Are redshift-space distortions actually a probe of growth of structure

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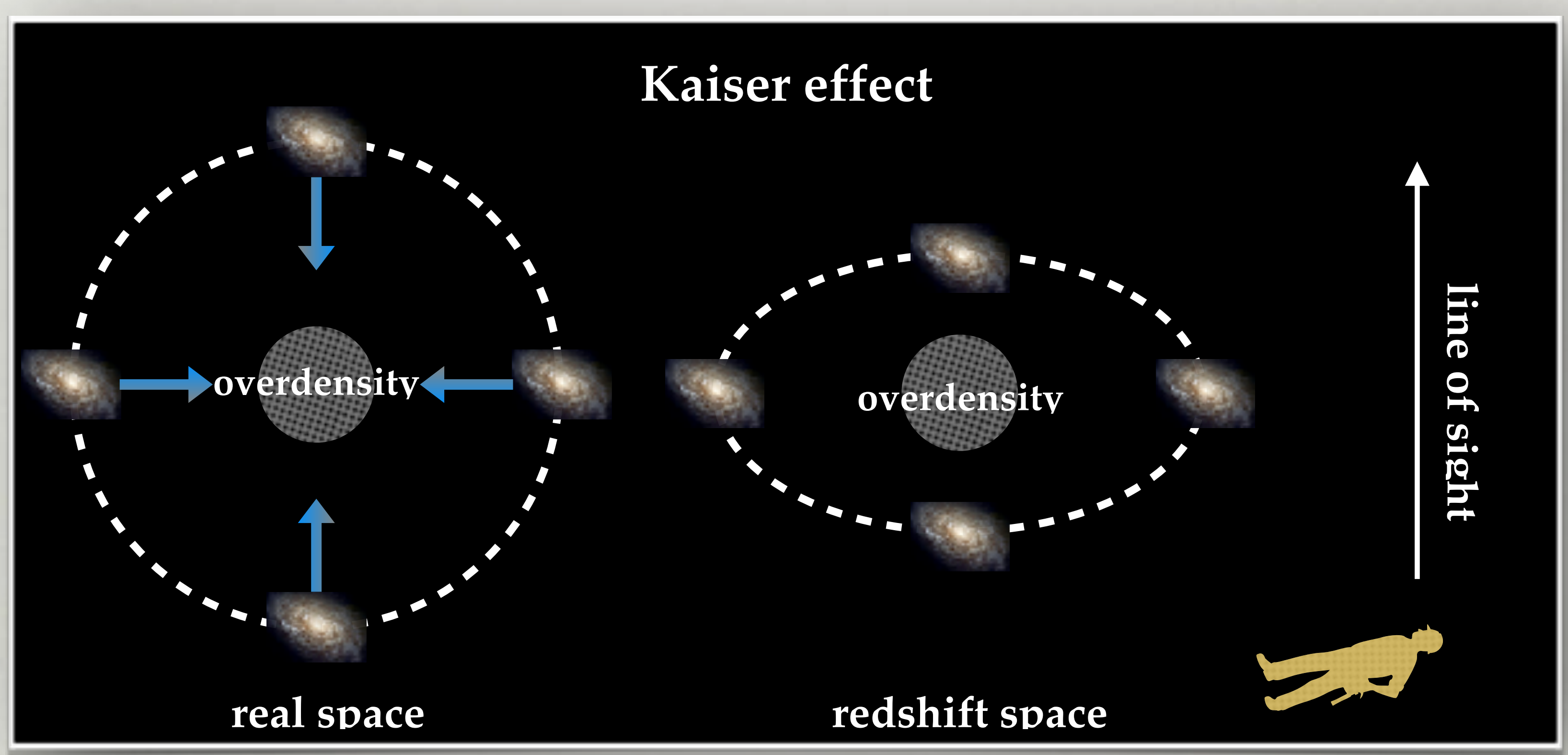
Standard Cosmology I



