General relativity with running couplings and cosmological implications

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Running couplings

- General Relativity (GR) introduces two fundamental constants: G and Λ.
- In the context of QFT in curved spacetime, or some quantum gravity proposals (like asymptotic safety), they should effectively change depending on some scale μ.
  - It is qualitatively the same runnings that appear in QCD or QED — as derived from the Renormalization Group equations.
  - Contrary to the QED case, the infrared limit (large distance scales limit) may impose differences with respect to the standard classical picture.
  - The runnings change the dynamics and may explain some issue already found in observational data.

- The runnings of G and Λ are also considered from more phenomenological principles.
  - In this context: Is there a way to implement these runnings such that some anomaly may be solved?

General concepts and definitions

within Renormalization Group approaches at large distances

- The scale setting: the physical meaning of μ
  - μ should not be a new dynamical field.
  - μ is not expected to depend on anything external from the system considered.

- The β-functions: how G and Λ depend on μ.
  - G and Λ depend on a certain scale μ.
  - Fixing the β-functions for G and Λ is equivalent to stating the functions $G(\mu)$ and $\Lambda(\mu)$.

Three classes

At what level should the runnings be implemented?

- Reuter & Weyer (PRD 2004) classified this issue into three cases:
    - Improved solutions
        - Standard GR Solution $\Phi(G_0, \Lambda_0) \longrightarrow$ New solution $\Phi(G(\mu), \Lambda(\mu))$.
    - Improved field equations
        - $G_{\alpha\beta} + \frac{1}{2} g_{\alpha\beta}\Lambda_0 = 8\pi G_0 T_{\alpha\beta} \longrightarrow \; G_{\alpha\beta} + \frac{1}{2} g_{\alpha\beta}\Lambda(\mu) = 8\pi G(\mu) T_{\alpha\beta}$
    - Improved action
        - $\frac{1}{16\pi}\int\left(\frac{R - 2\Lambda_0}{G_0}\right)\sqrt{-g}d^4x \longrightarrow \frac{1}{16\pi}\int\left(\frac{R - 2\Lambda(\mu)}{G(\mu)}\right)\sqrt{-g}d^4x$

- All of the cases above were considered in several publications.

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Most of the cosmological applications are here.

One can choose $\nabla_\alpha T^{\alpha\beta} = 0$

We will develop this case.

- All of the cases above were considered in several publications.

Improved action I

Action with external fields

- Refs. (Reuter, Weyer PRD 2004; Shapiro, Stefancic, Solà JCAP 2004; Rodrigues, Letelier, Shapiro JCAP 2010…) considered the action

$$S[g, \Psi] = \frac{1}{16\pi} \int \frac{R - 2\Lambda}{G} \sqrt{-g} d^4x + S_m[g, \Psi].$$

Ψ represents any matter fields.

- G and Λ in the action above are not constants, they are external fields.

$$\mathcal{G}_{\alpha\beta} + \Lambda g_{\alpha\beta} = 8\pi G T_{\alpha\beta} \, ,$$

$$\mathcal{G}_{\alpha\beta} \equiv G_{\alpha\beta} + G \Box G^{-1} g_{\alpha\beta} - G \nabla_\alpha \nabla_\beta G^{-1}.$$

- How G and Λ depend on μ, and what is μ constitute information to be appended to the field equations.

- Possible interpretation: the runnings come from non-classical arguments, hence G and Λ are taken as external fields.

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These terms do not appear in the improved equations approach.

- How G and Λ depend on μ, and what is μ constitute information to be appended to the field equations.

- Possible interpretation: the runnings come from non-classical arguments, hence G and Λ are taken as external fields.

