What can Cosmology tell us about Gravity?

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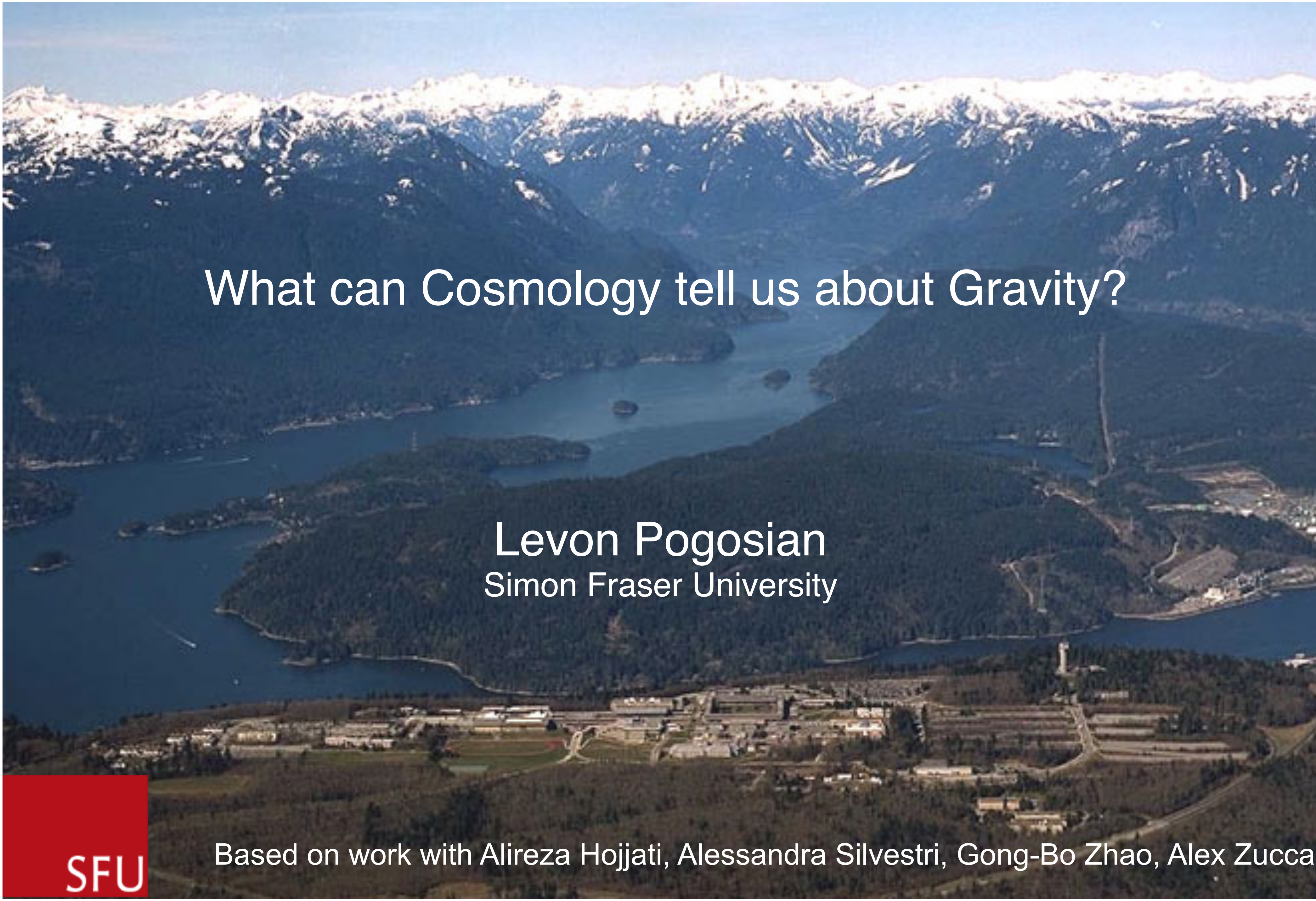
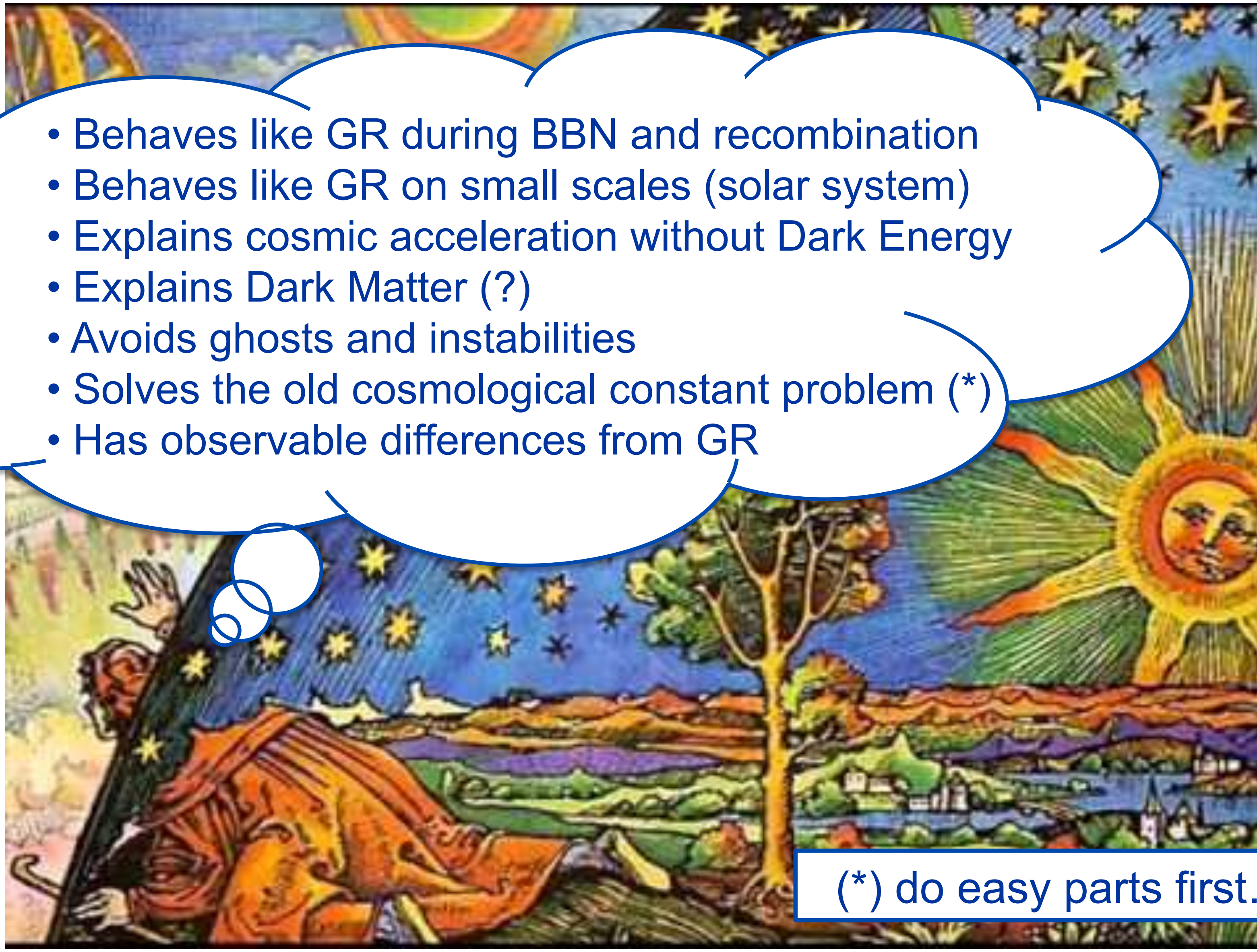
Based on work with Alireza Hojjati, Alessandra Silvestri, Gong-Bo Zhao, Alex Zucca