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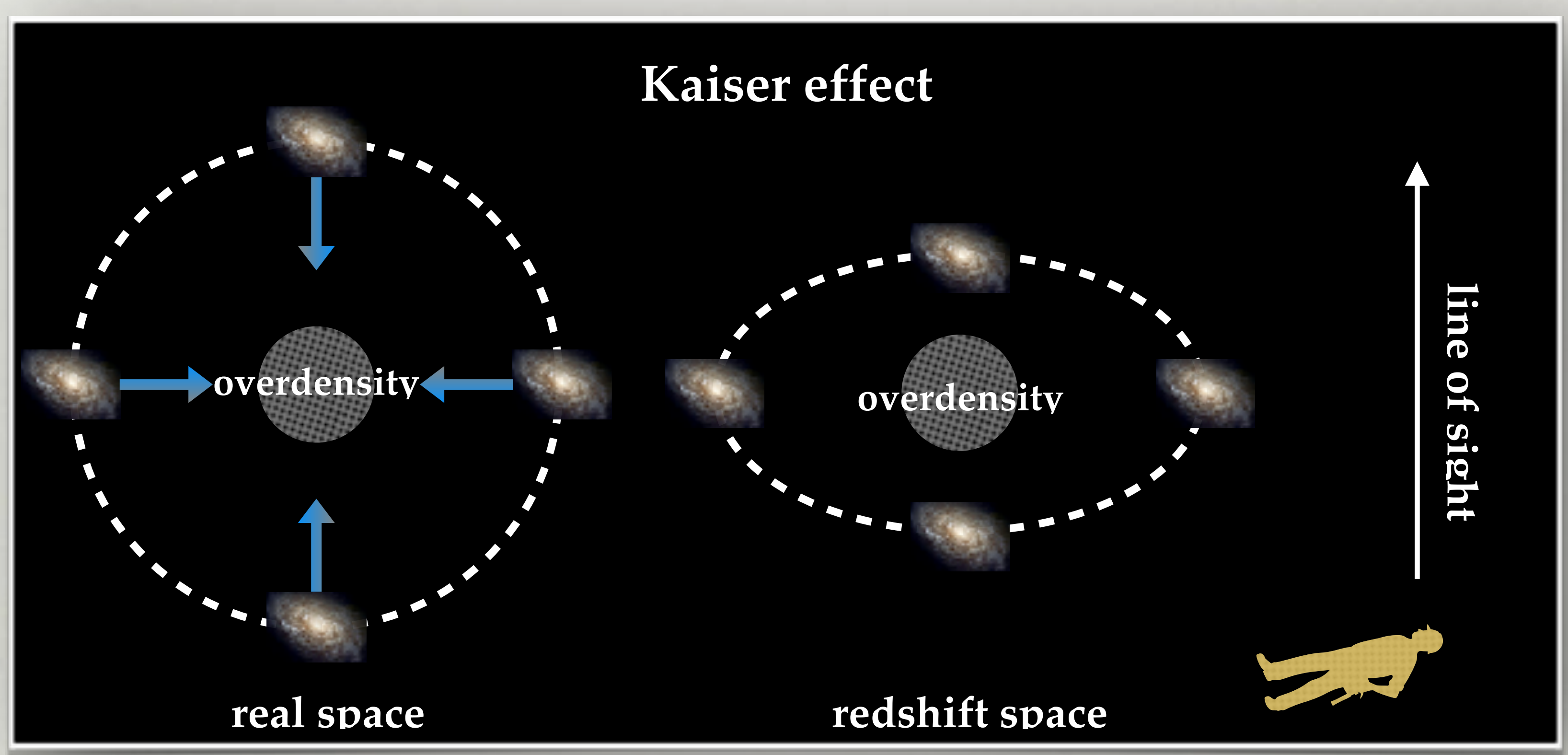