Improved action II

No external fields, but external scale setting

- As realised by Koch & Ramirez (CQG 2011), see also (Rodrigues at al MNRAS 2014), actually there is no need to use external fields. Let

$$S[g, \mu, \Psi] = \frac{1}{16\pi} \int \frac{R - 2\Lambda(\mu)}{G(\mu)} \sqrt{-g}\, d^4x + S_m[g, \Psi].$$

- Field equations:

$$\mathcal{G}_{\alpha\beta} + \Lambda g_{\alpha\beta} = 8\pi G T_{\alpha\beta}\,,$$

$$\frac{d}{d\mu}\frac{\Lambda}{G} = \frac{1}{2} R \frac{dG^{-1}}{d\mu} \Rightarrow \nabla_\alpha \frac{\Lambda}{G} = \frac{1}{2} R \nabla_\alpha G^{-1} \Rightarrow \nabla_\alpha T^{\alpha\beta} = 0\,.$$

- The additional field equation implies energy-momentum conservation, which was already needed due to diffeomorphism invariance of the matter action.

- However, μ does not come from the action: its definition is outside the action.

Improved action III

Complete action

- Even though the underlying dynamics may have non-classical origin, large complex systems are expected to be fully described by some classical (effective) action.
- By using a Lagrangian multiplier (λ) (Rodrigues, Chauvineau, Piattella JCAP 2015), let

$$S[g, \mu, \lambda, \Psi] = \int \left[\frac{R - 2\Lambda(\mu)}{16\pi G(\mu)} + \lambda \left[\mu - f(g, \Psi) \right] \right] \sqrt{-g}\, d^4x + S_m[g, \Psi].$$

  - See also (Koch, Rioseco, Contreras PRD 2015).
- The scale setting information is in the action. Fixing it is choosing a function $f(g, \Psi)$.
  - μ is neither external nor dynamical field.
- The complete action approach is fully consistent, but it is not equivalent to the previous case.
  - The action approaches are dynamically equivalent only if $\lambda = 0$ at the field equations level.
  - If $\partial_\Psi f \neq 0$, then $S \neq S_{\text{gravity}}[g, \phi_i] + S_{\text{matter}}[g, \psi_i]$, and hence $\nabla_\alpha T^{\alpha\beta}$ needs not to be zero.

Improved action IV

Complete action with multiple scales

- There may be more than one scale. The generalization is straightforward (Bertini, Hipólito-Ricaldi, Melo-Santos, Rodrigues EPJC 2020),

$$S[g,\mu,\lambda,\Psi] = \frac{1}{16\pi}\int\left[\frac{R-2\Lambda(\mu)}{G(\mu)}+\sum_p \lambda_p\left[\mu_p - f_p(g,\Psi)\right]\right]\sqrt{-g}\,d^4x + S_m[g,\Psi]$$

$$\mathcal{G}_{\alpha\beta} + \Lambda g_{\alpha\beta} + f_{\alpha\beta} = 8\pi G T_{\alpha\beta}\;,$$

$$2\frac{\partial}{\partial\mu_p}\frac{\Lambda}{G} - R\frac{\partial}{\partial\mu_p}G^{-1} = \lambda_p\,,$$

$$\mu_p = f_p\,.$$

Definition:

$$f_{\alpha\beta} \equiv -\frac{G}{\sqrt{-g}}\sum_p\int\lambda'_p\frac{\delta f'_p}{\delta g^{\alpha\beta}}\sqrt{-g'}\,d^4x'$$

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New contributions from λ_p.

Scale settings from the action

Definition:

$$f_{\alpha\beta} \equiv -\frac{G}{\sqrt{-g}}\sum_p\int\lambda'_p\frac{\delta f'_p}{\delta g^{\alpha\beta}}\sqrt{-g'}\,d^4x'$$

Scale setting I

Well known examples within cosmology

- Shapiro & Solà (JHEP 2002) propose that for cosmology, and using the improved equations case,

$$\mu \sim H \Longrightarrow \delta\Lambda \propto H^2.$$

- The above was justified from RG expectations. Latter it was re-considered within more phenomenological grounds, not dependent on RG arguments (e.g., Borges et al PRD 2008; Rezaei, Malekjani, Solà PRD 2019).
- Several works use the scale above (or something similar/equivalent).
- Lauscher & Reuter (PRD 2002) argued in favour of $\mu \sim 1/t$, with similar phenomenology.
- For any of the improved action cases, the choice $\mu \sim R$ leads to $f(R)$ theory (Koch, Ramirez CQG 2011; Hindmarsh, Saltas PRD 2012).
  - We will not consider this case further: we are looking for new gravitational phenomena.

