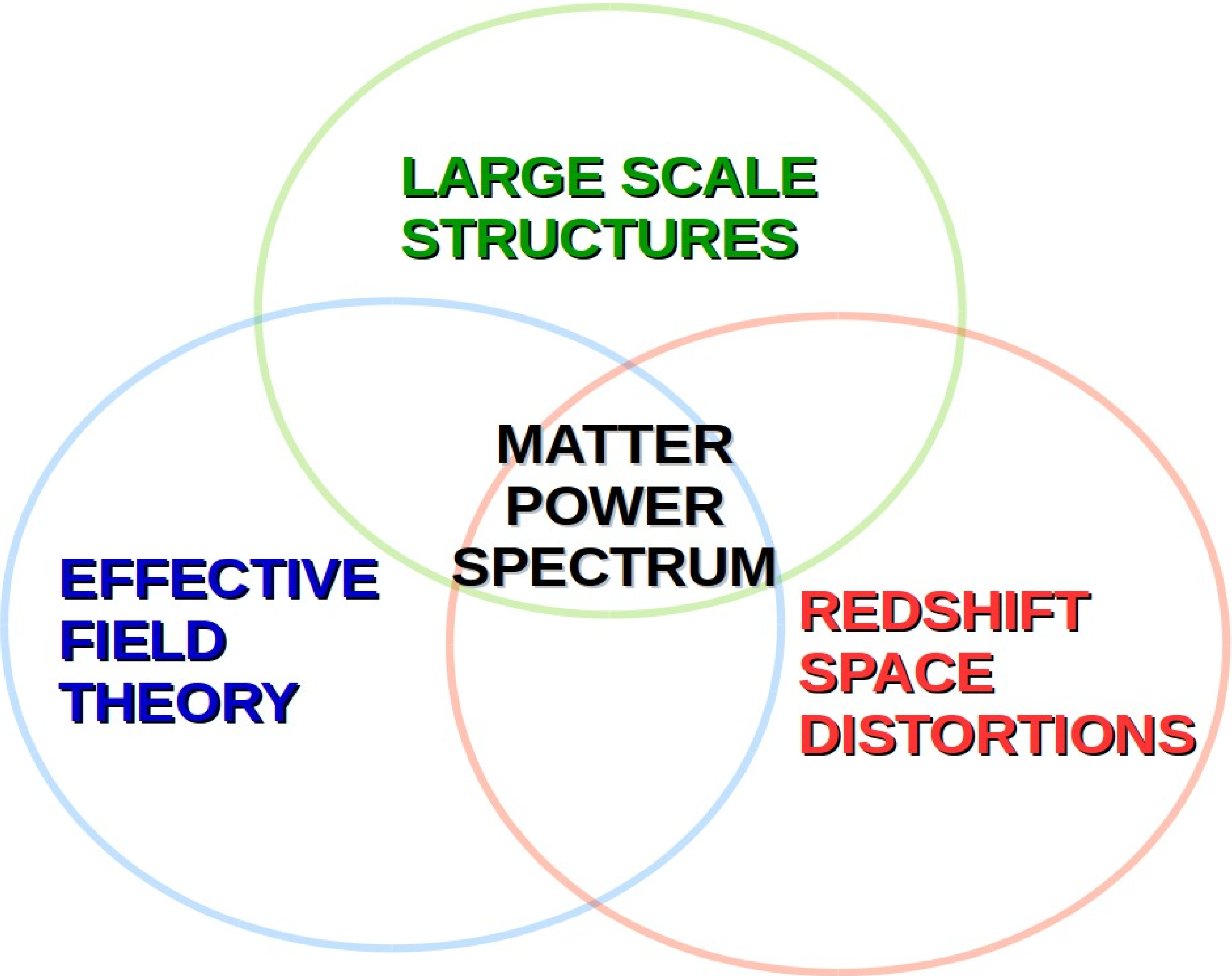
In collaboration with D.Seery and D. Regan

April, 22nd

CPT
Aix*Marseille université

University of Sussex
Physics & Astronomy

# ...we'll talk about



# I. Introduction-

1) Large Scale Structures

2) Effective Field Theory formalism

3) Redshift Space Distortions

# Large scale structures

...why is this important?

- Learn about our **Universe**
- Large scales
  - Most information for Cosmology.
  - Galaxy point-like object.
  - Universe as a fluid.
- Structures:
  - Clusters, filaments, voids...

