Generalized Einstein-Aether as a dark energy fluid

Progress on Old and New Themes in cosmology
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Motivation

- ΛCDM is the most popular cosmological model for the universe.

- But there are problems…

- Alternatives? An easy way is to add a new field; scalar (Quintessence…), vector (Einstein-Aether…), tensor (bimetric…)

Generalized Einstein-Aether: the model

$$\mathcal{L}_A = M^2\mathcal{F}(\mathcal{K}) + \lambda(g_{\mu\nu}A^\mu A^\nu + 1)$$

$$\mathcal{K} = \frac{1}{M^2}K^{\alpha\beta}{}_{\mu\nu}\nabla_\alpha A^\mu \nabla_\beta A^\nu \qquad K^{\alpha\beta}{}_{\mu\nu} = c_1 g^{\alpha\beta}g_{\mu\nu} + c_2\delta^\alpha_\mu\delta^\beta_\nu + c_3\delta^\alpha_\nu\delta^\beta_\mu + c_4 A^\mu A^\nu g_{\mu\nu}$$

- A new vector field called the Aether.
- Constrained to be of time-like unit norm. This breaks Lorentz invariance.
- Similar to k-essence, the kinetic terms are generalized to a free function.
- “Kinetic terms” + “Potential terms”

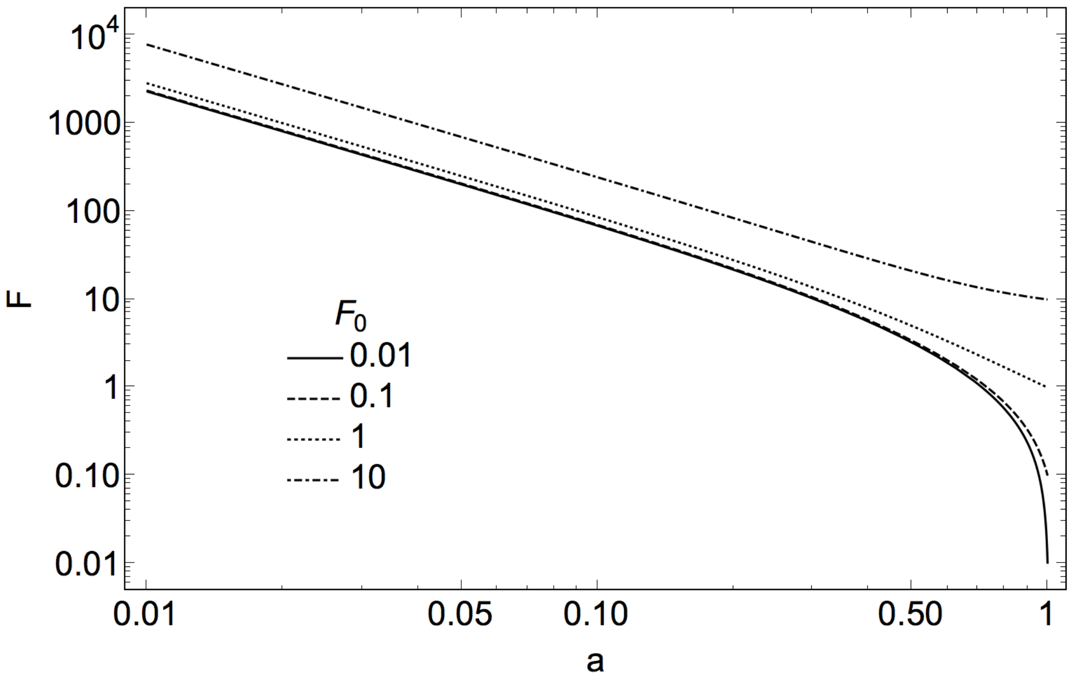
Background cosmology

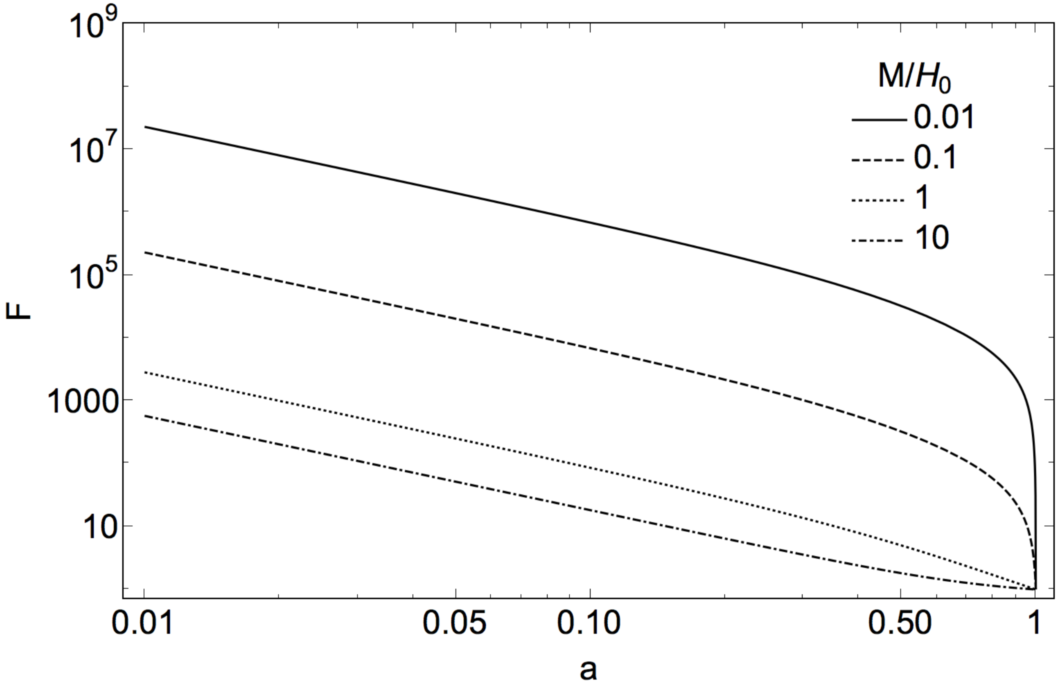
- What is F? It would be nice if we could specify some other observational parameters and obtain F from them e.g. designer F(R).

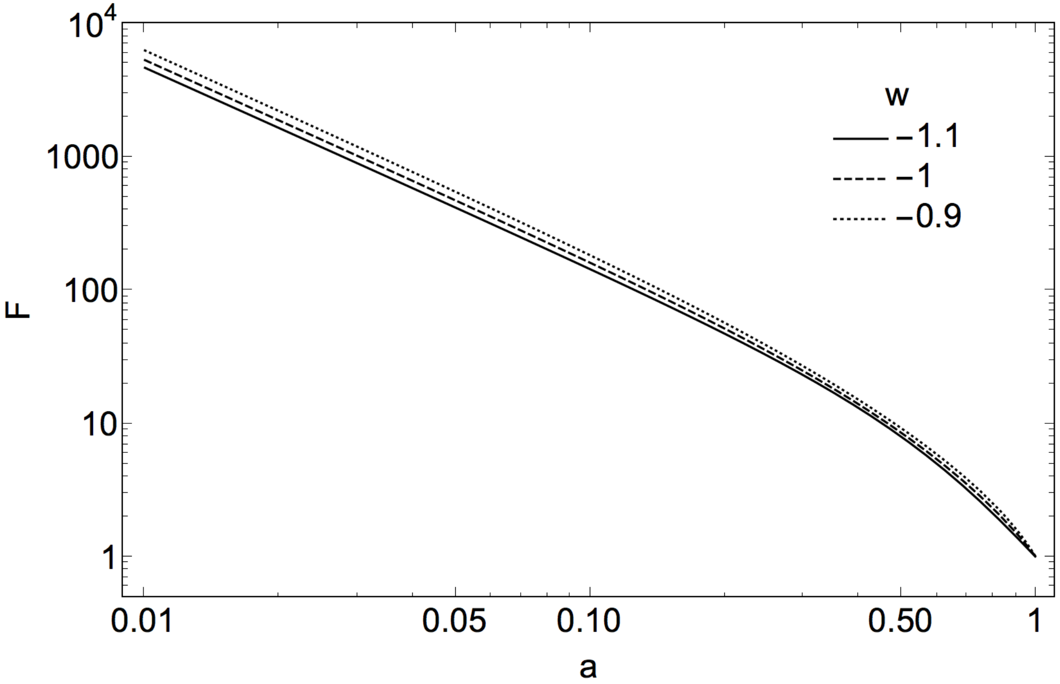
$$(1+w)\left(2\mathcal{K}\mathcal{F}_{\mathcal{K}} - \mathcal{F}\right) = \left(2\mathcal{K}\mathcal{F}_{\mathcal{K}\mathcal{K}} + \mathcal{F}_{\mathcal{K}}\right)\left[\mathcal{K} + \frac{1}{2}\alpha w\left(2\mathcal{K}\mathcal{F}_{\mathcal{K}} - \mathcal{F}\right)\right]$$