Scale setting II

Scale setting for local interactions

- For local interactions with spherical symmetry, the following ansatz appeared several times

$$\mu \sim 1/r\,.$$

- In a quasi-Newtonian context, we improved this scale setting to a physically reasonable one by using (Rodrigues, Letelier, Shapiro JCAP 2010)

$$\mu \sim \Phi_{\rm N}\,,$$ The Newtonian potential.

and applied it to real galaxies (not point-like galaxies): implying possible impact for dark matter.

- But this scale was explicitly non-covariant. We extended it towards a covariant definition (Rodrigues, Chauvineau & Piattella JCAP 2015) in the context of relativistic fluids,

$$\mu \sim W \equiv U^\alpha U^\beta (g_{\alpha\beta} - \gamma_{\alpha\beta}) \approx -2\Phi_{\rm N}.$$

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Non-dynamical and non-external tensor field. For local systems ~ Minkowski.

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No new vector fields, but *a priori* nontrivial interaction with the matter sector.

Non-dynamical and non-external tensor field. For local systems ~ Minkowski.

All the principles together

(Bertini, Hipólito-Ricaldi, Melo-Santos, Rodrigues EPJC 2020)

- $ds^2 = -a^2(\eta)(1+2\psi)d\eta^2 + a^2(\eta)(1-2\phi)\delta_{ij}dx^i dx^j$
- $S[g,\mu,\lambda,\gamma,\Psi] = \frac{1}{16\pi}\int \left[\frac{R - 2\Lambda(\mu_1,\mu_2\ldots)}{G(\mu_1)} + \lambda_1(\mu_1 - f_1(W)) + \sum_{p=2} \lambda_p \left[\mu_p - f_p(g,\Psi)\right]\right]\sqrt{-g}\, d^4x + S_m[g,\Psi]$
  - $W \equiv U^\alpha U^\beta (g_{\alpha\beta} - \gamma_{\alpha\beta})$ and U^α is one of the Ψ (matter) fields.
- Up to first order on ψ and ϕ, it is not necessary to specify $G(\mu_1)$, $f_1(W)$ or Λ, but we assume

$$\Lambda|_{W=0} = \Lambda_0 \text{ and } G_0 G^{-1}(W) = 1 + \nu W + O(W^2).$$

- We look for solutions that preserve the GR background.
  - The RG scale will be a function of the wavenumber k, not the time.

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Single dimensionless parameter that sets the strength of the running effects. That is, $\nu = 0$ leads to GR.

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- $ds^2 = -a^2(\eta)(1+2\psi)d\eta^2 + a^2(\eta)(1-2\phi)\delta_{ij}dx^i dx^j$
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- We look for solutions that preserve the GR background.
  - The RG scale will be a function of the wavenumber k, not the time.

This is sufficient for finding $\mu_2, \mu_3\ldots, \lambda_1, \lambda_2\ldots, \Lambda(\mu_1,\mu_2,\ldots)$ and the ϕ, ψ solutions.

The background field equations

They have the same form of GR, as expected

- Any possible correction will only appear if $W \neq 0$.
- No corrections to the GR background implies that $\gamma_{\alpha\beta} = {}^{(0)}g_{\alpha\beta}$.
  - This implies $W \equiv U^\alpha U^\beta (g_{\alpha\beta} - \gamma_{\alpha\beta}) = 0$ at background level.
- Indeed, at background level,

$$\mathcal{G}_{\alpha\beta} + \Lambda g_{\alpha\beta} + f_{\alpha\beta} = 8\pi G T_{\alpha\beta}$$

$$\Downarrow$$

$${}^{(0)}G_{\alpha\beta} + \Lambda_0 \, {}^{(0)}g_{\alpha\beta} = 8\pi G_0 \, {}^{(0)}T_{\alpha\beta}\,.$$

Recalling that...