Mapping to redshift space

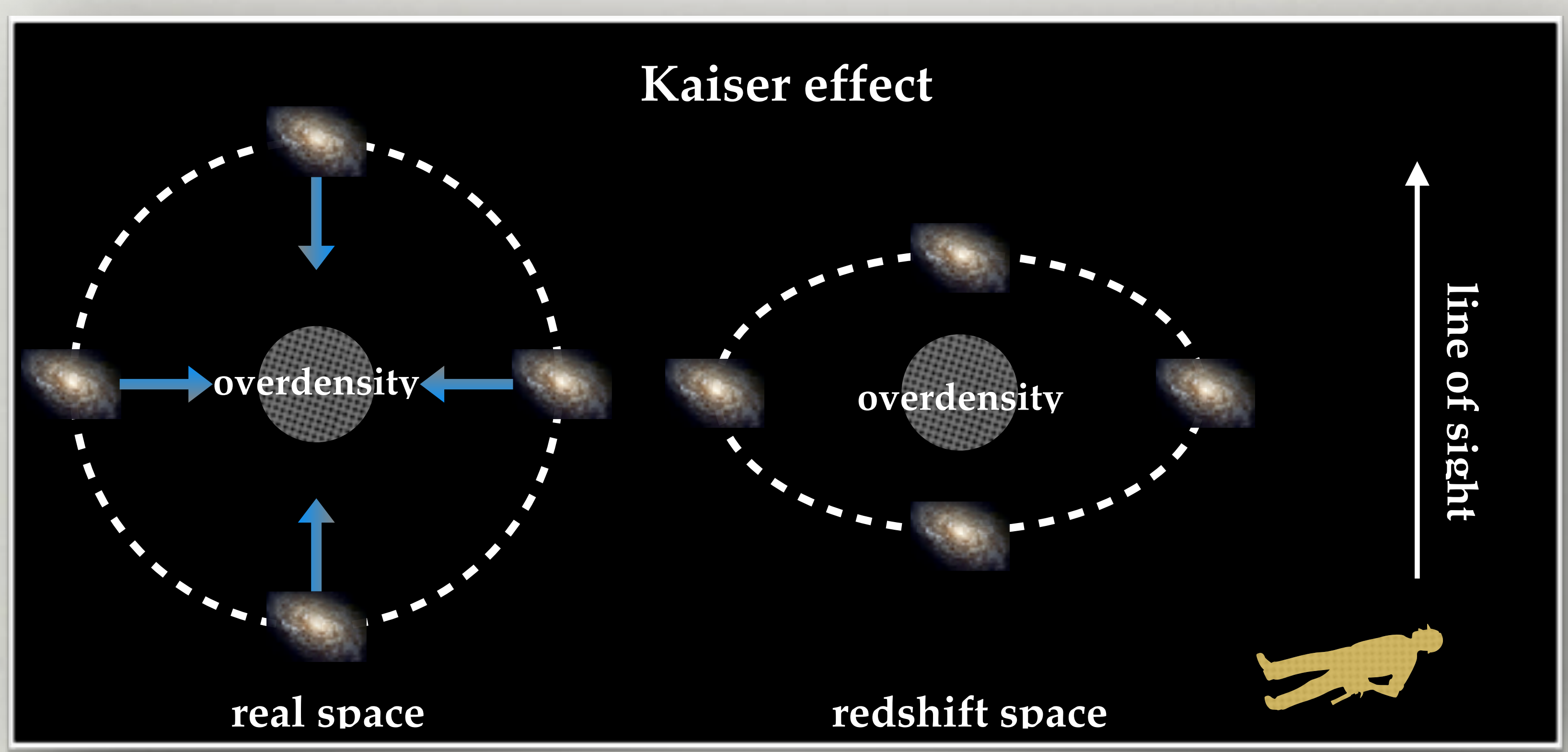
galaxy density contrast in real space

galaxy density contrast in redshift space

$$\delta_{g,s} = \delta_g - \frac{1}{aH}\nabla_z v_{g,z}$$

line of sight component of galaxy peculiar velocity

STANDARD COSMOLOGY I



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Galaxy vs. matter distribution