Millenium simulation, Springer et al 2005

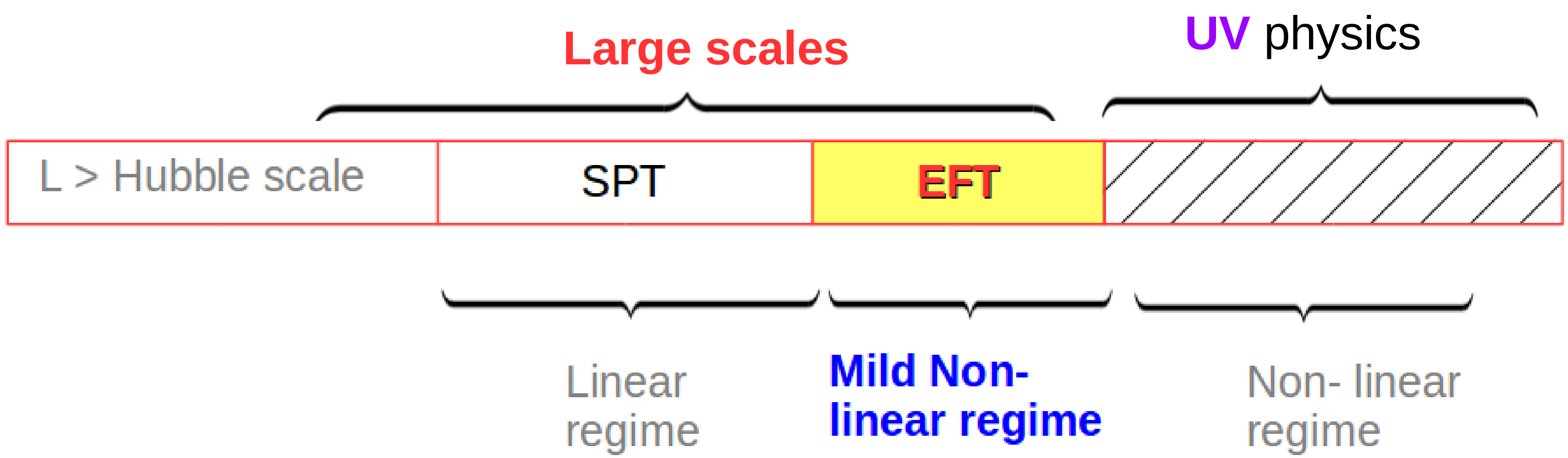
How?

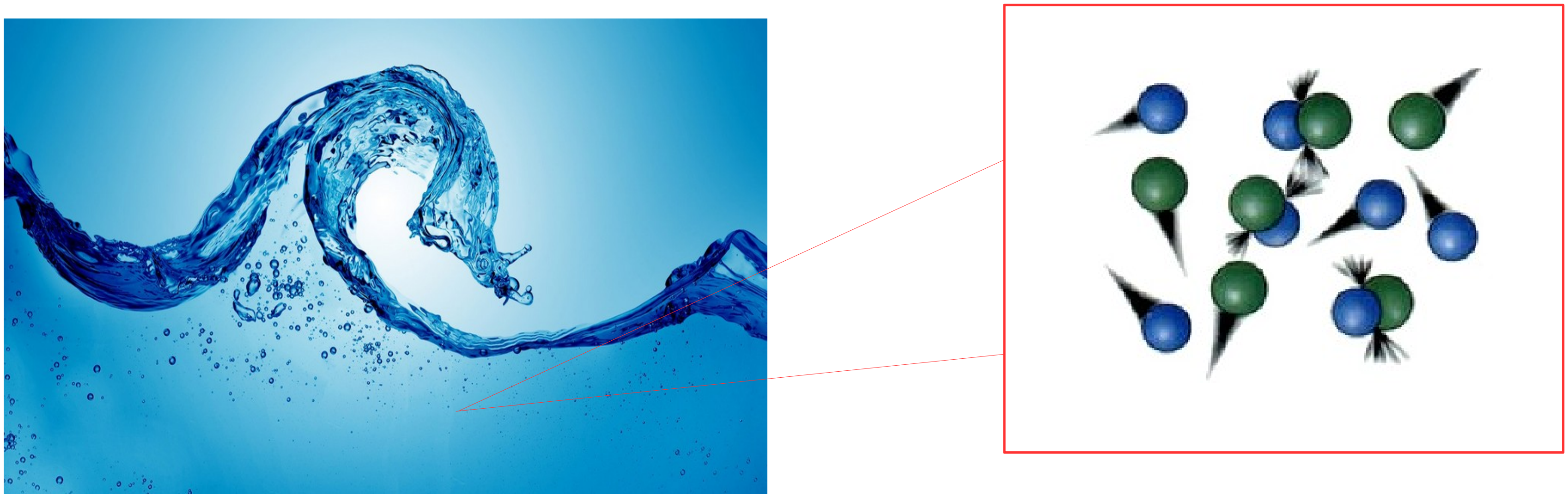
- Simulations.
- Observational data!

**Theoretical tool ?**

# Effective Field theory formalism

Carrasco et al 2012



# Standard Perturbation

## vs

# Effective Field Theory

## ~~Standard Perturbation~~

- **Good** in the linear regime (very large distances).
- Perfect fluid
- UV sensitive → **cut-off** dependent.

Bernardeau et al., 2002

## EFToLSS

- Probes scales of interest where **SPT breaks down**.
- Viscosity, dissipation...
- No UV sensitivity → **counterterms**!