$$\mathcal{G}_{\alpha\beta} \equiv G_{\alpha\beta} + G \Box G^{-1} g_{\alpha\beta} - G \nabla_\alpha \nabla_\beta G^{-1}$$

$$f_{\alpha\beta} \equiv - \frac{G}{\sqrt{-g}} \sum_p \int \lambda'_p \frac{\delta f'_p}{\delta g^{\alpha\beta}} \sqrt{-g'}\, d^4x'$$

$$2 \frac{\partial}{\partial \mu_p} \frac{\Lambda}{G} - R \frac{\partial}{\partial \mu_p} G^{-1} = \lambda_p$$

The Λ solution I

Vacuum case

- By varying the action with respect to $\gamma_{\alpha\beta}$,

$$0 = \int \lambda_1' \frac{\delta f_1'}{\delta \gamma_{\alpha\beta}} \sqrt{-g'} d^4x' = \lambda_1 \frac{\partial f_1}{\partial W} U^\alpha U^\beta \sqrt{-g} \;\Rightarrow \lambda_1 = 0.$$

- And using that $R \approx 4\Lambda_0$, we find

$$2\frac{\partial}{\partial \mu_1}\frac{\Lambda}{G} - R\frac{\partial}{\partial \mu_1}G^{-1} = \lambda_1 \Longrightarrow \frac{\partial}{\partial \mu_1}\Lambda = \Lambda_0 G_0 \frac{\partial}{\partial \mu_1} G^{-1},$$

$$\Lambda = \Lambda_0 G_0 G^{-1}.$$

- The relation above appeared many times in the RG literature (e.g., Bonanno, Esposito, Rubano CQG 2004). And it also agrees with our previous work (Rodrigues, Chauvineau, Piattella JCAP 2010).
  - For this case, no other scales appear apart from the first one (actually, this is valid for any μ_1, not only $\mu_1 \sim W$). For this case, can find that $\lambda_p = 0$.

The Λ solution II

General perfect fluid case

- The “consistence equation” becomes harder to solve in the presence of matter, since R is no longer a constant. It can be rewritten as

$$\partial_{\mu_p}\Lambda = (\Lambda_0 - 4\pi G_0\, {}^{(0)}T)G_0\partial_{\mu_p}G^{-1} + \frac{1}{2}G_0\lambda_p,$$

- Since ${}^{(0)}T$ is a function of time only, Λ cannot be a function of W alone, implying that a second scale will be necessary. Indeed, the solution reads

$$\Lambda = \Lambda_0 + (\Lambda_0 - 4\pi G_0\, {}^{(0)}T)\,(G_0G^{-1} - 1) = \Lambda(\mu_1, \mu_2),$$

$$\mu_2 = f_2({}^{(0)}T),$$

$$\lambda_2 \propto \partial_{\mu_2}\, {}^{(0)}T,$$

$$\lambda_p = 0\ \forall p \neq 2.$$

Equations of motion with relativistic fluid

- From diffeomorphism invariance of the matter action

$$0 = \delta_\xi S_m[g,\Psi] = \int \left(-\frac{1}{2} T_{\alpha\beta}\sqrt{-g}\, \nabla^\alpha \xi^\beta + \frac{\delta S_m}{\delta \Psi}\delta_\xi \Psi \right) d^4x$$

$$= \int \left(\frac{1}{2} \nabla^\alpha T_{\alpha\beta}\sqrt{-g}\, \xi^\beta + \frac{1}{16\pi} \sum_p \int \lambda_p' \frac{\delta f_p'}{\delta \Psi} \sqrt{-g'}\, d^4x'\ \delta_\xi \Psi \right) d^4x.$$

- Hence, using the previous results,

$$\nabla^\alpha T_{\alpha\beta} = (G_0 G^{-1} - 1)\partial_\beta {}^{(0)}T.$$

- Up to first perturbative order, standard equations of motion are found for any fluid if using comoving coordinates at background level. — See the paper.

$$(\varepsilon + p)\frac{DU^\beta}{D\tau} + \nabla^\beta p + U^\beta \frac{Dp}{D\tau} = 0.$$