$$\delta_g = b_g \delta_m \qquad \text{(linear bias)}$$

$$v_g = v_m$$

Standard Cosmology II

- Newtonian gauge $$\mathrm{d}s^2 = -[1+2\Phi(t,\boldsymbol{x})]\mathrm{d}t^2 + a^2(t)[1-2\Psi(t,\boldsymbol{x})]\mathrm{d}\boldsymbol{x}^2$$
- Basic equations (sub-horizon approximation)

$$\frac{k^2}{a^2}\Psi = \frac{k^2}{a^2}\Phi = -4\pi G\rho_{\rm m}\delta_{\rm m}$$ (Poisson equation)

$$\dot{\delta}_{\rm m} + \frac{k^2}{a^2}v_{\rm m} = 0 \qquad \dot{v}_{\rm m} - \Phi = 0$$ (**continuity** & Euler equation)

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- Growth factor $D_{\rm m}$ $$\delta_{\rm m}(t,\mathbf{k}) = D_{\rm m}(t)\,\delta_0(\mathbf{k})$$ δ_0 : Initial density contrast
- Linear growth rate $f_{\rm m}$ $$f_{\rm m}(t) \equiv \frac{\mathrm{d}\ln D_{\rm m}}{\mathrm{d}\ln a}$$

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Standard Cosmology III

Kaiser formula

the cosine of the angle between the line of sight & Fourier momentum

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Power spectrum in redshift space

matter power spectrum

$$\beta \equiv \frac{f_{\mathrm{m}}}{b_{\mathrm{g}}}$$

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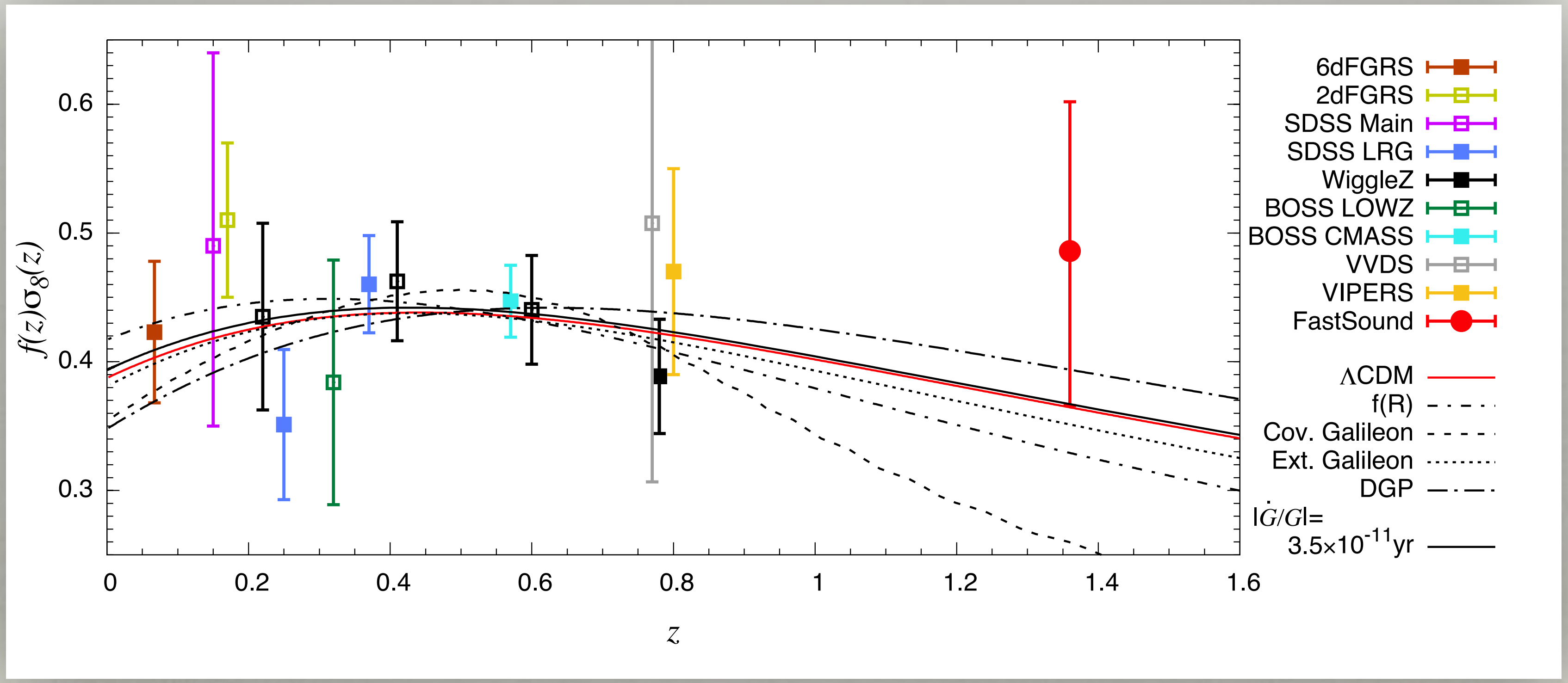

