Observational Signature for Modified Gravity

Particle Physics and Cosmology 2012

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Observational Signals for Modified Gravity

Outline

Observations

- Background evolutions (SNe).
- Linear perturbations (CMB, LSS).
- Non-Linear perturbations (Clusters).

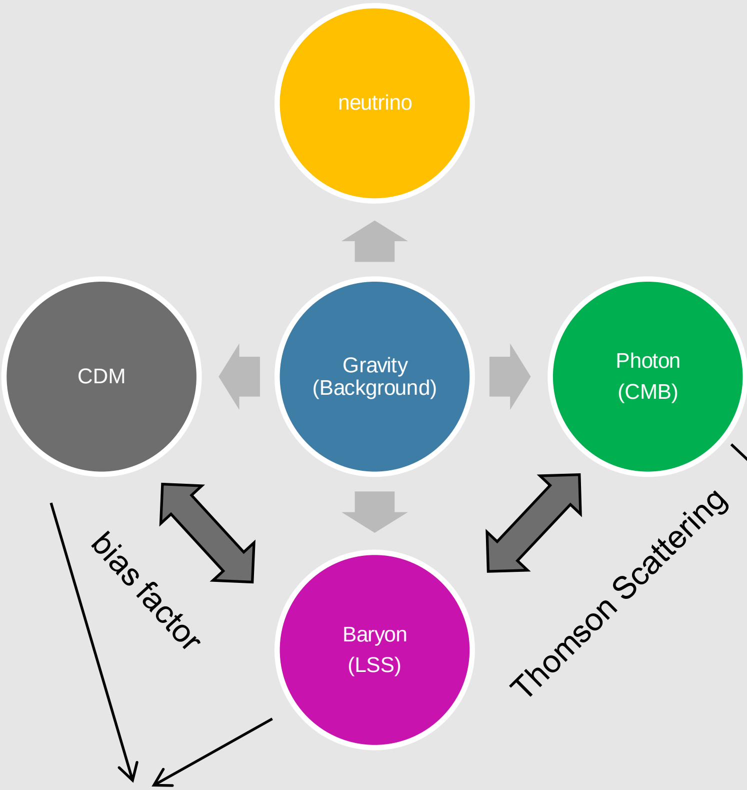
Modification on Observations

- Jordan or Einstein Frame
- Changes in linear densities
- Changes in critical density, mass function, and normalization.

Conclusion

Observational Signals for Modified Gravity

Cosmic expansion & Growth of Structure



- Cosmic background evolution is determined by all the constituents
- Baryon and photon are coupled by Thomson scattering
- b-γ fluid moves under gravitational potential well generated by CDM
- Assume massless ν

Linear perturbation

Both linear & nonlinear

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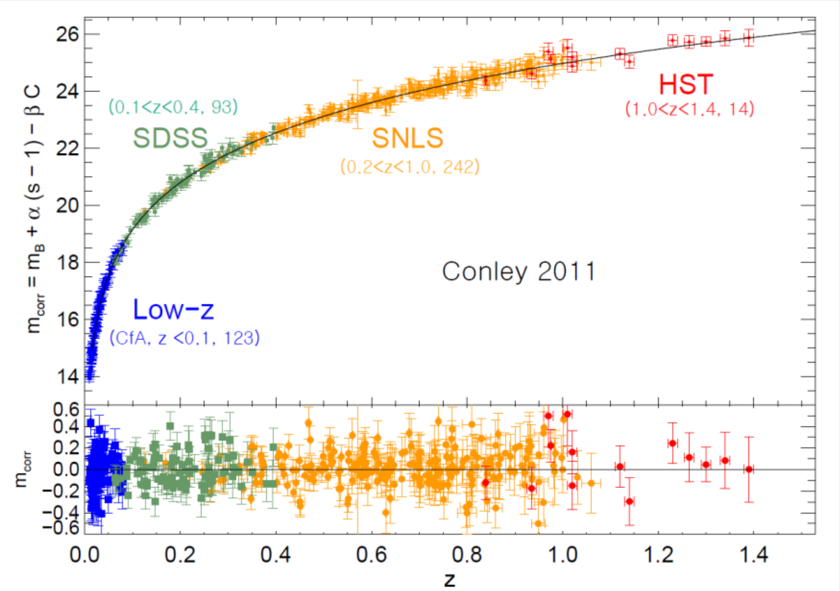
Parameter Dependence : SNe