Are there reasons to expect GR to be modified on cosmological scales?

A popular viewpoint	A different viewpoint
GR has, so far, passed all experimental tests The LCDM model is in good agreement with observations Alternative models tend to create more problems than they solve GR is appealing for its beauty alone	GR is yet to be seriously tested on cosmological We do not know how the vacuum gravitates and why the universe is accelerating at the current rate We do not know what Dark Matter is

Cosmologists' Dream Modified Gravity Theory



- Behaves like GR during BBN and recombination
- Behaves like GR on small scales (solar system)
- Explains cosmic acceleration without Dark Energy
- Explains Dark Matter (?)
- Avoids ghosts and instabilities
- Solves the old cosmological constant problem (*)
- Has observable differences from GR

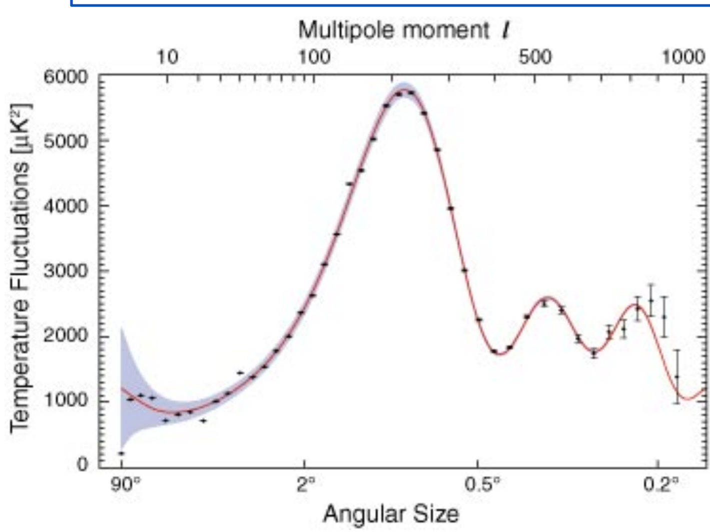
(*) do easy parts first…

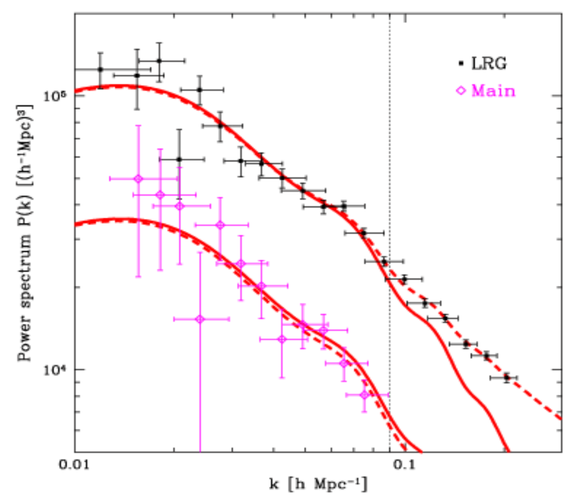
What does Cosmology test?

FLRW Metric + Initial conditions (Inflation) + Content: CDM, baryons, photons, neutrinos, Λ

Conservation Equations
Einstein's Equations
for the background and perturbations

Observables: statistics of CMB, galaxy distribution, …





Linear perturbations in FLRW universe

$$ds^2 = a^2(\eta)[-(1+2\Psi)d\eta^2 + (1-2\Phi)d\mathbf{x}^2]$$

$$D_\mu T^{\mu\nu} = 0 \longrightarrow \begin{aligned} \delta' + \frac{k}{aH}V - 3\Phi' &= 0 \\ V' + V - \frac{k}{aH}\Psi &= 0 \end{aligned}$$

Einstein's equations

$$\begin{aligned} k^2\Phi &= -4\pi G a^2 \rho \left(\delta + \frac{3aH}{k}V\right) \equiv -4\pi G a^2 \rho \Delta \\ k^2(\Phi - \Psi) &= 12\pi G a^2 (\rho + P)\sigma \end{aligned}$$

Linear perturbations in FLRW universe

$$ds^2 = a^2(\eta)[-(1+2\Psi)d\eta^2 + (1-2\Phi)d\mathbf{x}^2]$$

$$D_\mu T^{\mu\nu} = 0 \longrightarrow \begin{aligned} \delta' + \frac{k}{aH}V - 3\Phi' &= 0 \\ V' + V - \frac{k}{aH}\Psi &= 0 \end{aligned}$$

Einstein's equations with dust

$$\begin{aligned} k^2\Phi &= -4\pi G a^2 \rho \Delta \\ \Phi &= \Psi \end{aligned}$$