Okumura et al. Publ. Astron. Soc. Japan (2015) 00(0), 1–23

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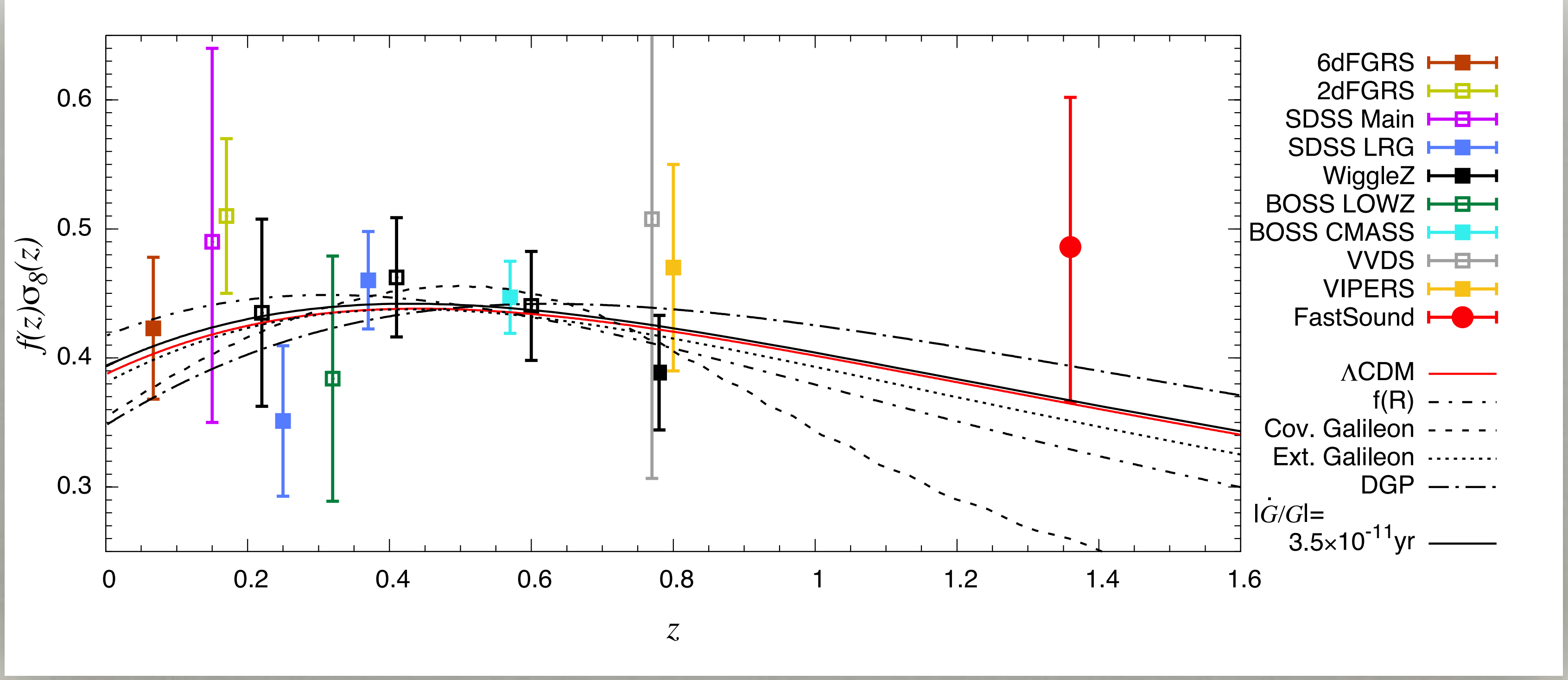