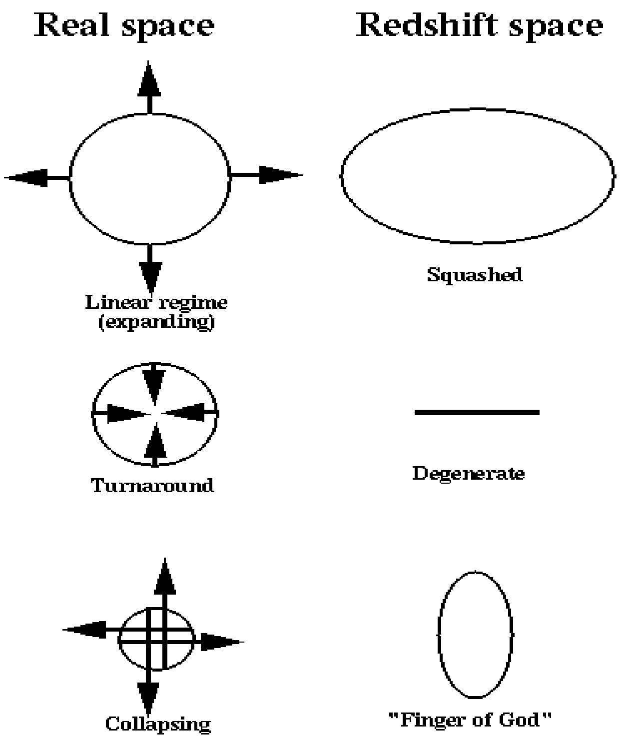
Carrasco et al 2012

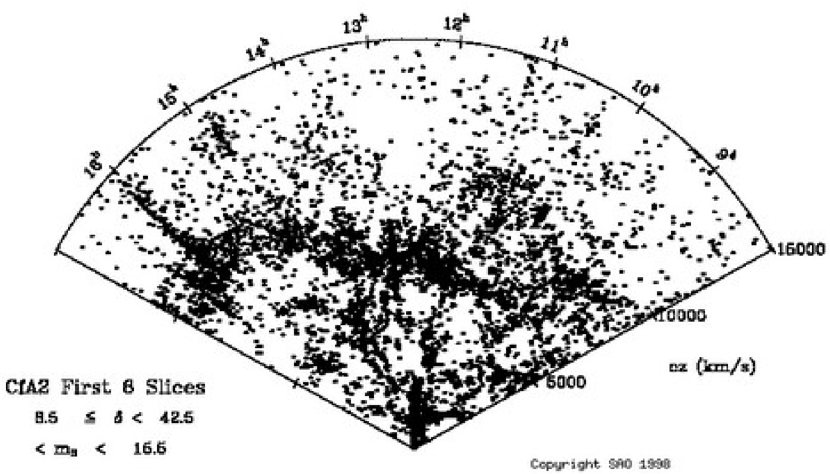
# Redshift space distortions

**WHY?**

- **Surveys** in redshift space.
- Redshift depends on **peculiar v** (along line of sight).
- Unknown random motions within clusters

Kaiser 1987




- Fingers of God.
- Learning about **velocity fields**.

# II. EFToLSS in real space-

1) Fluid equations
2) Cosmological matter pertutbations
3) Counterterms idea
4) Matter density contrast
5) 1-loop matter power spectrum
6) UV divergences

# Fluid equations (General Relativity)

$$ds^2 = -e^{2\Psi(t,\vec{x})}dt^2 + a(t)^2 e^{2\Phi(t,\vec{x})}d\vec{x}^2$$

Equations of motion (expanding Universe)

Density conservation

$$\partial_t \rho + \partial_m(\rho v^m) + 3\rho(H + \dot{\Phi}) = 0,$$

Newton's law

$$\partial_t v^i + v^m \partial_m v^i + 2Hv^i + \frac{\partial^i \Psi}{a^2} = 0,$$

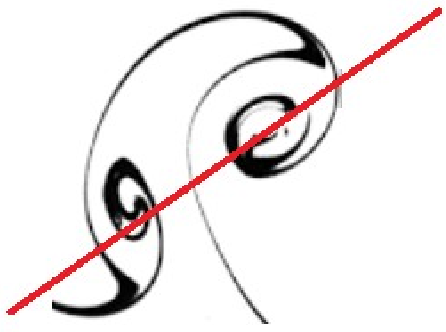
Poisson's equation

$$\frac{\partial^2 \Phi}{a^2} + \frac{\delta\rho}{2M_p^2} = 0.$$

# Cosmological matter perturbations

Density contrast $\delta = \delta\rho/\rho_0$

velocity divergence $\Theta = \partial_i v^i$



Standard Perturbation Theory

$$\dot{\delta} + \Theta = -\Theta\delta - (\partial_m \partial^{-2}\Theta)\partial^m \delta,$$

$$\dot{\Theta} + 2H\Theta + \frac{3}{2}H^2\Omega_M(z)\delta = -\partial_m\partial^{-2}\Theta\partial_m\Theta - \partial_i\partial_m\partial^{-2}\Theta\partial_m\partial_i\partial^{-2}\Theta.$$