Things we can agree to keep

FLRW background with small perturbations:

$$ds^2 = a^2(\eta)[-(1+2\Psi)d\eta^2 + (1-2\Phi)d\mathbf{x}^2]$$

Conservation of matter energy-momentum:

$$\boxed{D_\mu T^{\mu\nu} = 0} \longrightarrow \boxed{\begin{aligned} \delta' + \frac{k}{aH}V - 3\Phi' &= 0 \\ V' + V - \frac{k}{aH}\Psi &= 0 \end{aligned}}$$

(!) Need two additional equations to close the system of four variables

Two ways of modeling linear perturbations

(1) Parameterize new terms in the effective action

(Gubitosi et al, 1210.0201; Bloomeld et al, 1211.7054, Gleyzes et al, 1304.4840, Bellini & Sawicki, 1404.3713)

$$S_{\rm g}^{(2)} = \int d^3x dt\, a^3 \frac{M^2}{2}\Big[\delta K^i_j \delta K^j_i - \delta K^2 + R\delta N + (1+\alpha_{\rm T})\delta_2\left(\sqrt{h}R/a^3\right) + \alpha_{\rm K} H^2 \delta N^2 + 4\alpha_{\rm B} H \delta K \delta N\Big],$$

- New terms determined by symmetries
- Perturbations in broad classes of theories described by a few functions of time
- Difficult to constrain individual functions simultaneously

(2) Use algebraic relations in Fourier space

(MGCAMB, Hojjati, Zhao, Zucca, LP, Silvestri)

- Closely related to observables
- Maps onto theories in the quasi-static limit

$$\begin{aligned} k^2\Psi &= -\mu(a,k)\ 4\pi G a^2 \rho\Delta \\ \Phi &= \gamma(a,k)\ \Psi \end{aligned}$$

GR+ΛCDM: $\mu = \gamma = 1$

$$
\boxed{\begin{aligned} k^2\Psi &= -\mu(a,k)\ 4\pi G a^2 \rho\Delta \\ \Phi &= \gamma(a,k)\ \Psi \end{aligned}}
$$

GR+ΛCDM

$$\mu = \gamma = 1$$

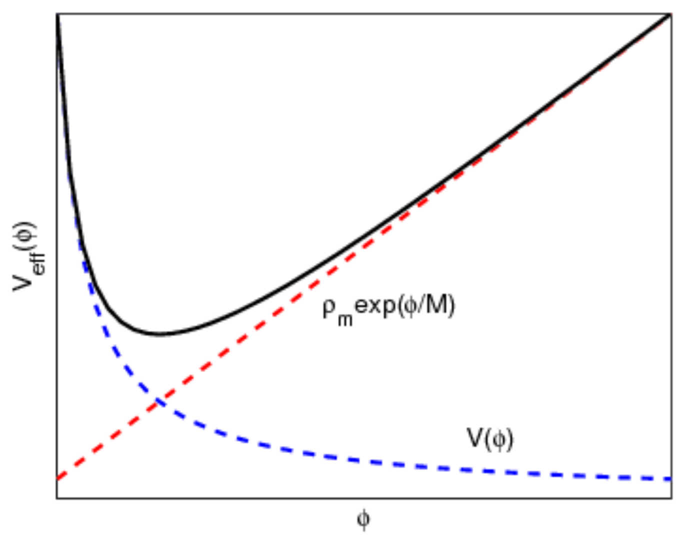
Example: scalar-tensor models of chameleon type

Khoury & Weltman, astro-ph/0309300, PRL'04

$$
S_E = \int d^4x\sqrt{-\tilde{g}}\left[\frac{M_P^2}{2}\tilde{R} - \frac{1}{2}g^{\tilde{\mu}\nu}(\tilde{\nabla}_\mu\phi)\tilde{\nabla}_\nu\phi - V(\phi)\right] + S_i\left(\chi_i, e^{-\kappa\alpha_i(\phi)}\tilde{g}_{\mu\nu}\right)
$$

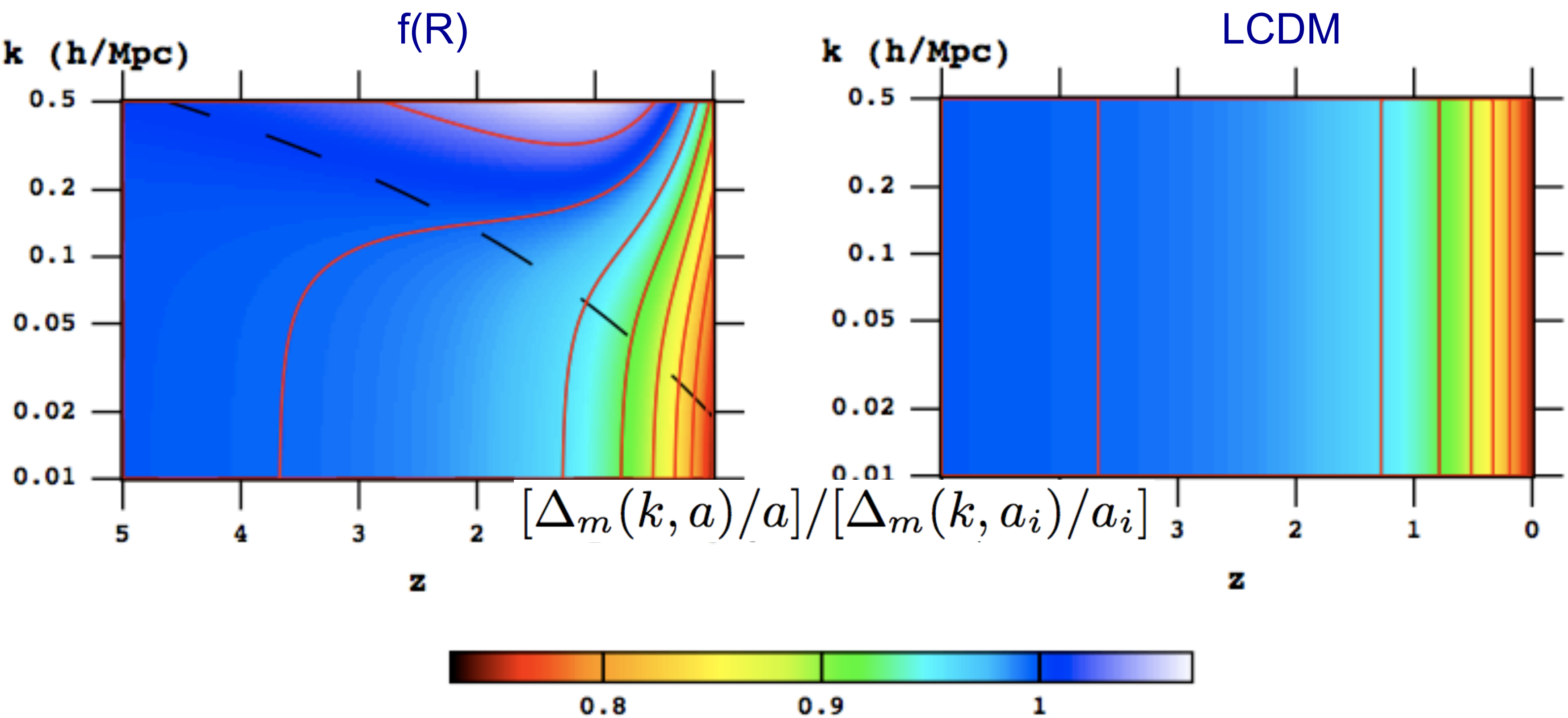
$$
\mu(a,k) \approx e^{-\kappa\alpha(\phi)}\frac{1+\left(1+\frac{1}{2}\alpha'^2\right)\frac{k^2}{a^2m^2}}{1+\frac{k^2}{a^2m^2}}
$$