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Growth rate can directly measured by RSD

(bias can be fixed by cross-correlation of LSS & weak lensing)

Non-minimally Coupled DM

- **GR** + **scalar field** (Dark energy) $S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R[g] + \mathcal{L}_\phi[g,\phi]\right] + S_{\rm b} + S_{\rm c}$

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- Matter = (standard) **baryon** + **non-minimally coupled** **cold dark matter**

$$S_{\rm b} = \int d^4x\sqrt{-g}\mathcal{L}_{\rm b}[g_{\mu\nu},\psi_{\rm b}]$$

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$$\bar{g}_{\mu\nu} = A(\phi,X)g_{\mu\nu} + B(\phi,X)\partial_\mu\phi\partial_\nu\phi$$

(**conformal** & **disformal** coupling)

Baryon :	**sensitive** to solar-system experiments	→	**minimal** coupling
CDM :	**insensitive** to solar system experiments	→	**non-minimal** coupling

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Energy transfer between dark energy and CDM

Basic Equations

- Basic equations

EM tensor for the total matter

$$T^{(\mathrm{m})}_{\mu\nu} := T^{(\mathrm{b})}_{\mu\nu} + T^{(\mathrm{c})}_{\mu\nu}$$

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{1}{M_{\mathrm{Pl}}^2}\left(T^{(\mathrm{m})}_{\mu\nu} + T^{(\phi)}_{\mu\nu}\right)$$ (Einstein equation)

$$\nabla^\mu T^{(\mathrm{b})}_{\mu\nu} = 0$$ (Conservation equation for baryon)

$$\nabla^\mu T^{(\mathrm{c})}_{\mu\nu} = -Q\,\partial_\nu \phi$$ (Conservation equation for DM & DE)

$$\Box\phi - V_\phi = Q$$ (scalar field equation)

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- Q roughly represents **the magnitude of the coupling between DM & DE**

$$Q \equiv -\frac{1}{\sqrt{-g}}\frac{\delta(\sqrt{-g}\mathcal{L}_{\mathrm{c}})}{\delta\phi} = \nabla_\mu W^\mu - Z$$

$$Z = \frac{1}{2A}\left[\left\{A_\phi + \frac{A_X X(A_\phi - 2B_\phi X)}{A - A_X X + 2B_X X^2}\right\}T_{(\mathrm{c})} + \left\{B_\phi + \frac{B_X X(A_\phi - 2B_\phi X)}{A - A_X X + 2B_X X^2}\right\}T^{\mu\nu}_{(\mathrm{c})}\partial_\mu\phi\partial_\nu\phi\right]$$

$$W^\mu = \frac{1}{2A}\left[2B\,T^{\mu\nu}_{(\mathrm{c})}\partial_\nu\phi - \frac{A - 2BX}{A - A_X X + 2B_X X^2}\times\left(A_X T_{(\mathrm{c})} + B_X T^{\alpha\beta}_{(\mathrm{c})}\partial_\alpha\phi\partial_\beta\phi\right)\partial^\mu\phi\right],$$

