Painting Gravity Red: A General RSD Template

Benjamin Bose

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Outline

Standard Eulerian Perturbation Theory (SPT)

Conservation of energy and momentum lead to the **Continuity** and **Euler** equations:

- $a\frac{\partial\delta(\mathbf{k},a)}{\partial a} + \theta(\mathbf{k},a) = -\int \frac{d^3\mathbf{k}_1 d^3\mathbf{k}_2}{(2\pi)^3}\delta_{\rm D}(\mathbf{k}-\mathbf{k}_1-\mathbf{k}_2)\alpha(\mathbf{k}_1,\mathbf{k}_2)\,\theta(\mathbf{k}_1,a)\delta(\mathbf{k}_2,a)$
- $a\frac{\partial\theta(\mathbf{k},a)}{\partial a} + \left(2+\frac{aH'}{H^2}\right)\theta(\mathbf{k},a) - \left(\frac{k}{a\,H}\right)^2\Psi(\mathbf{k},a) =$
  $-\frac{1}{2}\int \frac{d^3\mathbf{k}_1 d^3\mathbf{k}_2}{(2\pi)^3}\delta_{\rm D}(\mathbf{k}-\mathbf{k}_1-\mathbf{k}_2)\beta(\mathbf{k}_1,\mathbf{k}_2)\,\theta(\mathbf{k}_1,a)\theta(\mathbf{k}_2,a)$

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Separation of variables works well for GR :

- $$\delta_1(\mathbf{k},a)=D(a)\delta_0(\mathbf{k})$$

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Separation of variables works well for GR :

- $$\delta_1(\mathbf{k},a) = D(a)\delta_0(\mathbf{k})$$

The **Power Spectrum** is a k-space correlation measurement of these perturbations:

- $\langle\delta_0(\mathbf{k})\delta_0(\mathbf{k}')\rangle = (2\pi)^3\delta_{\rm D}(\mathbf{k}+\mathbf{k}')\,P_L(k)$

Loop Corrections

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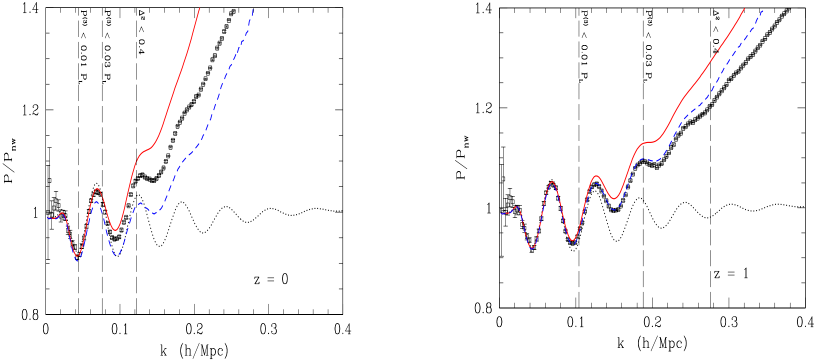
$P_{1-loop}(k) = P_L(k) \ + \ [\ P_{22}(k) + P_{13}(k)\ ]$

where
$\langle \delta_2(\mathbf{k})\delta_2(\mathbf{k}')\rangle = (2\pi)^3\delta_{\rm D}(\mathbf{k}+\mathbf{k}')\, P_{22}(k)$

$\langle \delta_0(\mathbf{k})\delta_3(\mathbf{k}') + \delta_3(\mathbf{k})\delta_0(\mathbf{k}')\rangle = (2\pi)^3\delta_{\rm D}(\mathbf{k}+\mathbf{k}')\, P_{13}(k)$

A Gain and A Problem



- **Linear** , 1-loop and 2-loop SPT at $z = 0$ and $z = 1$ with N-body results.