- Distance module $\mu \equiv 5log_{10}\left(\frac{D_L(z)}{10pc}\right)$

$$D_L(z) = (1+z)\int_0^z \frac{dz'}{H_0\sqrt{\Omega_{m0}(1+z')^3 + \Omega_{DE0}(1+z')^{3(1+\omega)}}}$$

- Background evolution
- Also BAO, H, CMB 1st peak location

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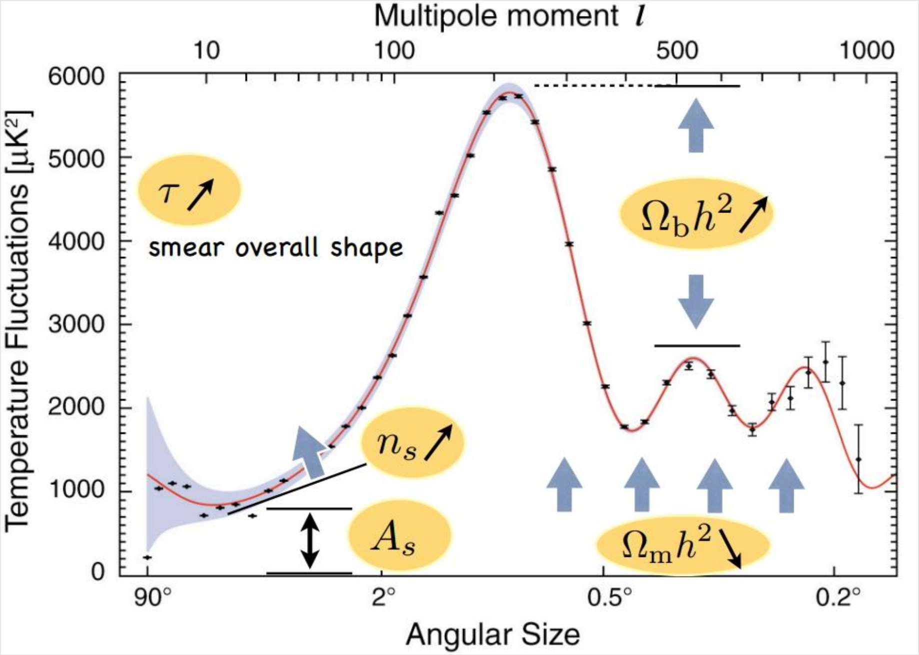
Parameter Dependence : CMB (also see Arman`s talk)



- τ (reionization optical depth) : amplitude lowered by $e^{-\tau}$
- As (normalization) : primordial density fluctuation $A_s = 2\pi^2\delta_H^2(c/H_0)^{n_s+3}$
- ns : SW plateau l < 40
- Maximum compressions = odd peaks

: increase as baryon density does

- Maximum rarefactions = even peaks

: increase as dark matter does

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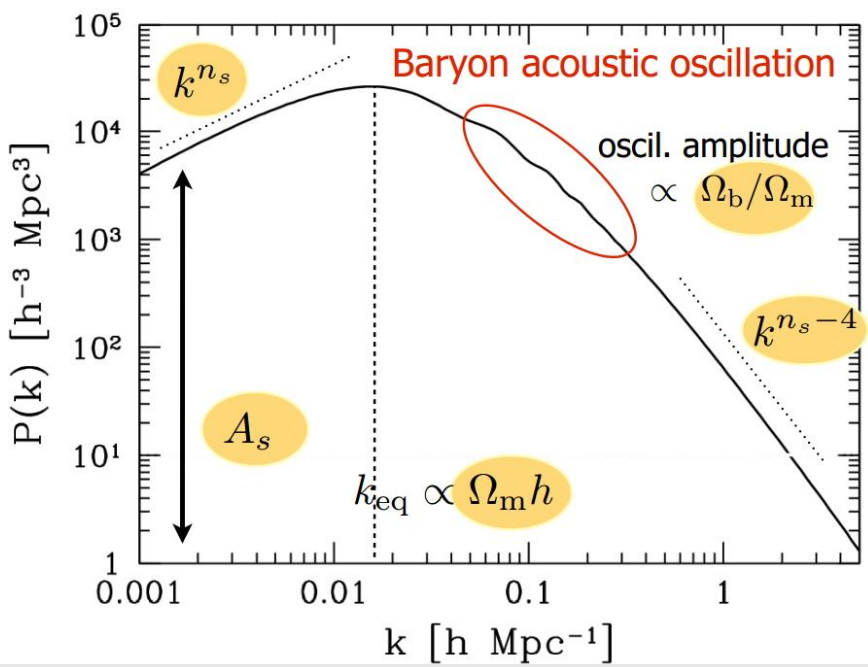
Parameter Dependence : LSS