$$
\gamma(a,k) \approx \frac{1+\left(1-\frac{1}{2}\alpha'^2\right)\frac{k^2}{a^2m^2}}{1+\left(1+\frac{1}{2}\alpha'^2\right)\frac{k^2}{a^2m^2}}
$$



The growth of cosmological perturbations in f(R)

L.P. and A. Silvestri, PRD (2008)



$$\alpha' = \frac{d\alpha}{d\phi} = \sqrt{\frac{2}{3}}$$

$$\mu(a,k) \approx \frac{1 + 4/3k^2\lambda_C^2}{1 + k^2\lambda_C^2} \rightarrow_{k^{-1} \ll \lambda_C} \frac{4}{3}$$

$$\gamma(a,k) \approx \frac{1 + 2/3k^2\lambda_C^2}{1 + 4/3k^2\lambda_C^2} \rightarrow_{k^{-1} \ll \lambda_C} \frac{1}{2}$$

An alternative choice of modified relations

$$\text{“}G_{matter}\text{”}$$

$$k^2\Psi = -4\pi\,\mu(a,k)G\,a^2\rho\Delta$$

$$k^2(\Psi+\Phi) = -8\pi\,\Sigma(a,k)G\,a^2\rho\Delta$$

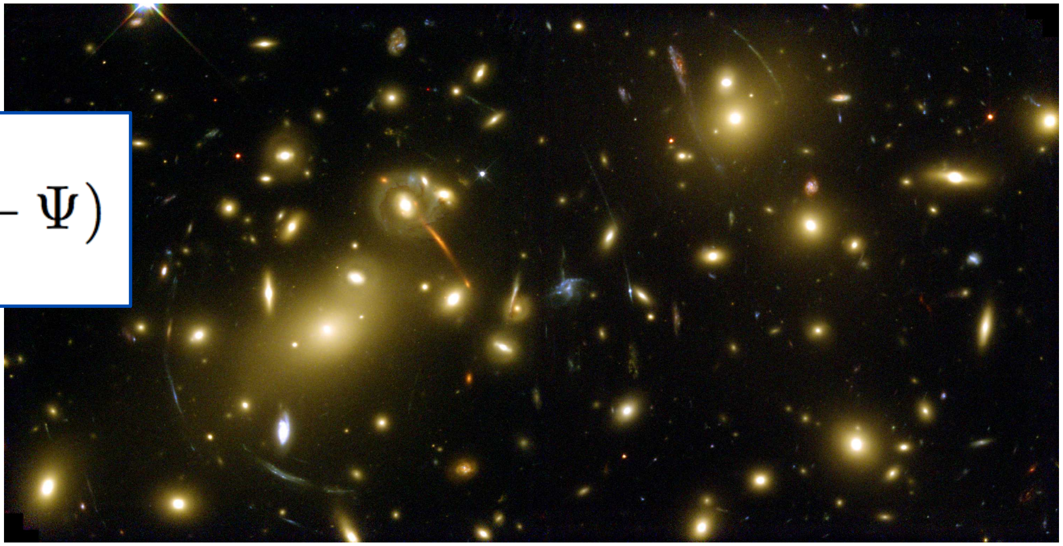
$$\text{“}G_{light}\text{”}$$

A smoking gun of new gravitational physics

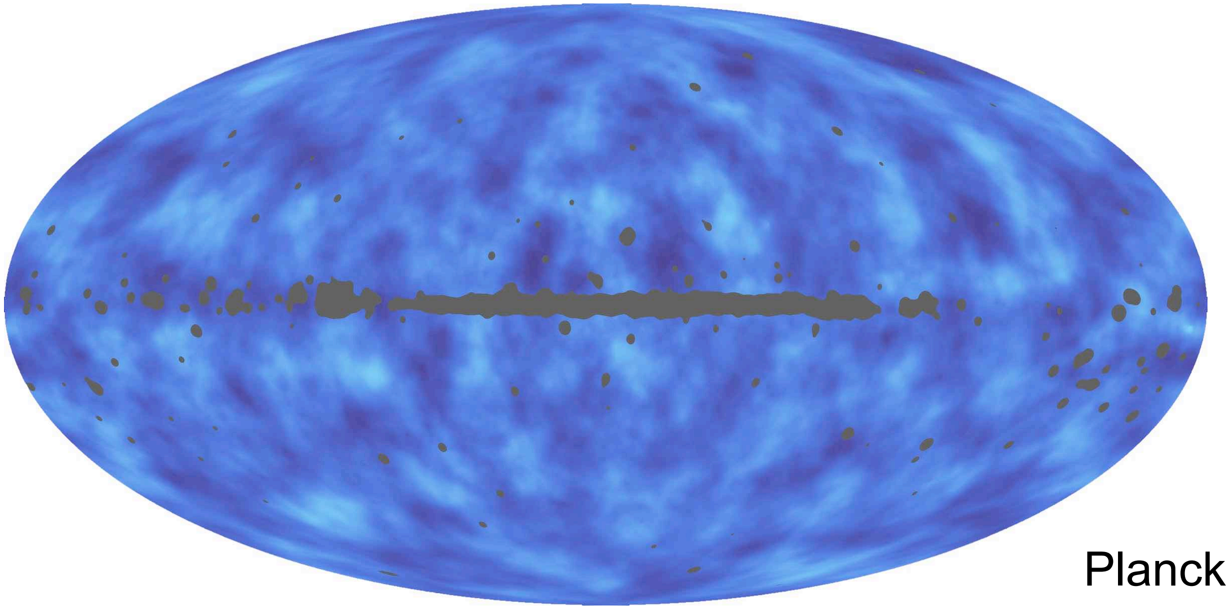
$$\boxed{G_{matter} \neq G_{light} \quad \text{or} \quad \Phi \neq \Psi}$$