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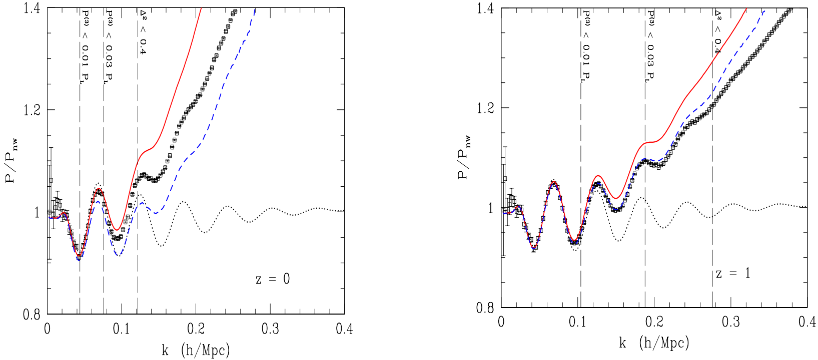

- **Linear** , 1-loop and 2-loop SPT at $z = 0$ and $z = 1$ with N-body results.
- Less non-linear structure formation at high z so better SPT performance.

Modified Gravity in PT

Modifications to gravity enter the perturbative scheme via the Poisson term within the Euler equation.

- $-\left(\frac{k}{aH}\right)^2 \Psi = \frac{3\Omega_m(a)}{2}\mu(k,a)\,\delta(\mathbf{k}) + S(\mathbf{k})$

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$S(\mathbf{k})$ is the non-linear source term which is needed for screening.

- $S(\mathbf{k}) = \int \frac{d^3\mathbf{k}_1 d^3\mathbf{k}_2}{(2\pi)^3}\,\delta_{\rm D}(\mathbf{k}-\mathbf{k}_{12})\gamma_2(\mathbf{k}_1,\mathbf{k}_2;a)\delta(\mathbf{k}_1)\,\delta(\mathbf{k}_2)$
  $+ \int \frac{d^3\mathbf{k}_1 d^3\mathbf{k}_2 d^3\mathbf{k}_3}{(2\pi)^6}\delta_{\rm D}(\mathbf{k}-\mathbf{k}_{123})\gamma_3(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3;a)\delta(\mathbf{k}_1)\,\delta(\mathbf{k}_2)\,\delta(\mathbf{k}_3)$

Redshift Space Distortions : TNS Model

- **TNS**:

$$P^S(k,\mu) = D_{FoG}[\mu f \sigma_v k]\{P_{\delta\delta}(k) + 2f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) + A(k,\mu) + B(k,\mu)\}$$

$$A(k,\mu) \sim B_\sigma^{cross}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$$
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- Includes corrections (A and B) coming from non-linear coupling between velocity and density.
- D_{FoG} term treated non-perturbatively but phenomenologically - **free parameter** σ_v .

RSD in MG - A Generalised Framework: 1606.02520v2

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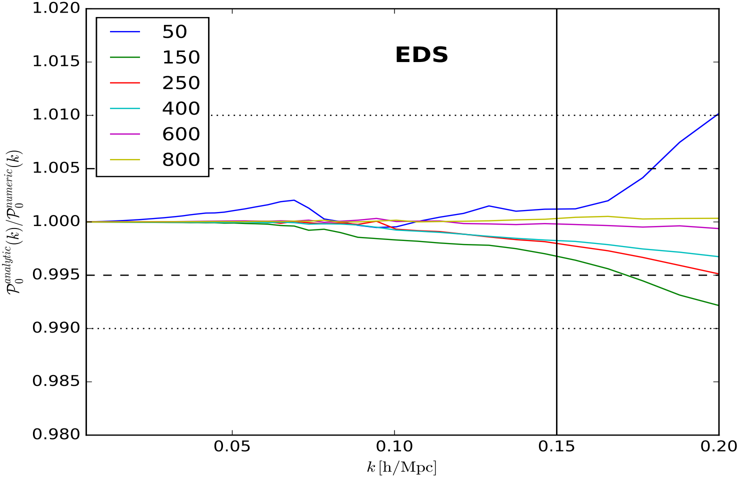
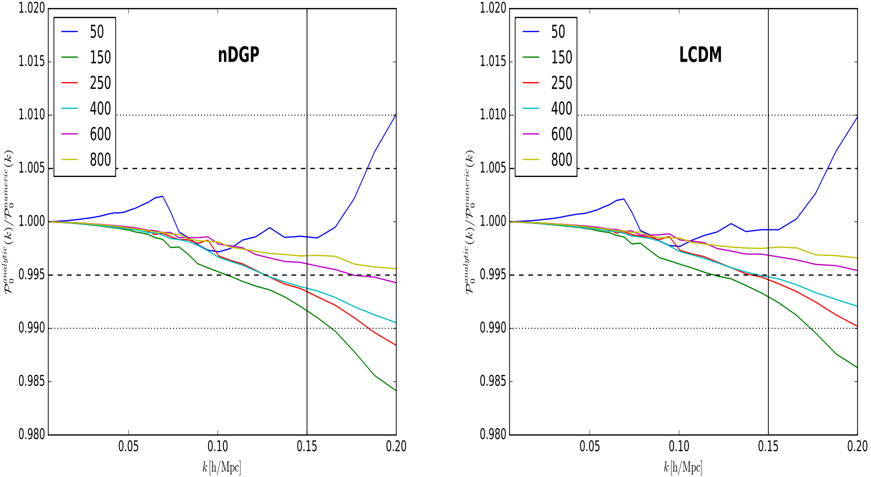
- Framework tested for Vainshtein and Chameleon screened model : nDGP and Hu-Sawicki form of f(R) gravity.