- Harrison-Zeldovich : ns ≈ 1
- As (normalization) : primordial density fluctuation
- keq : $k_{eq} = 2\pi \frac{a(t_{eq})}{d_H(t_{eq})}$
- BAO
- Below Jean’s length : suppressed by k^4 (impossible to measure)

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Parameter Dependence : CL

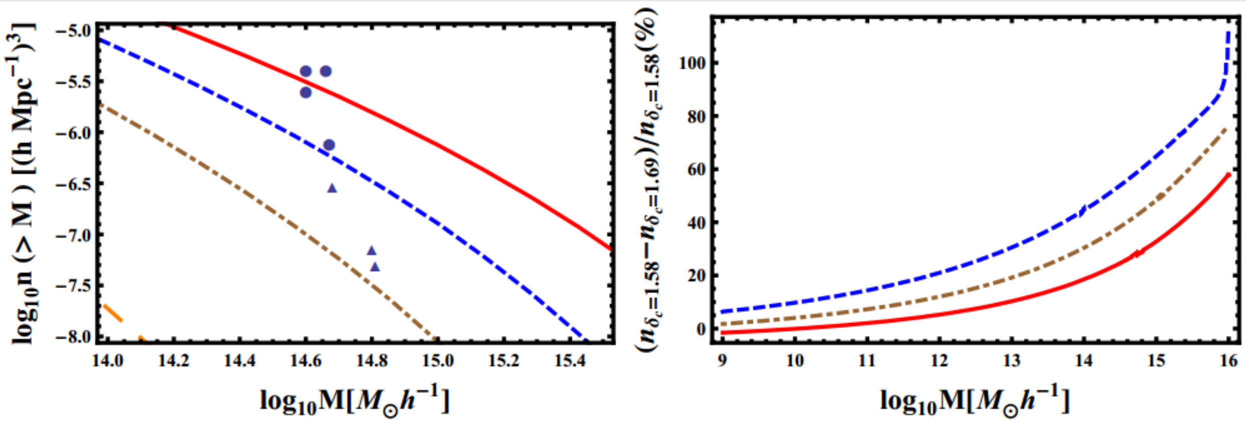

Figure 5: a) The comoving number density of clusters n of mass greater than M for different values of $z = 0$, 0.5, 1.0, and 2.0 (from top to bottom) when $\omega_Q = -1$ and $\delta_c = 1.58$. The circular ($z \simeq 0$) and triangular ($0.18 \le z \le 0.85$) dots represent the data from Ref. [33]. b) Errors of n when we use the correct threshold density contrast $\delta_c = 1.58$ instead of 1.69 for different values of $z = 0$, 0.5, and 1.0 (from bottom to top).

$$dn(M,z) = \sqrt{\frac{2}{\pi}} \frac{\rho_m^0}{M^2} \left| \frac{d\ln\sigma}{d\ln M} \right| \frac{\delta_c}{\sigma} \exp\left[-\frac{\delta_c^2}{2\sigma^2}\right] dM$$

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Background evolutions on Jordan vs Einstein Frame

$$\begin{aligned}
S &= \frac{1}{2\kappa}\int d^4x\sqrt{-g}f(R) + S_m(g_{\mu\nu},\psi) \\
&= \frac{1}{2\kappa}\int d^4x\sqrt{-g}\Big[f(\chi)+f'(\chi)(R-\chi)\Big] + S_m(g_{\mu\nu},\psi)\ ,\chi = R\,, f''(\chi)\neq 0 \\
&= \frac{1}{2\kappa}\int d^4x\sqrt{-g}\Big[\Phi R - V(\Phi)\Big] + S_m(g_{\mu\nu},\psi)\ ,\Phi = f'(\chi)\,, V(\Phi) = \chi\Phi - f(\chi) \\
&= \int d^4x\sqrt{-g^E}\Big[\frac{R^E}{2\kappa} - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\Big] + S_m(\frac{g^E_{\mu\nu}}{\Phi},\psi)\ g^E_{\mu\nu} = \Phi g_{\mu\nu}
\end{aligned}$$

- Mathematically two frames are same.
- How about physics? Any preferences? Still under debate
- However, one should stick on one frame after using one frame for the background evolution. Because

$$dt^E = \sqrt{\Phi}dt,\ a^E = \sqrt{\Phi}a,\ H^E = H/\sqrt{\Phi} + (1/2)\dot{\Phi}/\Phi^{3/2}$$

