TBD

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Contents

- Post-Friedmann Formalism

- Frame Dragging Potential

- N-body simulations and Tesselations

- Result

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Post-Friedmann Formalism

- Framework for structure formation beyond Newtonian limit

- Uses Newtonian/Post-Newtonian style $\frac{1}{c}$ expansion

- PN philosophy in Cosmology different from Solar System:

  Metric evolution $\Rightarrow$ Need consistent solution of Einstein Equations

- Gives Newtonian+ limit on small scales

- Bonus: Gives linear perturbation theory on large scales

Leading Order Gravitational Equations

$$\frac{1}{c^2}\nabla^2 V_N = -\frac{4\pi G a^2 \rho_b}{c^2}\delta$$

$$\frac{2}{c^2 a^2}\nabla^2(V_N - U_N) = 0$$

$$\frac{1}{c^3}\nabla^2 P_i^N = -\frac{16\pi G a^2 \rho_b}{c^3}(1+\delta)v_i + \frac{2}{c^3}\left(\dot{a}U_{N,i} + a\dot{V}_{N,i}\right)$$

- $g_{00} = -\left(1 - \frac{2U_N}{c^2} + \frac{1}{c^4}(2U_N^2 - 4U_P)\right)$
- $g_{0i} = -a\left(\frac{P_i^N}{c^3} + \frac{P_i^P}{c^5}\right)$
- $g_{ij} = a^2\left(\left[1 + \frac{2V_N}{c^2} + \frac{2V_N^2 + 4V_P}{c^4}\right]\delta_{ij} + \frac{h_{ij}}{c^4}\right)$

Frame-Dragging Potential

- What is it physically?

  An object's rotation affects spacetime; it "drags" spacetime around

- How can we calculate it?

$$\nabla \times \nabla^2 \vec{P}^N = - \left(16\pi G \rho_b a^2\right) \nabla \times [(1 + \delta)\vec{v}]$$

  Sourced by purely Newtonian quantities

  Doesn't affect matter at this order

  Could affect e.g. photon geodesics

N-body simulations & tesselation

- Theory

  An N-body simulation should contain δ and $\vec{v}$

  $\Rightarrow$ We can obtain the Vector potential

- Practice

  Extracting velocities non-trivial

  Delauney Tesselation Field Estimator (DTFE)[1]

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[1]Bernardeau, F. & van de Weygaert, R. 1996, MNRAS, 279, 693

Schaap, W. E. & van de Weygaert, R. 2000, A& A, 363, L29 astro-ph/0011007

Schaap, W. PhD thesis "DTFE: the Delaunay Tessellation Field Estimator"

van de Weygaert, R. & Schaap, W. 2009, 665, 291 arXiv: 0708.1441

Cautun, M. & van de Weygaert, R., "The DTFE public software" arXiv: 1105.0370

Tesselation

- Why?

  "Normal" estimators-CIC etc, give mass-averaged not

  volume-averaged velocities

  Velocity field artificially set to zero in sparse regions

- How?

  Constructs tetrahedra, with nodes located at the particles' positions

  Velocities interpolated across tetrahedra $\Rightarrow \vec{v}$ known everywhere

  Field sampled at random points within grid cell and averaged
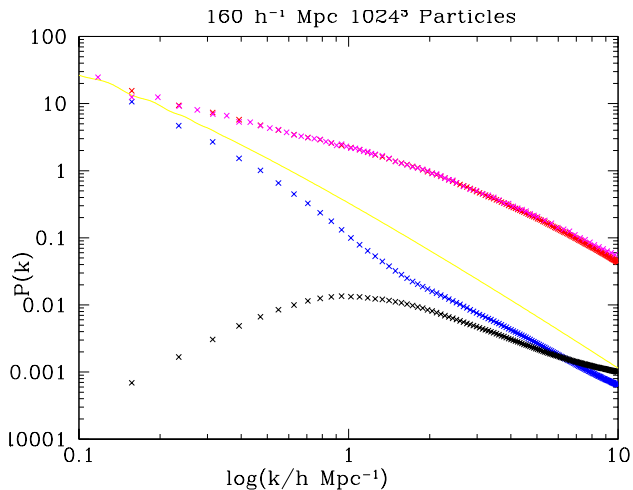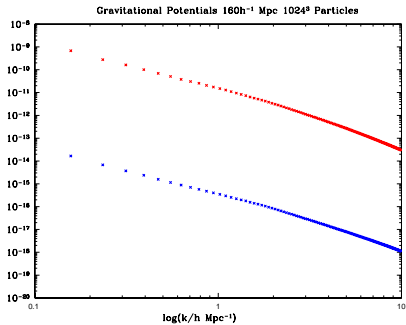
Extracted Power Spectra

Figure: Power Spectra of stuff

How much smaller is the power spectrum of P_i^N compared to the
Newtonian potential?

- 10 times smaller
- 10^3 times smaller
- 10^5 times smaller
- 10^7 times smaller
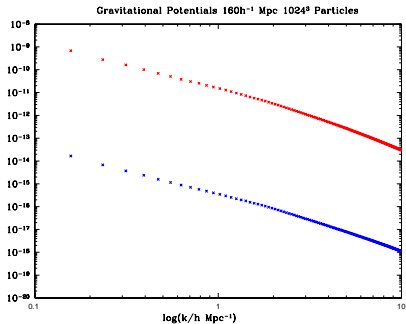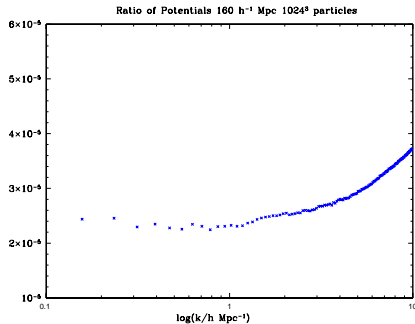- 10^9 times smaller

Results

Power Spe1tra of the S1alar Potential (red)

and Ve1tor Potential (blue)

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Ratio of Ve1tor potential to

s1alar potential

- Effect on convergence/weak lensing E-modes

Should we care?

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- Weak Lensing B-modes?

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  Here, other terms would contribute at same order $\left(\frac{1}{c^4}\right)$

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- Lensing of CMB photon polarisation?

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"A numerical evaluation of the frame-dragging potential in a

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3 ...!:

"How Einstein gravity is created from Newton's gravity getting in a twist"

Conclusions

- A consistent solution of the Einstein Equations in Cosmology suggests the existence of the vector potential

- We have measured the vector potential at this order (in the Post Friedmann/Newton expansion)

- This could be observable-Weak Lensing? CMB Polarisation? Suggestions?