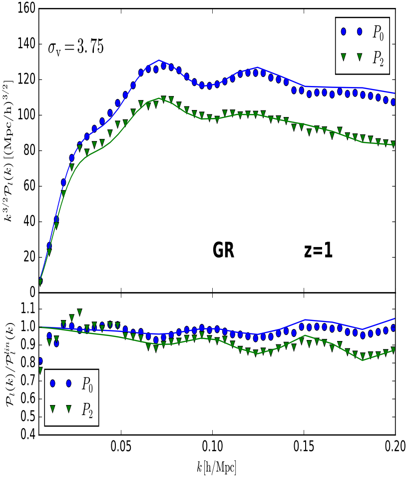
Consistency Test: Einstein De Sitter

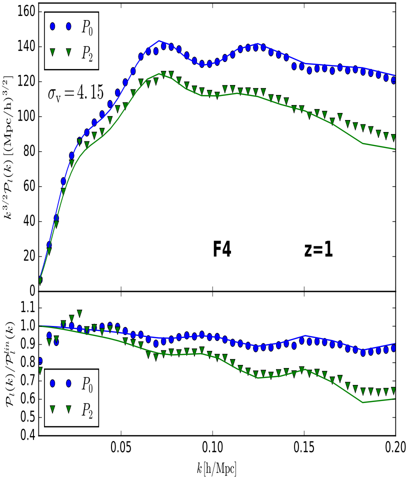


Separability Ansatz Test: nDGP and LCDM

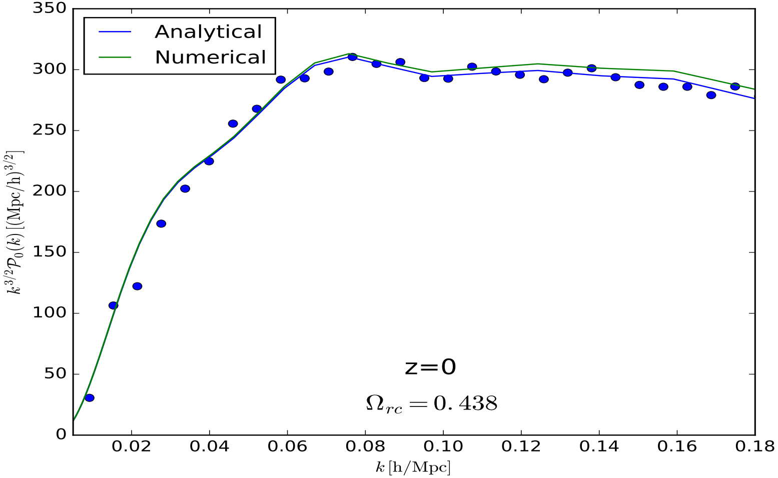


Comparison to n-body 1: f(R)

