Degeneracy between primordial non-Gaussianity and interaction in the dark sector

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Non-Gaussianity as a Probe of the Early Universe Physics

- The standard paradigm of inflation is mostly the best explanation of the origin of structure formation in the Universe.
- Single-field Inflationary models predict a nearly "scale-invariant" and "Gaussian" spectrum of initial fluctuations

$$P_\phi(k) \propto k^{n_s-1},$$

where the spectral index $n_s \sim 0.9 \pm 0.15$.

- Deviations from Gaussian initial conditions is a powerful constraint for the Inflationary mechanism.
- Large Primordial Non-Gaussianity (PNG) could be produced within multi-field inflation models.
- We consider PNG of local-type arising in standard inflationary models

$$\Phi = \phi + f_{\rm NL}(\phi^2 - <\phi>^2),$$

where f_{NL} is the non-Gaussianity parameter.

Detecting PNG using Large Scale Structure Observations

- Higher order correlations of the three-dimensional galaxy distributions (eg. Galaxy Bispectrum)

$$B_\Phi(k_1, k_2, k_3) = 2f_{\mathrm{NL}} P_\Phi(k_1) P_\Phi(k_2) + 2\mathrm{cyc},$$

  where P_Φ is the power spectrum.

- The large scale clustering of galaxies (peaks of the density distribution)

$$P_g(k, z) = b^2(k, z) P_m(k, z), \qquad b = b_G(z) + \Delta b(k, z),$$

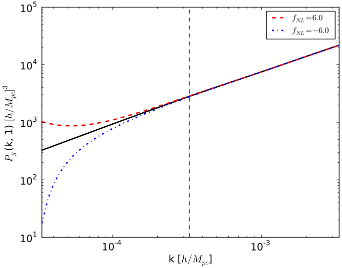
  where b is a scale-dependent bias between galaxies and underline dark matter.

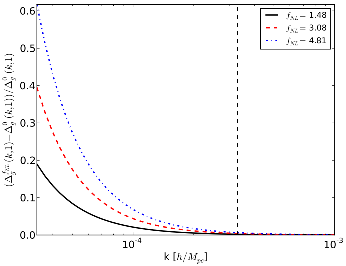
Non-Gaussian Scale-dependent Galaxy Bias

- The Scale-dependent galaxy bias is given by (Dalal et.al.)

$$\Delta b = 3 f_{\rm NL}(b_G - 1)\frac{\delta_c H_0^2 \Omega_{m0}}{k^2 T(k) D_m},$$

where D_m is the matter growth function and $T(k)$ is the transfer function.

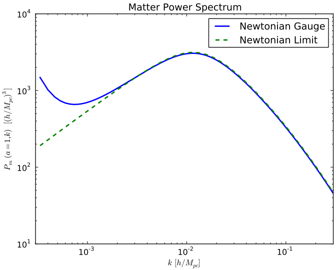




Other Large Scale Signals in the Galaxy Power Spectrum

- Gauge False signal (Bruni et.al.)

$$\nabla^2\Phi = \frac{3}{2}\mathcal{H}\Omega_m\left[\delta_m^N - 3\mathcal{H}v_m\right], \qquad \nabla^2\Phi \sim \frac{3}{2}\mathcal{H}\Omega_m\delta_m^c.$$



- To avoid gauge dependent bias, we use gauge-invariant matter overdensity

$$\Delta_m = \delta_m - 3\mathcal{H}v_m,$$

Other Large Scale Signals in the Galaxy Power Spectrum

- General Relativist (GR) Corrections to the observed galaxy overdensity including redshift space distortion and weak lensing (Duniya et.al.)

$$\Delta_g = b\Delta_m - \frac{1}{\mathcal{H}}(n^i\partial_i)^2 v_m$$

$$-(1-Q)\int_0^{r_0} \frac{dr}{r}\left[\nabla^2 - (n^i\partial_i)^2 - 2r^{-1}n^i\partial_i\right]\Phi + \Delta^{rel},$$

where Q is the magnification bias, n is the unite direction of observation and r is the comoving radial distance.

- Interaction in the Dark Sector

$$\nabla^2\Phi = \frac{3}{2}\mathcal{H}^2\Big(\sum\nolimits_A \Omega_A\Delta_A - \mathcal{Q}^\Phi\Big),$$

where

$$\mathcal{Q}^\Phi = \frac{a}{\rho_t}\sum\nolimits_A Q_A v_A = \frac{a}{\rho_t}Q_x(v_x - v_m).$$

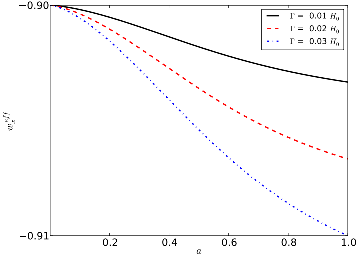
Coupled Multi-Dark Fluid: Background behaviour