Gravitational Lensing

$$\text{Distortion} \propto \int dz\ \partial_\perp(\Phi + \Psi)$$



Hubble

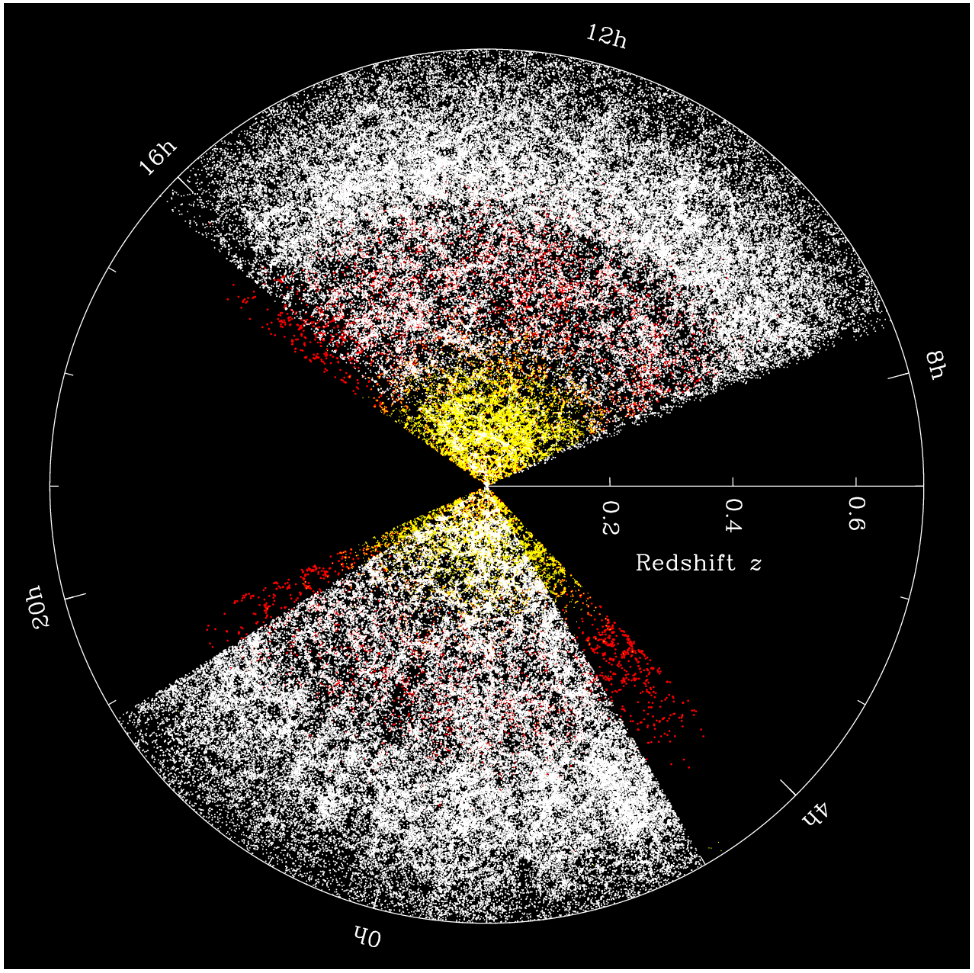


Planck

Galaxy Clustering

Redshift space distortions due to peculiar motion

$$V' + V = \frac{k}{aH}\Psi$$

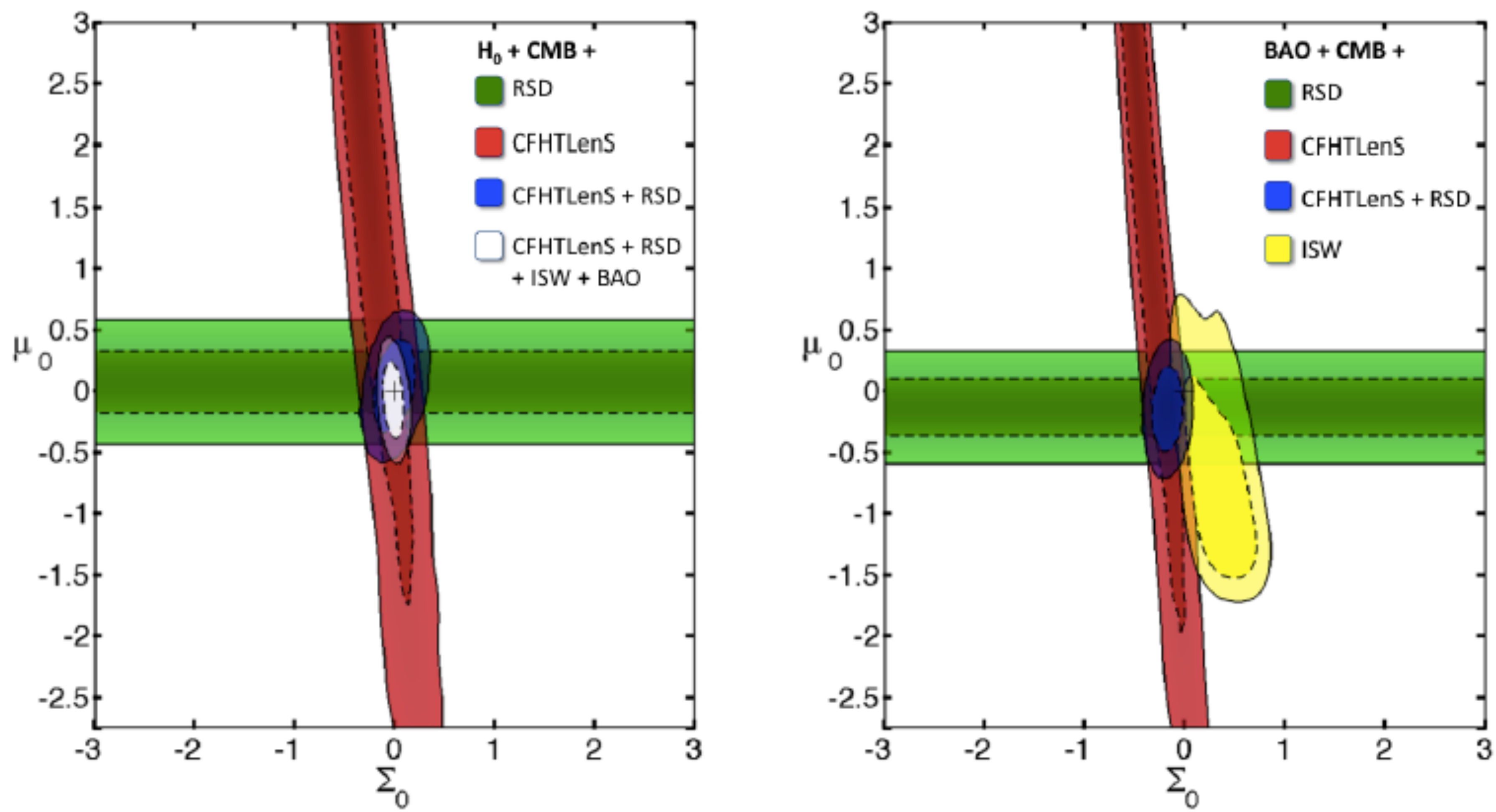


CFHTLenS: Testing the Laws of Gravity with Tomographic Weak Lensing and Redshift Space Distortions

1212.3339, MNRAS'13

Fergus Simpson[1⋆], Catherine Heymans[1], David Parkinson[2], Chris Blake[3], Martin Kilbinger[4,5,6], Jonathan Benjamin[7], Thomas Erben[8], Hendrik Hildebrandt[7,8], Henk Hoekstra[9,10], Thomas