**WHAT'S NEXT?** **+ COUNTERTERMS**

# Counterterms

(Effective energy momentum tensor)

**Small scale interactions**

**Diffusion/dissipation**
**stochastic term** → Random variable

**Deviations from perfect fluid**

**Viscosity, speed of sound ...** → Parametrise UV physics

$$Z_\delta \frac{\partial^2 \delta}{a^2}$$

$$Z_\Theta \frac{\partial^2 \Theta}{a^2}$$

# Matter density contrast (Fourier space)

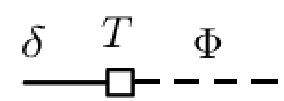
Linear equation — Counterterm

$$\epsilon = -\frac{\dot{H}}{H^2} \qquad ' \equiv \mathrm{d}/\mathrm{d}z$$

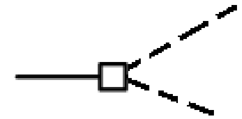
$$\delta_k'' - \frac{1-\epsilon}{1+z}\delta_k' - \frac{3}{2}\frac{\Omega_M(z)}{(1+z)^2}\delta_k = \frac{k^2}{H^2a^2}\frac{Z_\delta \delta_k + Z_\Theta H(1+z)\delta_k'}{(1+z)^2}$$
$$+\int \frac{\mathrm{d}^3\vec{q}\,\mathrm{d}^3\vec{r}}{(2\pi)^6}(2\pi)^3\delta(\vec{k}-\vec{q}-\vec{r}) \times \left[\alpha(\vec{q},\vec{r})\frac{3}{2}\frac{\Omega_M(z)}{(1+z)^2}\delta(\vec{q})\delta(\vec{r}) + \gamma(\vec{q},\vec{r})\delta'(\vec{q})\delta'(\vec{r})\right]$$

Non-linear contribution

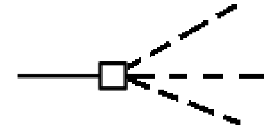
*Solving the equation...*

Linear order $\delta^{(1)}(k,z) = g(z)\delta_k^*$ 


$\delta_k^* \equiv T_k(z_*)\Phi_k^{Prim}$



Quadratic order $\delta^{(2)}$

Cubic order $\delta^{(3)}$ 

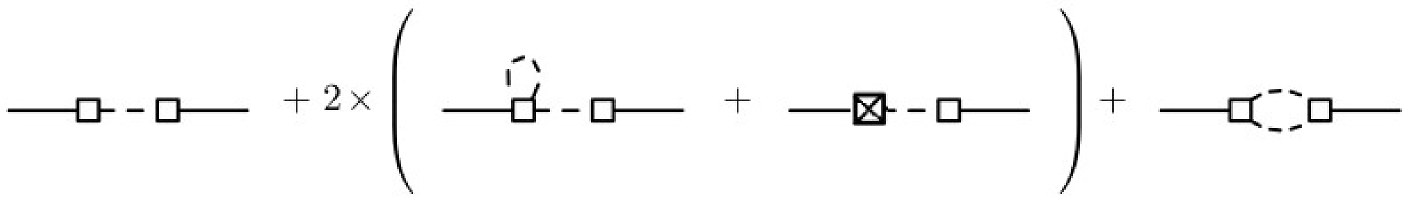
Counterterm $\delta^{CT}$ 

# 1 loop matter power spectrum

$$< \delta^{(n)}(k,z)\delta^{(n)}(k',z) >= (2\pi)^3\delta_D(\vec{k}+\vec{k}')P_{nn}(k,z)$$

The renormalised power spectrum at **1 loop**

$P_{MM}(q) =$



$$= P_{11}(q) + 2\times(P_{13}(q) + P_{CT}(q)) + P_{22}(q)$$

Tree level

UV

UV

Drop

**2 loop + ...**

and / or

$(k/k_{NL})^4 + \ldots$

$$P_{CT} \propto k^2$$

$$P_{stoch} \propto k^4$$

# UV divergences

Example of loop integrals in momentum space found in $P_{13}$

$$I_{\alpha\alpha}(\Lambda) = \int^{\Lambda} \frac{\mathrm{d}^3\vec{q}}{(2\pi)^3} \mathcal{P}_R(\vec{q})\alpha(\vec{k},-\vec{q})\alpha(\vec{k}-\vec{q},\vec{q})$$

$$= \underbrace{\int_0^{k_*} \frac{\mathrm{d}^3\vec{q}}{(2\pi)^3} \mathcal{P}_R(\vec{q})\alpha(\vec{k},-\vec{q})\alpha(\vec{k}-\vec{q},\vec{q})}_{\text{Linear regime, SPT, }\Lambda\text{-independent}}$$

$$+ \underbrace{\int_{k_*}^{\Lambda} \frac{\mathrm{d}^3\vec{q}}{(2\pi)^3} \mathcal{P}_R(\vec{q})\alpha(\vec{k},-\vec{q})\alpha(\vec{k}-\vec{q},\vec{q})}_{\text{Mild non-linear regime, UV sensitive}}$$