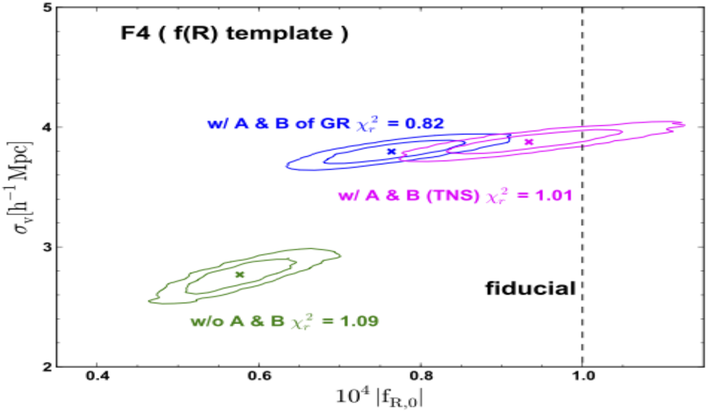




Comparison to n-body 2: nDGP



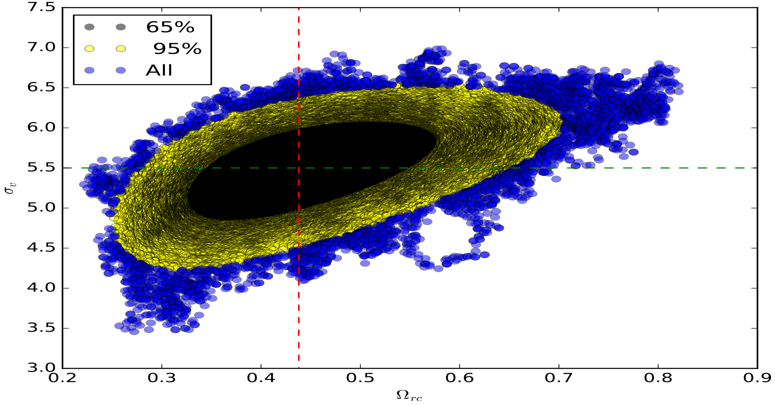
Parameter Recovery : Consistent Modelling Check



nDGP Case

Have integrated a simple MCMC algorithm into the code to do analysis for nDGP case.

Check of MCMC algorithm:



Effective Field Theory Extension

- Provides a range extension by introducing small-scale-uncertainty parameters c_s and c_s' (at loop level)

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$$P^{\delta\delta}_{EFT-one-loop} = P^{\delta\delta}_{1-loop} - c_s^2 k^2 P^{\delta\delta}_L$$
$$P^{\delta\theta}_{EFT-one-loop} \sim P^{\delta\theta}_{1-loop} - F[c_s^2, {c'}_s^2] k^2 P_L$$
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- Possibilities for cosmology independence - coarse grained approach to LSS (arXiv: 1407.1342v2).