D. Kitching[1], Yannick Mellier[11], Lance Miller[12], Ludovic Van Waerbeke[7], Jean Coupon[13], Liping Fu[14], Joachim Harnois-Déraps[15,16], Michael J. Hudson[17,18], Konrad Kuijken[9], Barnaby Rowe[19,20], Tim Schrabback[8,9,21], Elisabetta Semboloni[9], Sanaz Vafaei[7], Malin Velander[12,9].

$$\mu = 1 + \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda} \;, \quad \Sigma = 1 + \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$$



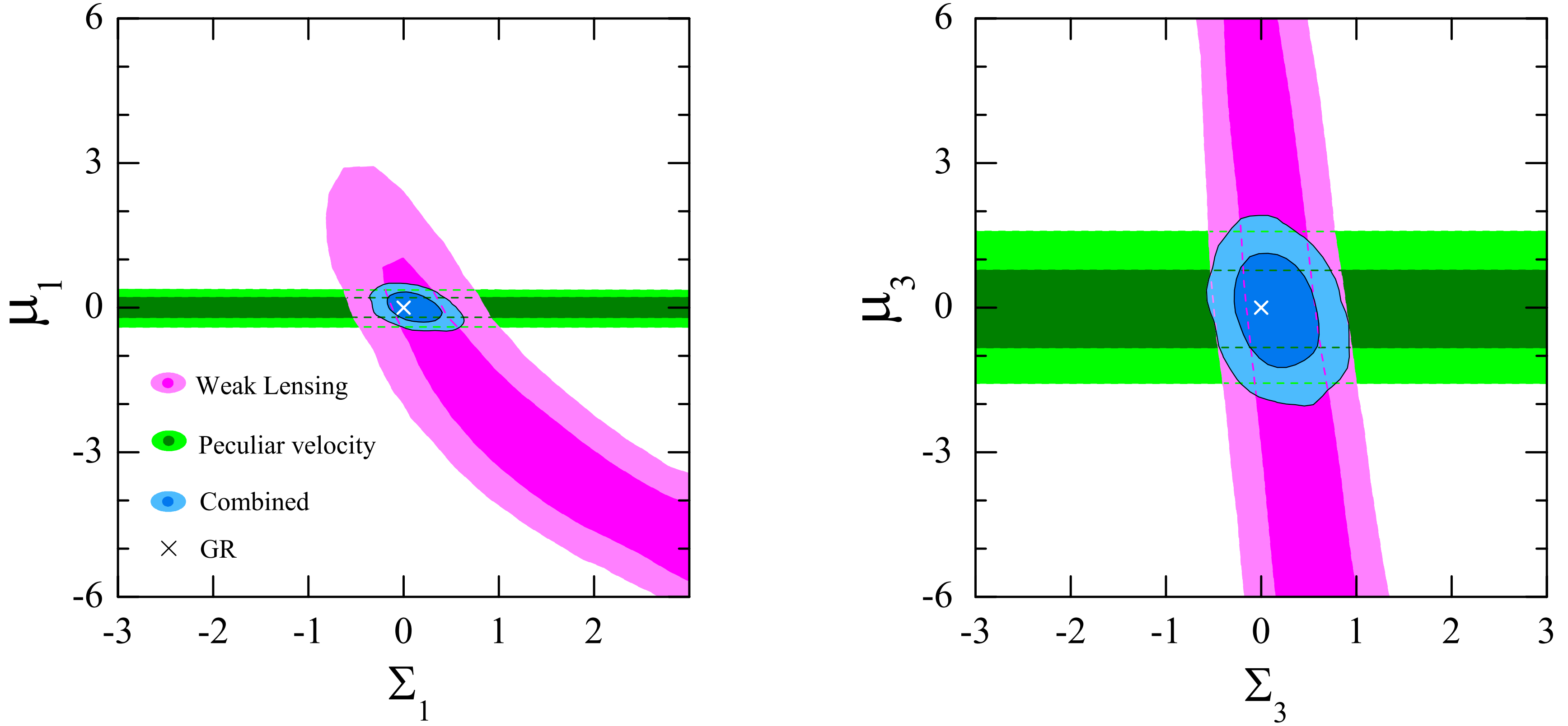
1011.2106, PRD'11

Complementarity of Weak Lensing and Peculiar Velocity Measurements in Testing General Relativity