Modified Kaiser Formula

(sub-horizon + quasi-static approximation)

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- Continuity & Euler equations for CDM are modified !!

$$\dot{\delta}_c + \frac{k^2}{a^2} v_c = R_0 \left(\dot{\delta}_c - \frac{Q_0}{\dot{\phi}} \delta_c \right)$$

v_c depends on time-derivative of density contrast and **density contrast**

$$\dot{v}_c - \Phi = \Gamma_1 \, v_c + \Gamma_2 \, \dot{\delta}_c + \Gamma_3 \, \delta_c$$

R_0, Q_0, Γ_i : depends on DM-DE coupling parameters

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- Evolution of density contrast of CDM

$$\ddot{\delta}_c + 2H_{\rm eff}\, \dot{\delta}_c - 4\pi G_{\rm eff}\, \rho_m \delta_m = 0$$

Growth rate also deviates from the standard cosmology

- Total matter = baryon + CDM $\left(T^{(\mathrm{m})}_{\mu\nu} := T^{(\mathrm{b})}_{\mu\nu} + T^{(\mathrm{c})}_{\mu\nu} \right)$

$$\delta_{\mathrm{m}} = \omega_{\mathrm{c}}\delta_{\mathrm{c}} + \omega_{\mathrm{b}}\delta_{\mathrm{b}} \qquad v_{\mathrm{m}} = \omega_{\mathrm{c}}v_{\mathrm{c}} + \omega_{\mathrm{b}}v_{\mathrm{b}} \qquad \omega_{\mathrm{I}} = \rho_{\mathrm{I}}/\rho_{\mathrm{m}}$$

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- Velocity of the total matter is modified due to modification of CDM equation

$$v_{\mathrm{m}}(t,\mathbf{k}) = -\frac{a^2 H}{k^2} f_{\mathrm{m}}^{\mathrm{eff}}(t)\delta_{\mathrm{m}}(t,\mathbf{k})$$

$$f_{\mathrm{m}}^{\mathrm{eff}} = f_{\mathrm{m}} + \Delta f_{\mathrm{m}}$$

Actual linear growth rate

DM-DE coupling effect

$$f_{\mathrm{m}}(t) \equiv \frac{\mathrm{d}\ln D_{\mathrm{m}}}{\mathrm{d}\ln a}$$

$$\Delta f_{\mathrm{m}} = -\omega_{\mathrm{c}}\frac{D_{\mathrm{c}}}{D_{\mathrm{m}}}\frac{\Upsilon_2}{1-\Upsilon_1}\left(f_{\mathrm{c}} - \frac{Q_0}{H\dot{\phi}}\right) - \omega_{\mathrm{b}}\frac{Q_0\dot{\phi}}{H\rho_{\mathrm{m}}}\frac{D_{\mathrm{c}}-D_{\mathrm{b}}}{D_{\mathrm{m}}}$$

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- **Single-redshift RSD observations** can not determine the actual growth rate and DM-DE coupling
- **Multiple-redshift RSD observations** can separate the actual growth rate and DM-DE coupling

Summary

Growth rate obtained from RSD

= actual growth rate + **DM-DE coupling effect**

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= actual growth rate + **DM-DE coupling effect**

- DM-DE interaction **modifies continuity and Euler equations** in a cosmological setup.
- Even in DM-DE **direct coupling** (not though conformal or disformal metric) we reach the same conclusion
- **Multiple-redshift RSD measurements** provide us information of both **the actual growth rate** and **DM-DE coupling**