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

**COUNTERTERMS**

# Renormalisation

Drop → 2 loop + ...
→ $(k/k_{NL})^4 + \dots$

$$P_{\delta\delta\,|\,1\text{-loop}} = P_{11} + P_{13} + P_{CT}$$

$P_{13}$
→ **SPT** linear regime → **CUBIC** POLYNOMIAL IN ***k***
→ **EFT mild non-linear** regime (Taylor expansion)

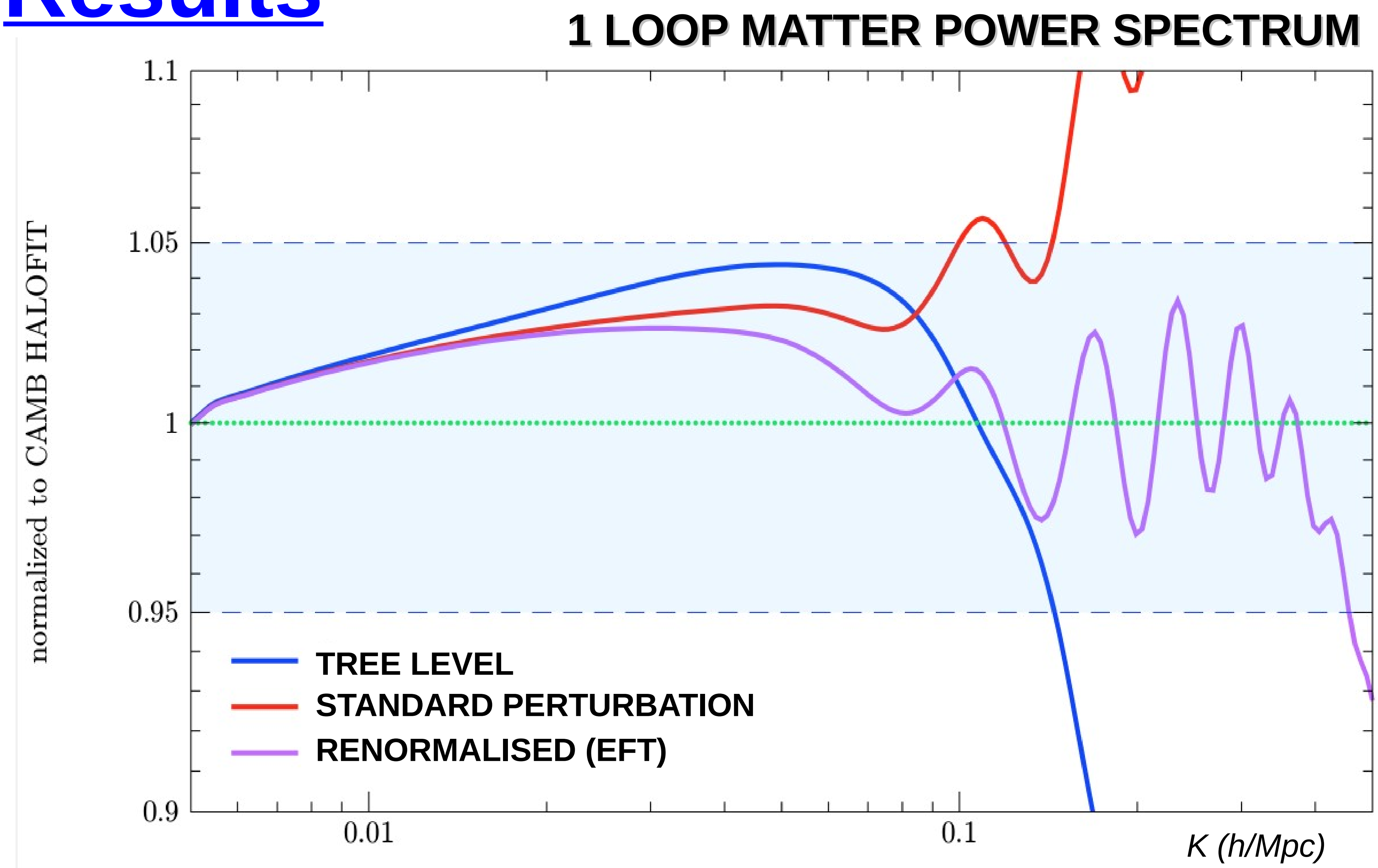
$$P_{13}(k,z) \approx P_{11}(k,z)\,k^2\,h(z)\underbrace{\int^{\Lambda}\frac{dq}{2\pi^2}\,\mathcal{P}_{\mathcal{R}}(q)}_{\mathcal{A}(\Lambda)}$$

$P_{CT}$ → **UV LIMIT**
It shares **k** & **z** dependence up to a constant

$$P_{\delta\delta\,|\,1\text{-loop}} = P_{11}\,[\,1 + c_s^2\,h(z)\,k^2 + b\,k^3 + O(k^4)\,]$$