Yong-Seon Song[1,2], Gong-Bo Zhao[2], David Bacon[2], Kazuya Koyama[2], Robert C Nichol[2], Levon Pogosian[3]
[1]*Korea Institute for Advanced Study, Dongdaemun-gu, Seoul 130-722, Korea*
[2]*Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth, PO1 3FX, United Kingdom*
[3]*Department of Physics, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada*

CFHTLS-Wide T003 (Fu et al, 2008), SDSS DR7

$$\Sigma = 1 + \Sigma_s a^s, \quad \mu = 1 + \mu_s a^s$$



Planck 2015 results. XIV. Dark energy and modified gravity

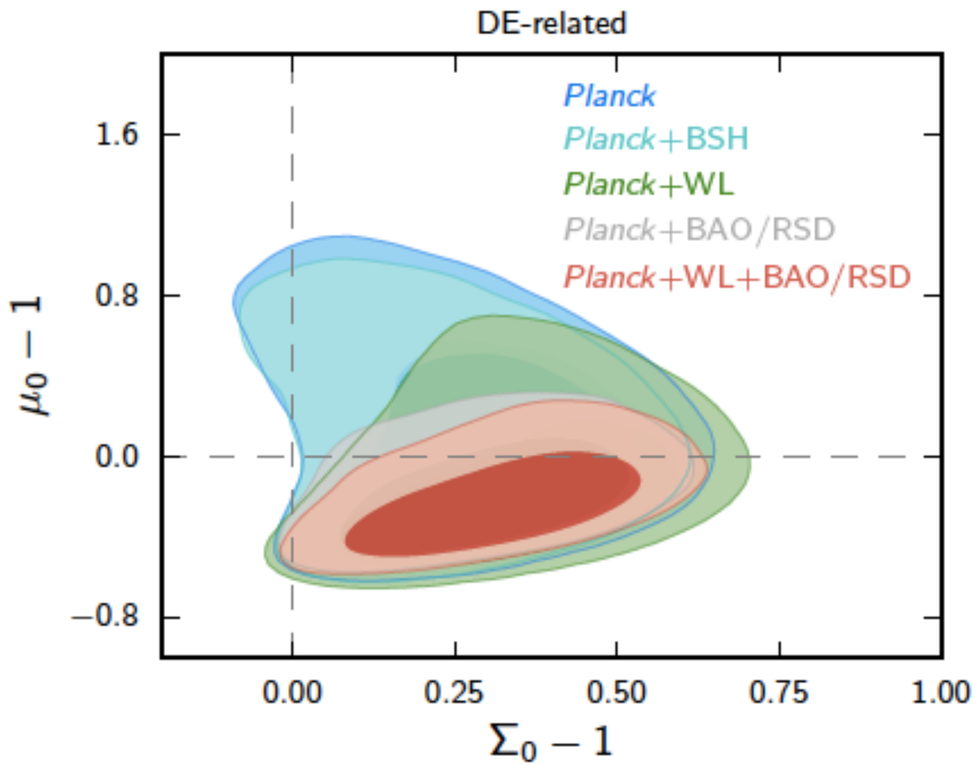


Fig. 15. Marginalized posterior distributions for 68% and 95% C.L. for the two parameters $\{\mu_0 - 1, \Sigma_0 - 1\}$ obtained by evaluating Eqs. (46) and (47) at the present time in the DE-related parametrization when no scale dependence is considered (see Sect. 5.2.2). Σ is obtained as $\Sigma = (\mu/2)(1 + \eta)$. The time-related evolution would give similar contours. In the labels, *Planck* stands for *Planck* TT+lowP.

Gregory Horndeski, *Talking About Gravity*

Most general second-order scalar-tensor theory

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\sum_{i=2}^{5} \mathcal{L}_i + \mathcal{L}_{\mathrm{m}}[g_{\mu\nu}] \right]$$

$$X = -\phi^{;\mu}\phi_{;\mu}/2$$

$$\mathcal{L}_2 = K(\phi,\, X)\,,$$

$$\mathcal{L}_3 = -G_3(\phi,\, X)\Box\phi\,,$$

$$\mathcal{L}_4 = G_4(\phi,\, X)R + G_{4X}(\phi,\, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]\,,$$

$$\mathcal{L}_5 = G_5(\phi,\, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi,\, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$

Generalized Brans-Dicke models

Includes models with “chameleon”, “symmetron” and “dilaton” type screening

$$K(\phi, X) = h(\phi)X - V(\phi)$$
$$G_4(\phi, X) = \frac{A^{-2}(\phi)}{16\pi G}$$
$$G_3 = G_5 = 0$$

$$S = \int d^4x\sqrt{-g}\left[\frac{A^{-2}(\phi)}{16\pi G}R - \frac{h(\phi)}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi) + \mathcal{L}_M(g_{\mu\nu}, \psi)\right]$$

In the Einstein frame: $\tilde{g}_{\mu\nu} = A^{-2}(\phi)g_{\mu\nu}$

$$S = \int d^4x\sqrt{-\tilde{g}}\left[\frac{\tilde{R}}{16\pi G} - \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \tilde{V}(\phi) + \mathcal{L}_M(A^2(\phi)\tilde{g}_{\mu\nu}, \psi)\right]$$

Phenomenology of generalized Brans-Dicke models

$$
\begin{aligned}
-k^2\Psi = &\ \mu(k,a) \quad 4\pi G a^2 \rho\delta \\
\Phi = &\ \gamma(k,a) \quad \Psi \\
-k^2(\Psi+\Phi) = &\ \Sigma(a,k) \quad 8\pi G\ a^2\rho\Delta
\end{aligned}
$$

Additional force mediated by the scalar: $\vec{f} = -\vec{\nabla}\Psi - \frac{d\ln A(\phi)}{d\phi}\vec{\nabla}\phi$