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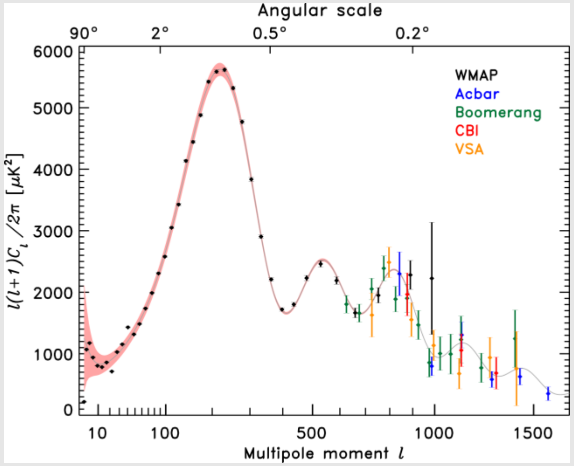
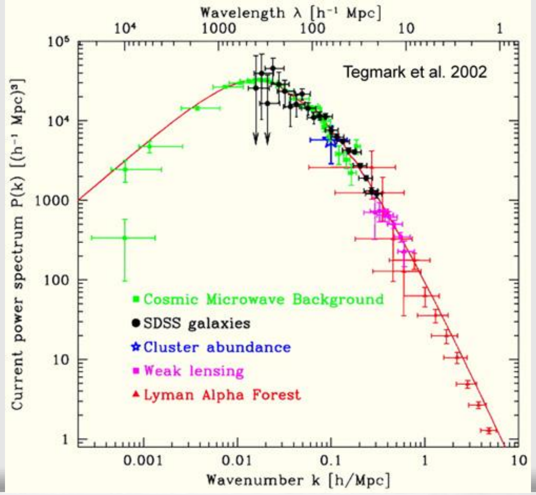
CMB



- $$\Delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$
- $$\begin{aligned} C_l &= \frac{1}{2l+1}\sum_{m=-l}^{l} |a_{lm}|^2 \\ &= \frac{2}{\pi}\int_0^\infty dk k^2 \boxed{P_{init}(k)} \left|\frac{\theta_l(k;\eta_0)}{\delta_m(k;\eta_{init})}\right|^2 \end{aligned}$$

LSS



- $$\frac{n_{gal}(\vec{x})}{\bar{n}_{gal}} - 1 = \int d^3\vec{x}\,\delta(\vec{k}) e^{i\vec{k}\cdot\vec{x}}$$
- $$\begin{aligned} P(k) &= \frac{1}{(2\pi)^3}\sum_{|\vec{k}|=k} |\delta(\vec{k})|^2 \\ &= \boxed{P_{init}(k)} \left|\frac{\delta_m(k;\eta_0)}{\delta_m(k;\eta_{init})}\right|^2 \end{aligned}$$

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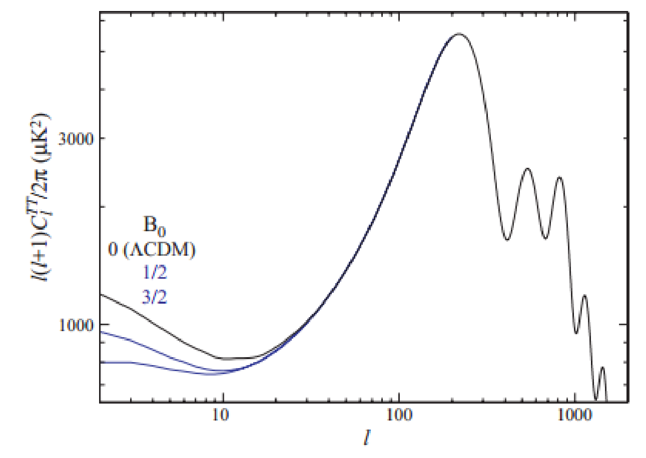
CMB



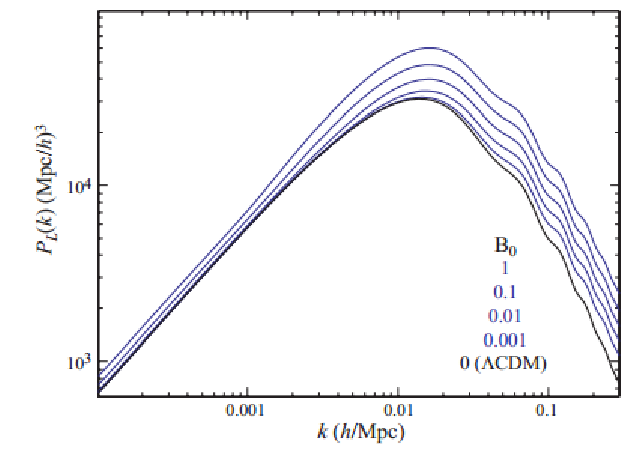
$$ds^2 = -(1+2\Phi)dt^2 + (1-2\Psi)a^2(t)d\vec{x}^2$$