→ **Renormalisation factor**
**fixed CAMB HALOFIT (data, simulations)**

# Results

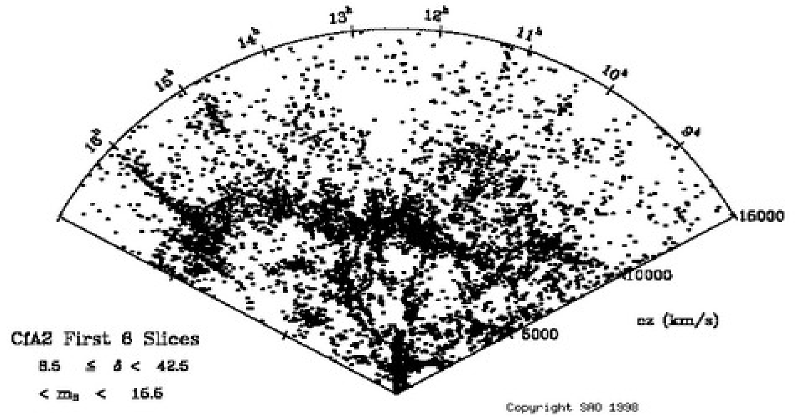

1 LOOP MATTER POWER SPECTRUM
1.1
1.05
1
0.95
0.9
normalized to CAMB HALOFIT
TREE LEVEL
STANDARD PERTURBATION
RENORMALISED (EFT)
0.01
0.1
K (h/Mpc)

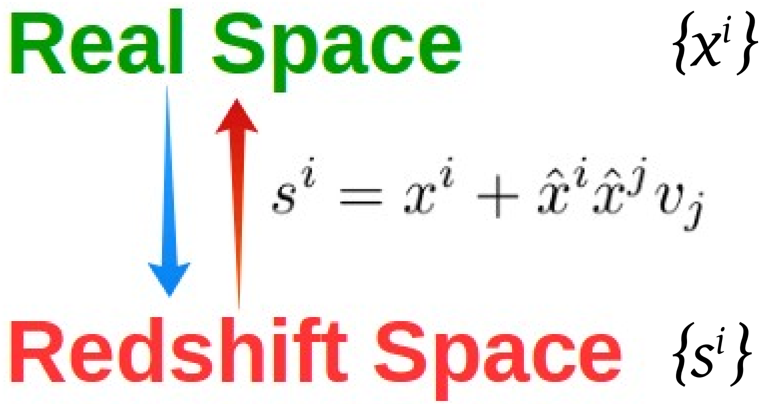
# III. Redshift Space -

1) Redshift Space Distortions
2) Density contrast in redshift space

# Redshift space distortions

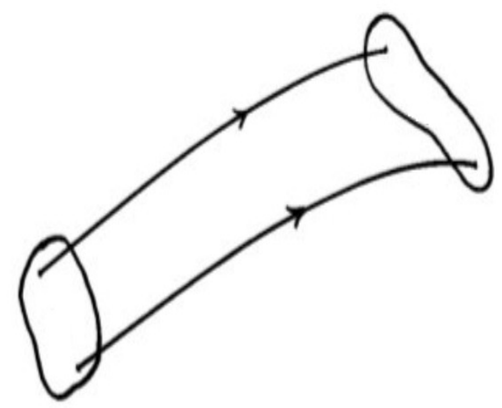
Kaiser 1987




- Conservation of density

$$\rho(\vec{s})\mathrm{d}^3\vec{s} = \rho(\vec{x})\mathrm{d}^3\vec{x}$$



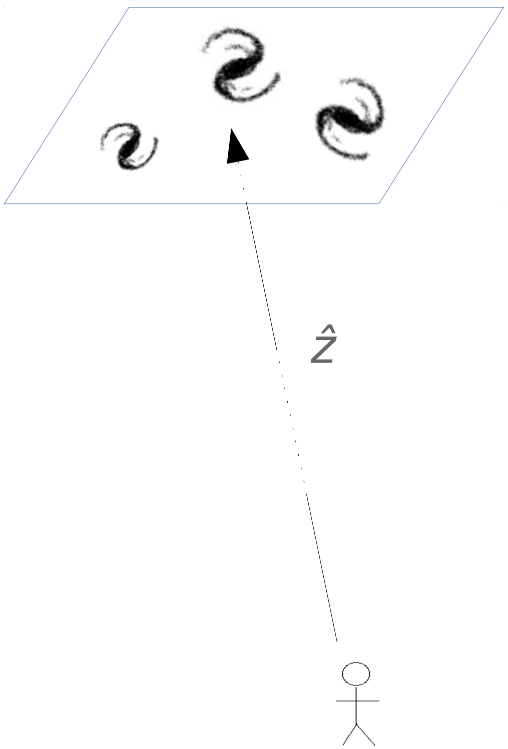
# Matter density contrast (Redshift space)