Equations for the cosmological perturbations

$$3\mathscr{H}(\phi' + \nu\psi') - \nabla^2(\phi + \nu\psi) + 3\mathscr{H}^2\psi + \frac{\delta\Lambda a^2}{2} =$$
$$= 4\pi G_0 a^2 (\delta T^0_0 + 2\nu\psi \, {}^{(0)}T^0_0) \, ,$$

$$\partial_i \left[\phi' + \nu\psi' + \mathscr{H}\psi(1-\nu)\right] = -4\pi G_0 a^2 \delta T^0_i \, , \qquad (64)$$

$$\left[\phi'' + \nu\psi'' + \mathscr{H}(\psi' + 2\phi' + \nu\psi') + \right. \qquad (65)$$
$$\left. + \frac{1}{2}\nabla^2(\psi - \phi - 2\nu\psi) + \psi\left(2\mathscr{H}' + \mathscr{H}^2\right) + \frac{\delta\Lambda a^2}{2}\right]\delta^i_j -$$
$$- \frac{1}{2}\partial_j\partial^i(\psi - \phi - 2\nu\psi) = 4\pi G_0 a^2 (\delta T^i_j + 2\nu\psi \, {}^{(0)}T^i_j) \, .$$

PPF-type parametrizations

- The gravitational slip is trivially found as (e.g., Amendola et al Liv.Rev.Rel. 2012)

$$\frac{\phi}{\psi} = 1 - 2\nu.$$

- The effective gravitational constant Y is defined from

$$-k^2\psi = 4\pi G_0 Y(a,k)\, a^2 \varepsilon\, \Delta_\varepsilon \text{ with } \Delta_\varepsilon \equiv \delta_\varepsilon + 3(1+w)\mathscr{H}\theta/k^2\,.$$

- and it is found to be

$$Y = \frac{1}{1 - \nu + \nu q(a)/k^2}, \text{ with } q(a) \equiv 12\pi G_0 ({}^{(0)}\varepsilon + {}^{(0)}p)a^2 \approx \frac{1}{a}(4\text{Gpc})^{-2}\,.$$

- From the slip, it is possible to estimate a bound for ν (Pizzuti et al JCAP 2016),

$$|\,\nu\,| \leq 0.30, \text{ at } 2\sigma \text{ level.}$$

Cosmological solutions I

Solutions for dust dominated universe

$$\psi \approx C_1 \left(1 + \frac{6}{5}\nu \ln\, \eta\right) + \frac{C_2}{\eta^5}\left(1 - \frac{6}{5}\nu \ln \eta\right).$$

- At subhorizon scales,

$$\delta_\varepsilon \approx -\frac{1}{6}k^2\eta^2(1-\nu)\psi.$$

$$\lambda_{\rm J} \equiv \frac{2\pi a}{k_{\rm J}} = c_s\sqrt{\frac{(1-\nu)\pi}{G_0\,{}^{(0)}\varepsilon}}.$$