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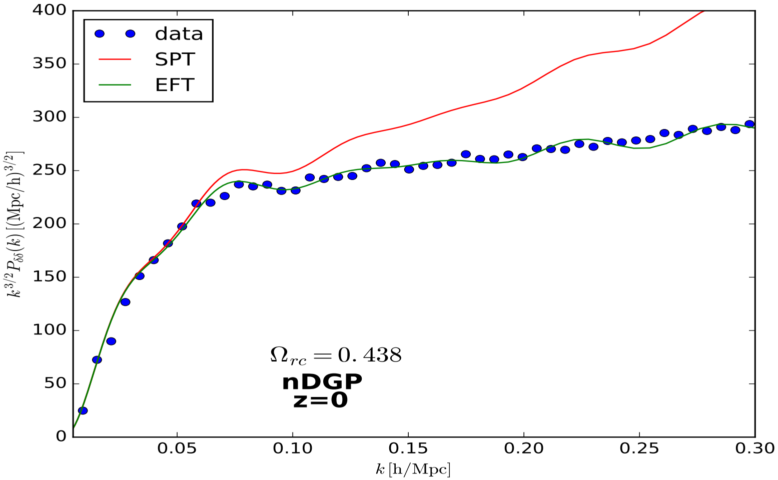
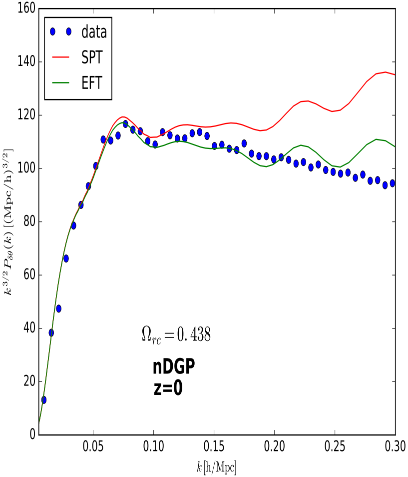
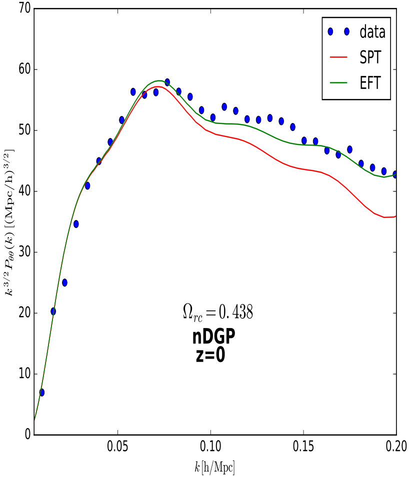
- Possibilities for cosmology independence - coarse grained approach to LSS (arXiv: 1407.1342v2).
- Investigate relation between c_s, c'_s and model parameters : matching has been done for n-body runs in $f(R)$ and nDGP models.

Some Preliminary Results



Some Preliminary Results 2





From k-Space to Redshift Space to Real Space: Gotta Code em All!

- Gaussian Streaming Model :

$$1 + \xi^s(r_y, r_z^s) = \int \frac{[1 + \xi^r(r)]}{\sqrt{2\pi\sigma_{12}^2}} e^{-[r_y - r_z - \mu v_{12}]^2/2\sigma_{12}^2} dy \qquad (1)$$

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- We have a working code which numerically computes v_{12} and σ_{12}^2 using SPT kernels.
- Very slow: some terms require 7 integrations + scale dependant kernel initialisation per step!


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AR
GSM Corr Func / CP 10^{10}
$\xi_s(r)$
C++
21

What else?

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- Check the template against galaxy mocks: MG mocks for BOSS are current works in progress.
- Use real data from ongoing and upcoming surveys and work towards gravity constraints : Euclid, DESI, SDSS and Subaru.

Summary and Conclusions

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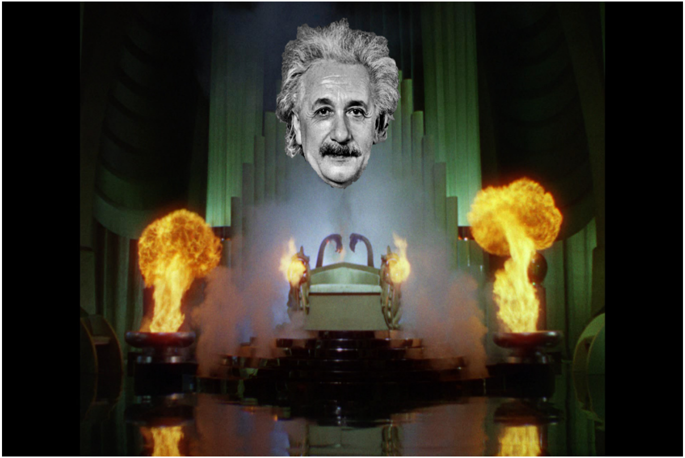
- Non-linear modelling is required to properly test them - TNS model.
- Code is capable of producing results and is working towards being very versatile.

Where is the curtain?



Thanks for listening!

Selected References:

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