Fourier space

$$\delta_s(\vec{k}) = \int \mathrm{d}^3\vec{x}\mathrm{e}^{-\mathrm{i}\vec{k}\cdot\vec{x}}\left[\mathrm{e}^{-\mathrm{i}\vec{k}\cdot\vec{x}(\vec{x}\cdot\vec{v})} - 1\right][1+\delta(\vec{x})]$$

Distant observer approximation

$$\begin{aligned}\delta_s(\vec{k}) =&\delta(\vec{k}) + \frac{k_z^2}{k^2}\frac{\dot{\delta}(\vec{k})}{H} - \epsilon^{zij}\frac{k_z k_i}{k^2}\frac{\pi_{(v)j}(\vec{k})}{H} \\ &+ \frac{\mathrm{i}^2}{2}\left(\frac{k_z}{aH}\right)^2[v_z^2]_{\vec{k}} - \frac{\mathrm{i}^3}{3}\left(\frac{k_z}{aH}\right)^3[v_z^3]_{\vec{k}} \\ &+ \frac{\mathrm{i}^2}{2}\left(\frac{k_z}{aH}\right)^2[\delta v_z^2]_{\vec{k}}.\end{aligned}$$




$v_z$ Projection along l.o.s.

$$v^i(\vec{x},t) = \frac{\pi^i(\vec{x},t)}{\rho(\vec{x},t)}$$

# IV. EFToLSS in Redshift Space-

1) The idea
2) 1-loop matter power spectrum
3) Divergences

# The idea...

- Redshift Space Distortions

$\delta$ redshift space = $\delta$ real space + V operators

- Renormalised density contrast

Renormalised $\delta$ redshift space = $\delta$ real space **+** COUNTERTERMS + Renormalised V operators

$P^{s}_{\delta\delta|1\text{loop}}$

**EFT of LSS**
(real space)

?

# Renormalised composite operators

- Diagrams: bare operator + UV information

$$[v_z^2]^R_{\vec{k}} = [v_z^2]_{\vec{k}} + \left(\frac{aH}{k_{NL}}\right)^2 \left[c_1 + \left(c_2 + c_3 \frac{k_z^2}{k^2}\right) \delta(\vec{k})\right]$$

$$[v_z^3]^R_{\vec{k}} = [v_z^3]_{\vec{k}} + \left(\frac{aH}{k_{NL}}\right)^2 3 c_1 v_z(\vec{k})$$

$$[\delta v_z^2]^R_{\vec{k}} = [\delta v_z^2]_{\vec{k}} + \left(\frac{aH}{k_{NL}}\right)^2 c_1 \delta(\vec{k})$$