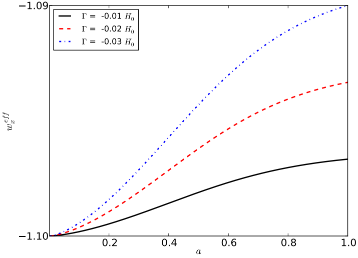
- The background continuity equations are (where $A = m, x$)

$$\rho_A' + 3(1 + w_A)\rho_A = \frac{aQ_A}{\mathcal{H}}, \quad Q_x = -Q_m.$$

- We can rewrite the above in terms of an effective equation of state:

$$\rho_A' + 3(1 + w_A^{\rm eff})\rho_A = 0, \quad w_A^{\rm eff} = w_A - \frac{aQ_A}{3\mathcal{H}\rho_A}.$$





$$Q_x = -Q_m = \Gamma\rho_x,$$

Coupled Multi-Dark Fluid: Perturbation System

For two coupled dark matter (A = m) and dark Energy fluids (A = x),

$$v'_A + v_A + \frac{c_{sA}^2}{(1+w_A)\mathcal{H}}\Delta_A + \frac{\Phi}{\mathcal{H}} = \mathcal{Q}_A^v,$$

$$\Delta'_A - 3w_A\Delta_A - \frac{k^2}{\mathcal{H}}(1+w_A)v_A - \frac{9}{2}\mathcal{H}(1+w_A)(1+w_t)(v_A - v_t) = \mathcal{Q}_A^\Delta,$$

where the source terms on the right encode the effect of interactions,

$$\begin{aligned}
\mathcal{Q}_A^v &= \frac{a}{(1+w_A)\rho_A\mathcal{H}}\Big[Q_A\,(v_t - v_A) + f_A\Big], \\
\mathcal{Q}_A^\Delta &= \frac{aQ_A}{\rho_A}\left[\frac{Q'_A}{Q_A} - \frac{\rho'_A}{\rho_A}\right]v_A \\
&\quad - \frac{aQ_A}{\rho_A}\left[3 + \frac{aQ_A}{(1+w_A)\rho_A\mathcal{H}}\right](v_t - v_A) \\
&\quad - \frac{a}{\rho_A}\left[3 + \frac{aQ_A}{(1+w_A)\rho_A\mathcal{H}}\right]f_A \\
&\quad + \frac{aQ_A}{\rho_A}\left[3(1+w_A) + \frac{aQ_A}{\rho_A\mathcal{H}}\right]v_A + \frac{a}{\rho_A\mathcal{H}}\delta Q_A
\end{aligned}$$

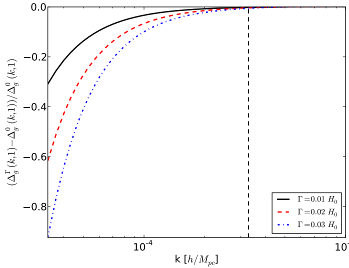
Scale-Dependent Matter Growth Function

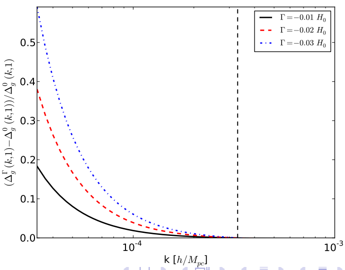
- We consider simple phenomenological model of interacting Dark Energy (IDE)

$$Q_x^\mu = -Q_m^\mu = \Gamma \rho_x u_x^\mu ,$$

where Γ is a constant interaction rate.

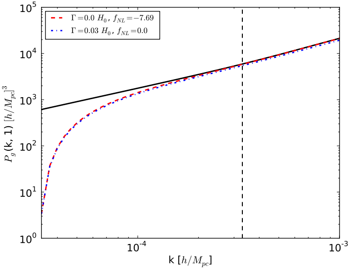
- $\Gamma > 0$ – represents a *transfer of energy density from dark matter to dark energy*. Stability of this model requires $w_x > -1$ (Valiviita et.al.).
- $\Gamma < 0$ – represents the *decay of dark energy to dark matter*. Stability of this model requires $w_x < -1$.

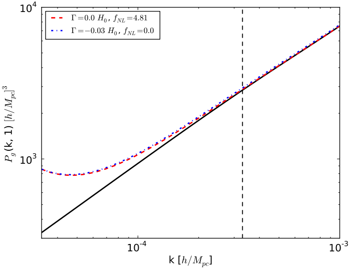




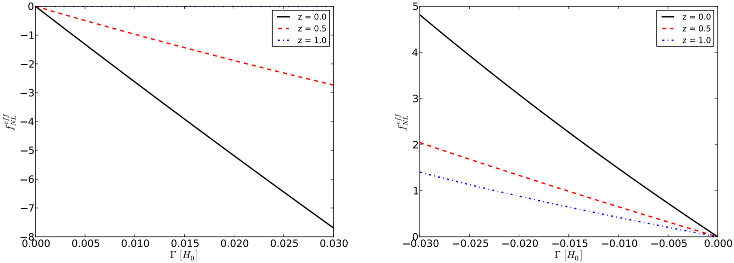
Mimicking PNG signal on large Scales

- Since IDE and PNG introduce a similar signal in the galaxy power spectrum on large scales, these signals might mimic each other.
- This raises the problem that attempts to constrain PNG through the galaxy power spectrum could be confused by interaction in the dark sector.





Effective NG and High Redshift Disentanglement



- On very large scales ($k << H_0$), the effective NG is given by

$$f_{\rm NL}^{\rm eff} \approx \left[\frac{5a_d}{9A}\frac{a\Omega_{md}\mathcal{H}_d^2}{\Omega_{m0}H_0^2}\frac{b_G}{(b_G-1)\delta_c}\frac{\Omega_x}{\Omega_m}\left(\frac{k}{H_0}\right)^{(4-n_s)/2}(v_x-v_m)\right]\Gamma$$

Summary

- PNG is a very good tool to distinguish between different inflationary mechanisms.
- PNG introduce scale-dependent bias between Galaxies and the underlying dark matter.
- Interaction in the dark sector also enhance the power spectrum on large scales via scale-dependent matter growth function.
- IDE and PNG Mimicking signs in the galaxy power spectrum make it no longer "robust" for LSS constraint.
- One could "disentangle" between the two signals by measuring the galaxy power spectrum at different redshifts.

THANK YOU