- Since the background is forced to match ΛCDM, the perturbations are now important.

- Gives us something to check for (e.g. CMB, weak lensing, …) without being contaminated by differences in background evolution.







Battye and Trinh, 2017; in prep.

Linear perturbations

- We have the dynamics at background level. Now we want the dynamics of the perturbations.
- We need to specify the metric, the Aether, and the gauge.

$$ds^2 = a^2(\tau)\left[-(1+2\Psi)d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j\right] \qquad \delta A^\mu = \frac{1}{a}(-\Psi, \partial^i V)$$

New degree of freedom

- We can now go ahead and compute all the equations of motion.

- How do we paramterize this theory (and other theories) at the level of linear perturbations?

Equation of State approach

Battye and Peasron, 2013

- Modified gravity or new fluid component?
- The EoS approach treats them as the same. It recasts any theory into an effective fluid.
- Ultimately a matter of interpretation.
- The EoS approach eliminates the new degrees of freedom induced by the modified gravity theory.

Equation of State approach

- At background, need an equation of state to close the equations of motion, w(a).

- What about for linear perturbations?

2 equations of state to compute

$$\left(\frac{\dot{\delta}}{1+w}\right) = -k^2\theta^S - \frac{1}{2}\dot{h} - \frac{3\mathcal{H}w}{1+w}\Gamma,$$

$$(1+w)\dot{\theta}^S = \mathcal{H}(1+w)\left(3\frac{dP}{d\rho} - 1\right)\theta^S + \frac{dP}{d\rho}\delta + w\Gamma + \frac{2}{3}w\Pi^S.$$

- If we can somehow specify $\Gamma = \Gamma(\delta, \theta^S, \dot{h}, \eta, \ldots)$ and $\Pi^S = \Pi^S(\delta, \theta^S, \dot{h}, \eta, \ldots)$ only then these equations close.

Equation of State approach

- Eventually will obtain:

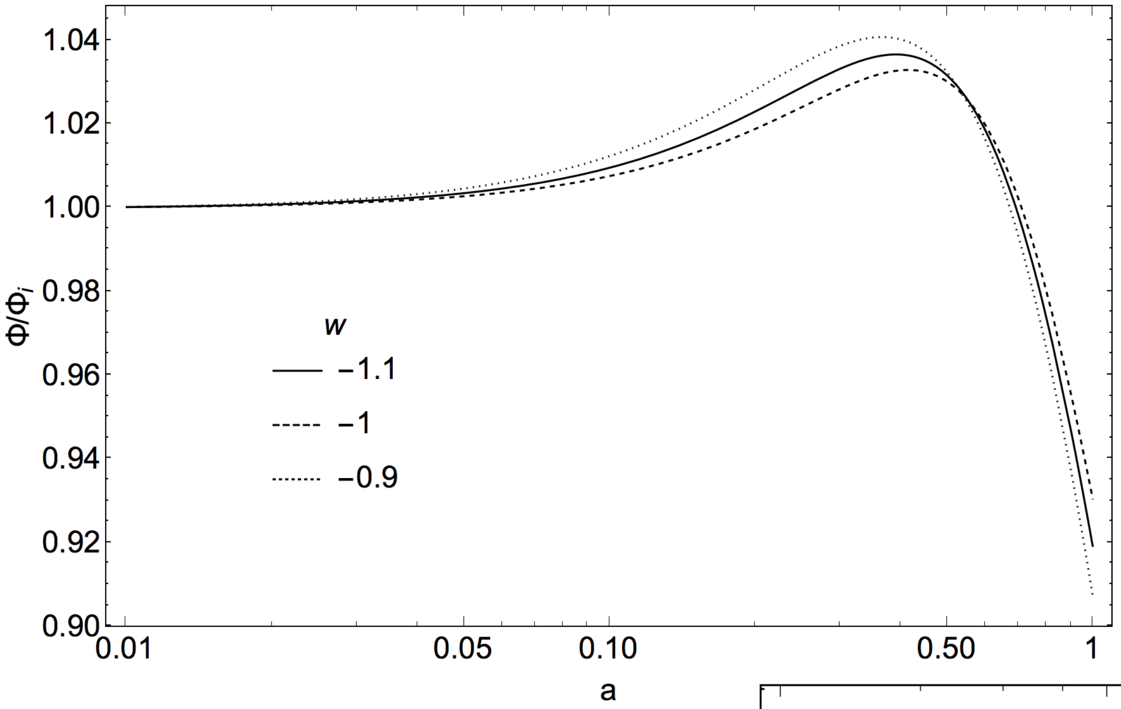
$$w\Pi^S = c_{\Pi\Delta_{\rm de}}\Delta_{\rm de} + c_{\Pi\Theta_{\rm de}}\hat{\Theta}_{\rm de} + c_{\Pi\Delta_{\rm m}}\Delta_{\rm m} + c_{\Pi\Theta_{\rm m}}\hat{\Theta}_{\rm m}$$

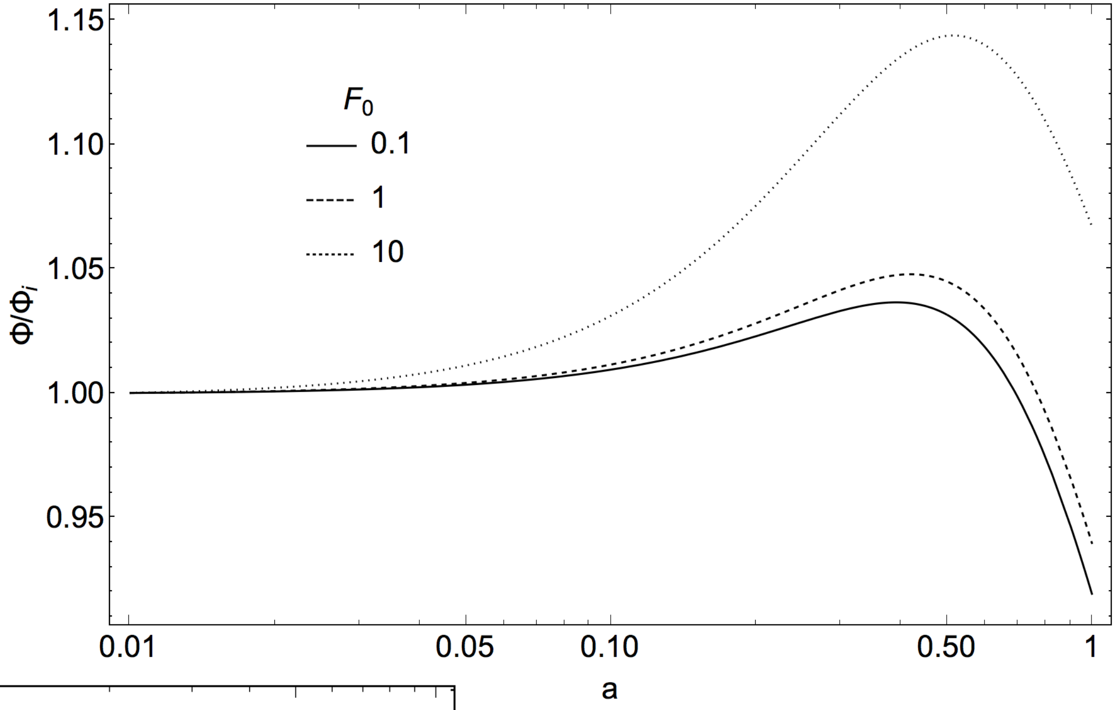
$$w\Gamma = c_{\Gamma\Delta_{\rm de}}\Delta_{\rm de} + c_{\Gamma\Theta_{\rm de}}\hat{\Theta}_{\rm de} + c_{\Gamma\Delta_{\rm m}}\Delta_{\rm m} + c_{\Gamma\Theta_{\rm m}}\hat{\Theta}_{\rm m}$$