Cosmological solutions II

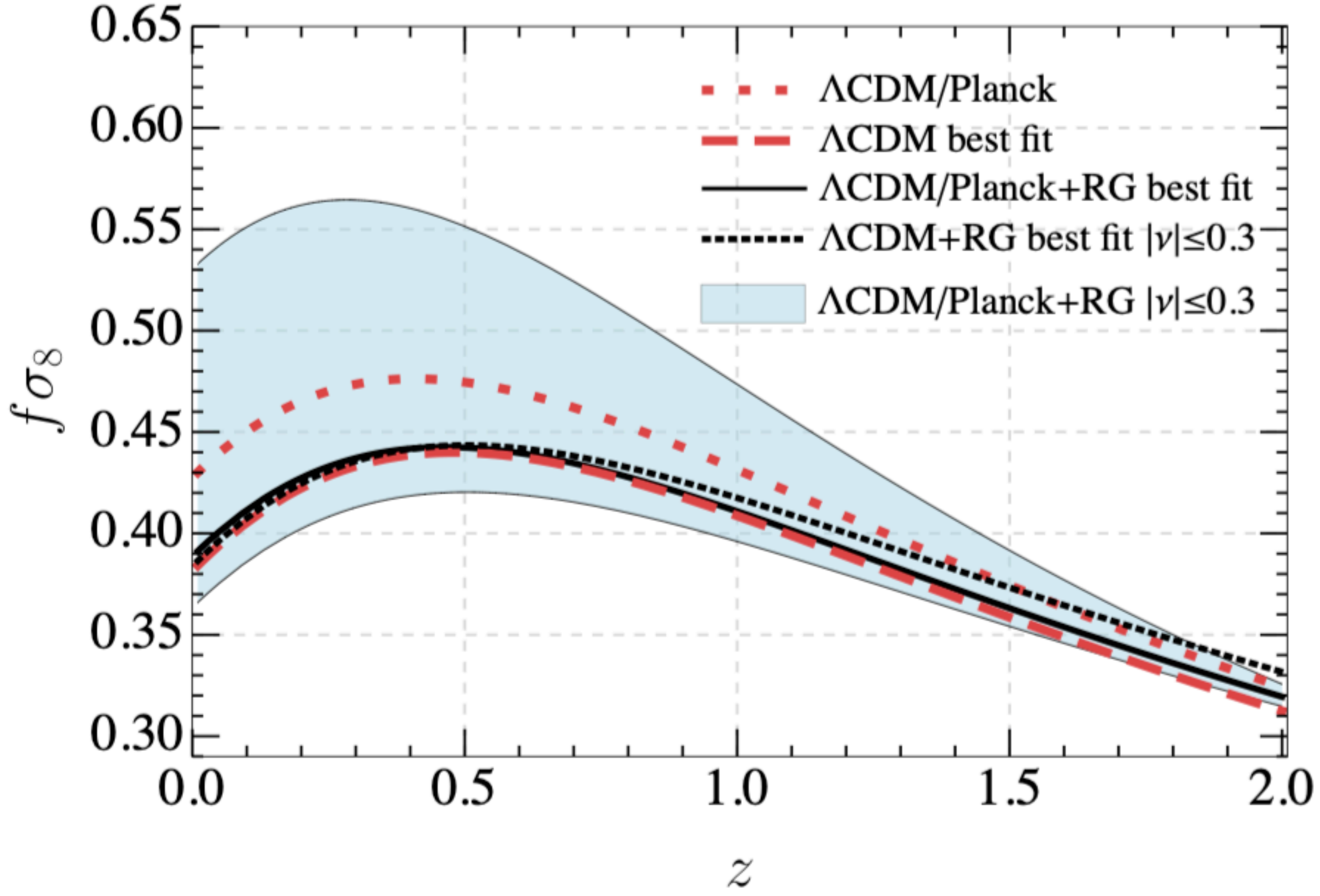
Solutions for radiation dominated universe