R → renormalised
$[\ \ ]_{\vec{k}}$ → convolution

# 1-loop matter power spectrum in Redshift Space

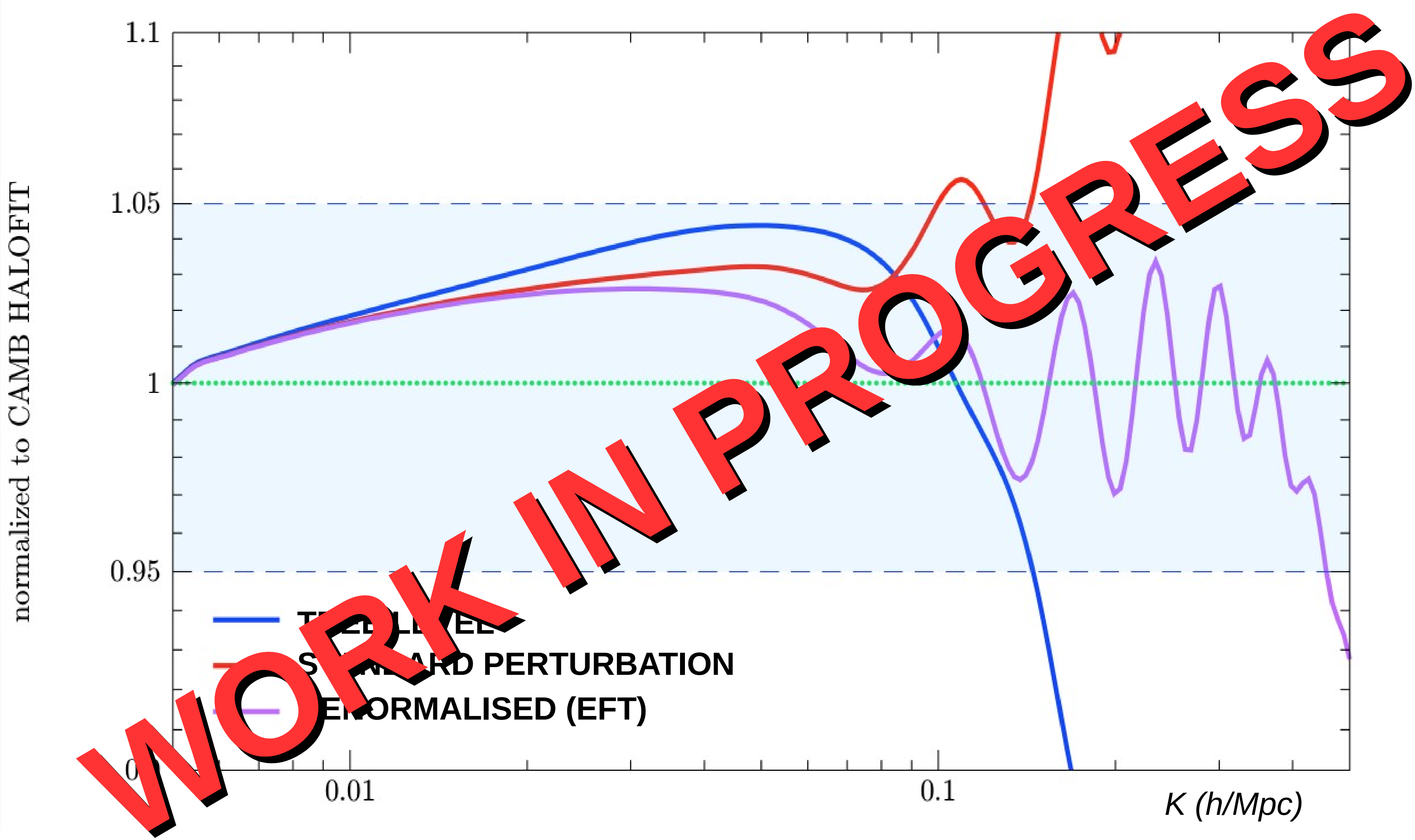
Senatore, Zaldarriaga 2014

Real space

$$
\begin{aligned}
P^s_{\delta\delta|1\text{loop}}(k,\mu,z) =\ & P_{\delta\delta|1\text{loop}}(k,z) + 2\mu^2 P_{\delta\frac{\dot\delta}{H}|1\text{loop}}(k,z) + \mu^4 P_{\frac{\dot\delta}{H}\frac{\dot\delta}{H}|1\text{loop}}(k,z) \\
& - \left(\frac{k\mu}{aH}\right)^2 P_{\delta[v_z^2]|\text{Tree}}(k,z) - \mu^2\left(\frac{k\mu}{aH}\right)^2 P_{\frac{\dot\delta}{H}[v_z^2]|\text{Tree}}(k,z) \\
& + \frac{1}{4}\left(\frac{k\mu}{aH}\right)^4 P_{[v_z^2][v_z^2]|\text{Tree}}(k,z) + (1+f\mu^2)\left(\frac{k\mu}{aH}\right)^2 P_{\delta[\delta v_z^2]|\text{Tree}}(k,z) \\
& + \frac{\mathrm{i}}{3}(1+f\mu^2)\left(\frac{k\mu}{aH}\right)^3 P_{\delta[v_z^3]|\text{Tree}}(k,z) \\
& - (1+f\mu^2)[(c_1+c_2)\mu^2 + (\tilde c_1 + c_3)\mu^4]\left(\frac{k}{k_{NL}}\right)^2 P_{\delta\delta|11}(k,z)
\end{aligned}
$$

$\mu \equiv k_z/k$ $\quad$ $v_z$ Projection along l.o.s. $\quad$ $f = \frac{\mathrm{dln}\delta}{\mathrm{dln}a}$ $\quad$ $\tilde c_1 \equiv c_1 f/aH$

# 1 LOOP MATTER POWER SPECTRUM in REDSHIFT SPACE



# Conclusions

# &

# future work

# 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...
- Large scale properties have memory of short distance physics.
- **Effective Field Theory of Large Scale Structures**
  - encodes small scale effects in the so called **counterterms** (deviations from perfect fluid).
  - Probes scales of interest where **Standard Perturbation Theory** breaks down.
- Adding **Redshif Space Distortion** effects allows us to learn about **peculiar velocities** within clusters.

# & PROSPECTS

- To obtain the renormalisation parameters for the 1 loop matter power spectrum in Redshift Space.
- To study possible IR divergences.
- Compare with observations and N-body simulations.
- To apply this tool to the analysis of the screening mechanism in theories of Modified Gravity in collaboration with L. Perenon & C. Marinoni.

# ...1-loop $P_{\delta\delta}$ renormalisation

- $P_{\delta\delta\,|\,1\text{-loop}} = P_{11} + P_{13} + P_{CT}$

  Tree level → UV-div

- Low-k behaviour (analytic terms) → Taylor expansion loop integrals

$$P_{13}(k,z) \approx P_{11}(k,z)\, k^2\, h(z) \underbrace{\int_0^{\Lambda} \frac{dq}{2\pi^2}\, \mathcal{P}_{\mathcal{R}}(q)}_{\mathcal{A}(\Lambda)}$$

Cutoff dependence eliminated by CT in the UV limit (same k & z dependence up to a constant )

Therefore,

$$P_{\delta\delta\,|\,1\text{-loop}} = P_{11}\left(1 + {c_s}^2\, h(z)\, k^2\right)$$

→ **Renormalisation parameter**
Fixed observationally or by simulations