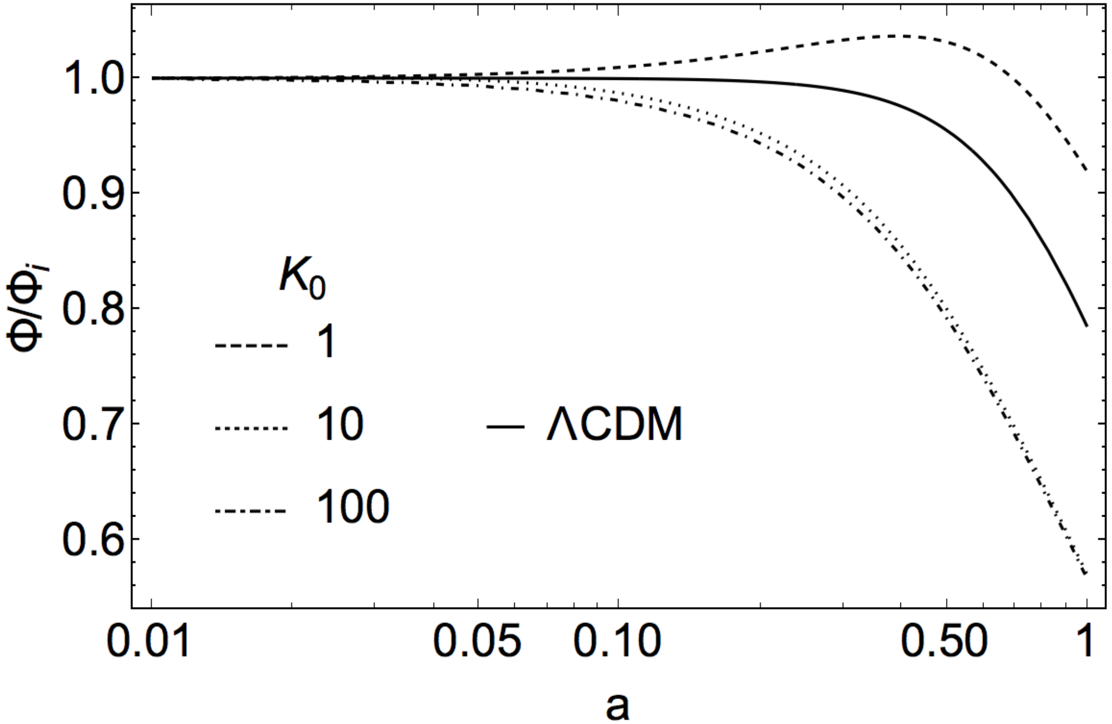
- The approach is model independent.

- Any theory dependence is packaged in the c coefficients.

- This has been done for example in F(R) (Battye et al., 2015, and Pace, in prep.), Quintessence and k-essence, Kinetic gravity braiding, and now Generalized Einstein-Aether.







Battye and Trinh, 2017; in prep.

Conclusions

- Generalized Einstein-Aether can give consistent results at background.
- Ultimately, the perturbations will tell us if this gives a viable alternative.
- There are many ways to parameterize theories at the perturbed level.
- We opt for the EoS approach which gives an elegant and straightforward way of solving the equations of motion.
- The two equations of state together with the equations of motion are all we need.