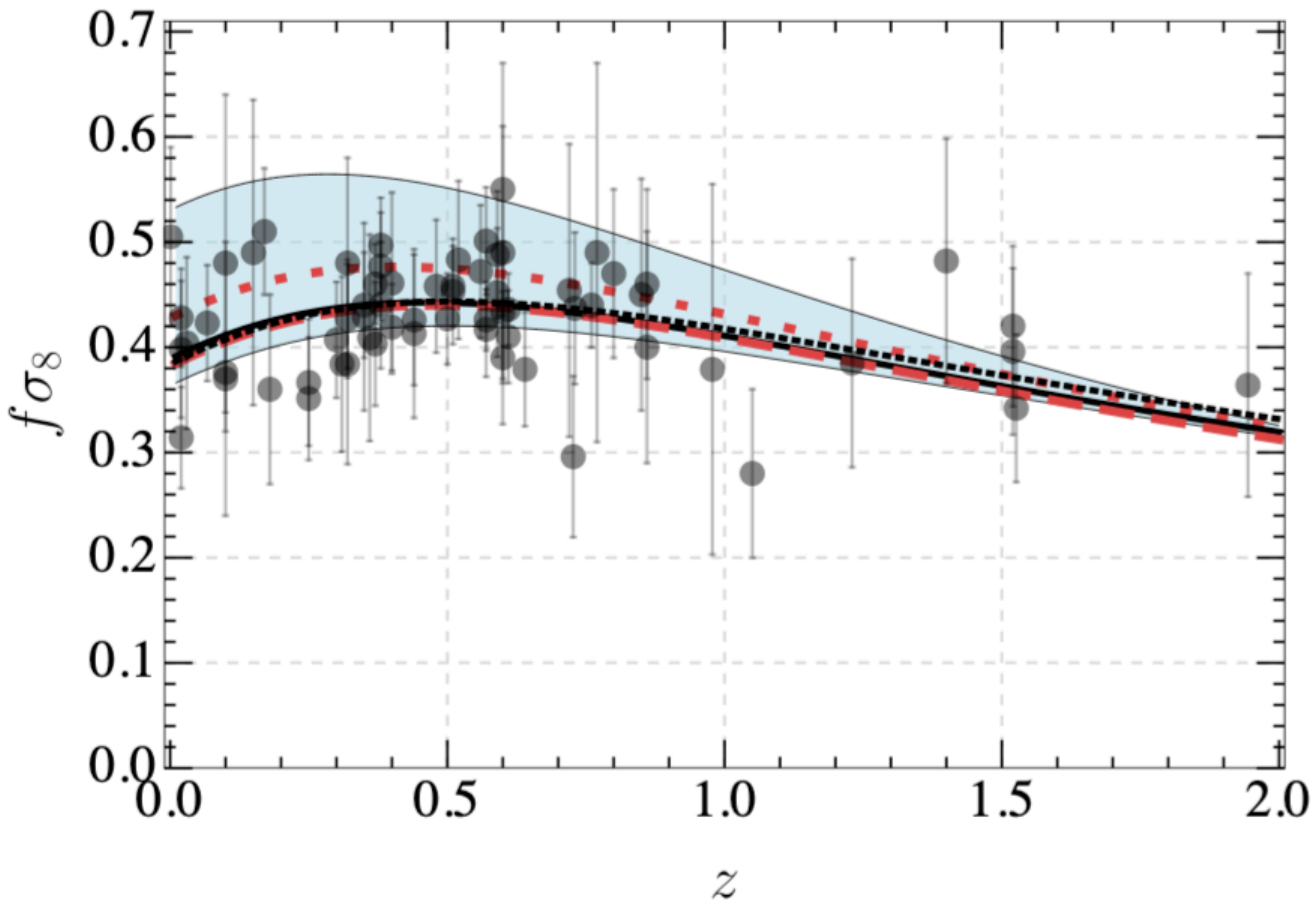
- They are the same of GR for the perturbations ψ, but not for ϕ.

$f\sigma_8$ analysis

Model	Variation	fitted parameters	$\chi^2_{\min}$	Ω_{m0}	σ_8	ν
ΛCDM	Planck-2018 parameters	None	51.34	0.315	0.811	0
ΛCDM	best fit from $f\sigma_8$ data	Ω_{m0}, σ_8	32.40	0.283	0.769	0
ΛCDM+RG	Only ν is fitted	ν	32.42	0.315	0.811	−0.167
ΛCDM+RG	best fit, no constraints	Ω_{m0}, σ_8, ν	32.04	0.355	0.981	−0.769
ΛCDM+RG	best-fit with $\|\nu\| \leq 0.3$	Ω_{m0}, σ_8, ν	32.14	0.316	0.855	−0.300

$f\sigma_8$ data from (Skara, Perivolaropoulos PRD 2020).





Ongoing CMB analysis

- (Melo-Santos, Hipólito-Ricaldi, von Marttens, Rodrigues, in prep.)
- Beautiful plots yet to appear.

Conclusions

- Inspired by possible large scale Renormalization Group effects, we considered the development of a complete action capable of fully describing the dynamics with running couplings (Rodrigues, Chauvineau, Piattella JCAP 2015), extending the previous approach of (Rodrigues, Letelier, Shapiro JCAP 2010) and introducing a covariant scale sensitive to spacetime perturbations.
- In (Bertini, Hipólito-Ricaldi, Melo-Santos, Rodrigues EPJC 2020), we applied the developments above to cosmology.
  - A second scale was necessary, hence we developed the framework accordingly.
  - Tests using PPF parametrizations and $f\sigma_8$ were used. It was found that ν was relevant for improving the ΛCDM fit. This is just a first indication. More tests are being performed.
  - Apart from the phenomenological results, we think the theory introduces a number of novelty approaches that could be useful for different frameworks.