$$\Psi - \Phi = \frac{\delta F}{F} \qquad \Psi \simeq \frac{1}{2F}\left(\delta F - \frac{a^2}{k^2}\kappa^2\delta\rho_m\right)$$

$$\Phi \simeq \frac{1}{2F}\left(\delta F + \frac{a^2}{k^2}\kappa^2\delta\rho_m\right) \qquad B = \frac{f_{RR}}{1+f_R}R'\frac{H}{H'}$$

$$\left.\frac{\Delta T}{T}\right|_{ISW} = -\int \frac{d(\Phi+\Psi)}{dt}a(t)d\chi \qquad \chi(z) = \int_0^z \frac{dz'}{H(z')}$$

LSS



$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G_{eff}\rho_m\delta_m \simeq 0$$

$$G_{eff} = \frac{G}{F}\frac{4+3M^2a^2/k^2}{3(1+M^2a^2/k^2)}$$

Current results are limited by a parameterized post Friedmann (PPF) framework based on $\omega_{eff} = -1$

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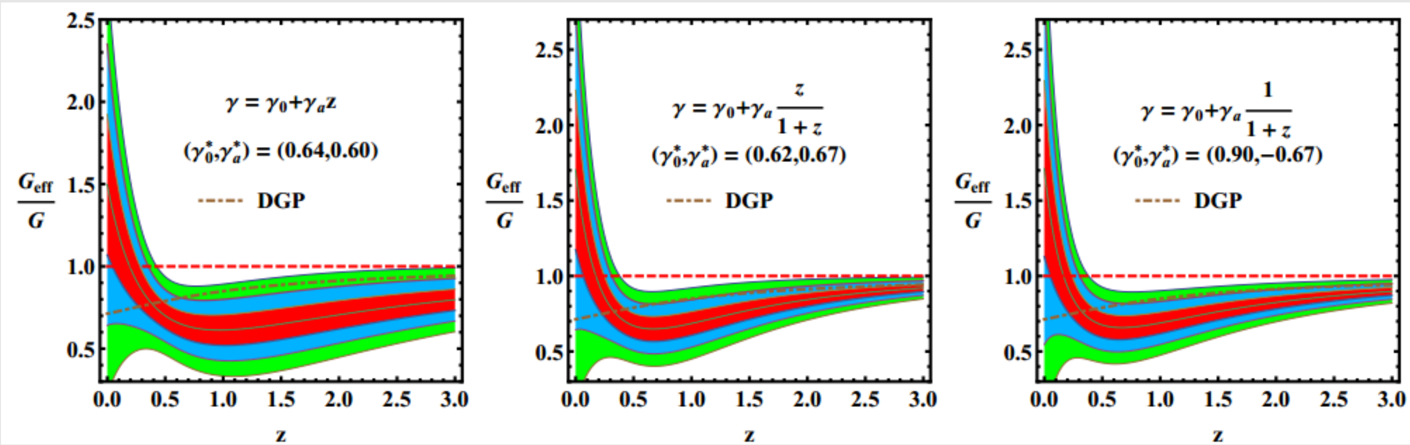
Observational evidence of deviation from ΛCDM (also see Shinji's talk)



- $f(a) \equiv \dfrac{d\ln D}{d\ln a} \simeq \Omega_{\rm m}(a)^{\gamma}$ $\quad \ddot{\delta}_{\rm m} + 2H\dot{\delta}_{\rm m} = 4\pi G_{\rm eff}\rho_{\rm m}\delta_{\rm m}$
- $$g(a) \equiv \frac{G_{\rm eff}}{G_{\rm N}} = \left(f(a)^2 + \left[\frac{1}{2} + 3\omega\Big(1 - \Omega_{\rm m}(a)\Big)(\gamma - \frac{1}{2}) + \frac{d\gamma}{d\ln a}\ln\Omega_{\rm m}(a)\right] f(a) \right) \frac{2}{3\Omega_{\rm m}(a)}$$

- Data may already show deviation from ΛCDM ?

Conclusions

Background

- Need to decide the frame first to fix the model parameters with background evolution
- Go beyond PPF (numerically difficult)

Perturbations

- How to perform Boltzmann equations without PPF
- Normalization and b(k,z)
- Beyond linear region ?

Thanks !