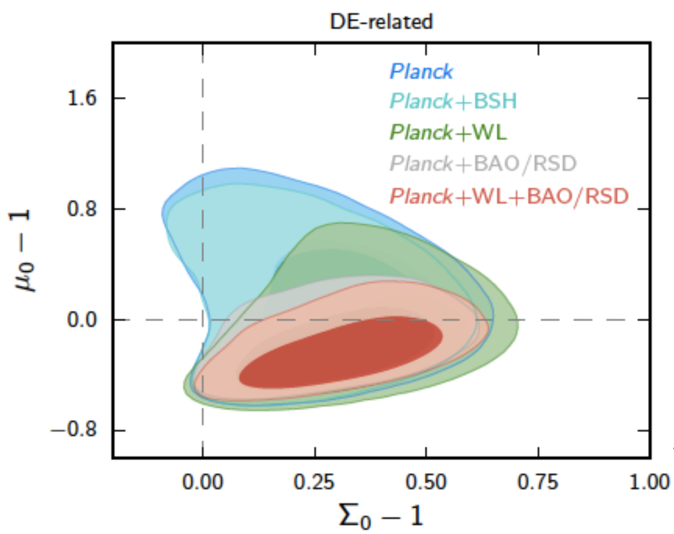
The range set by the density dependent mass: $m^2 = \frac{d^2 V_{\rm eff}}{d\phi^2}$

The coupling strength: $\beta = m_{\rm Pl}\frac{d\ln A}{d\phi}$

$$\epsilon(k,a) = \frac{2\beta^2(a)}{1+m^2(a)a^2/k^2}$$

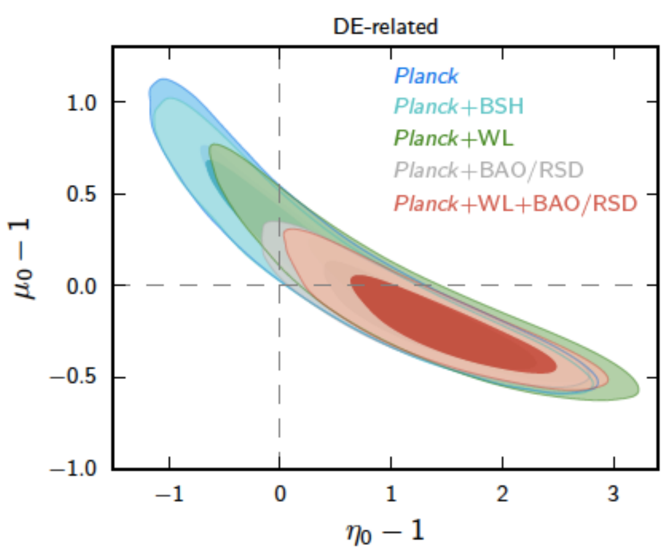
$$
\begin{aligned}
\mu &= A^2(\phi)[1+\epsilon(k,a)] \geq 1 \\
\gamma &= \frac{1-\epsilon(k,a)}{1+\epsilon(k,a)} \leq 1 \\
\Sigma &= A^2(\phi) \approx 1
\end{aligned}
$$

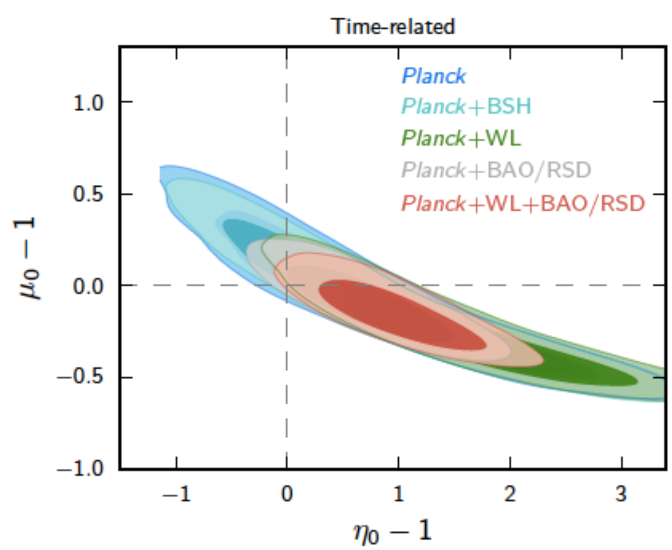
Planck 2015 results. XIV. Dark energy and modified gravity



$$\mu < 1$$
$$\gamma > 1$$
$$\Sigma > 1$$

would rule out all Brans-Dicke type models
(and pretty much all other scalar-tensor models)





Beyond Brans-Dicke: a general Horndeski model

$$\mathcal{L}_2 = K(\phi,\, X)\,,$$
$$\mathcal{L}_3 = -G_3(\phi,\, X)\Box\phi\,,$$
$$\mathcal{L}_4 = G_4(\phi,\, X)R + G_{4X}(\phi,\, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]\,,$$
$$\mathcal{L}_5 = G_5(\phi,\, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi,\, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$

$$S = \int dt d^3x a^3 \left[\text{background terms} + \frac{M_*^2}{4}\left(\dot{h}_T^2 - \frac{1+\alpha_T}{a^2}(\vec{\nabla}h_T)^2\right)\right]$$

Modified speed of gravity waves if $G_{4,X}$ is not zero, or G_5 is not constant

$$M_*^2 = 2(G_4 - 2XG_{4,X} + XG_{5,\phi} - \dot{\phi}HXG_{5,X})$$

$$\alpha_T = 2X(2G_{4,X} - 2G_{5,\phi} - (\ddot{\phi} - \dot{\phi}H)G_{5,X})M_*^{-2}$$

Gao & Steer, 1107.2642; De Felice & Tsujikawa, 1110.3878; Bellini & Sawicki, 1404.3713

Consistency tests of Horndeski theories

The large scale limit: $k/a \ll m_C$

$$\Sigma_0 = \frac{m_{\rm Pl}^2}{M_*^2}\left(1+\frac{\alpha_T}{2}\right)$$
$$\gamma_0 = \frac{1}{1+\alpha_T}$$
$$\mu_0 = \frac{m_{\rm Pl}^2}{M_*^2}(1+\alpha_T)$$

A deviation from unity on large scales indicates a modified speed of GW. Can be compared to GW speed bounds from compact sources and CMB

Pulsars constrain α_T today <0.02, but it can, in principle, vary in the past

Jimenez, Piazza, Velten, 1507.05047

LP & Silvestri, 1606.05339

Consistency tests of Horndeski theories

The small scale limit: k/a >> m_C

$$\mu_\infty = \frac{m_0^2}{M_*^2}(1 + \alpha_T + \beta_\xi^2),$$

$$\gamma_\infty = \frac{1 + \beta_B \beta_\xi}{1 + \alpha_T + \beta_\xi^2},$$

$$\Sigma_\infty = \frac{m_0^2}{M_*^2}\left(1 + \frac{\alpha_T + \beta_\xi^2 + \beta_B \beta_\xi}{2}\right)$$

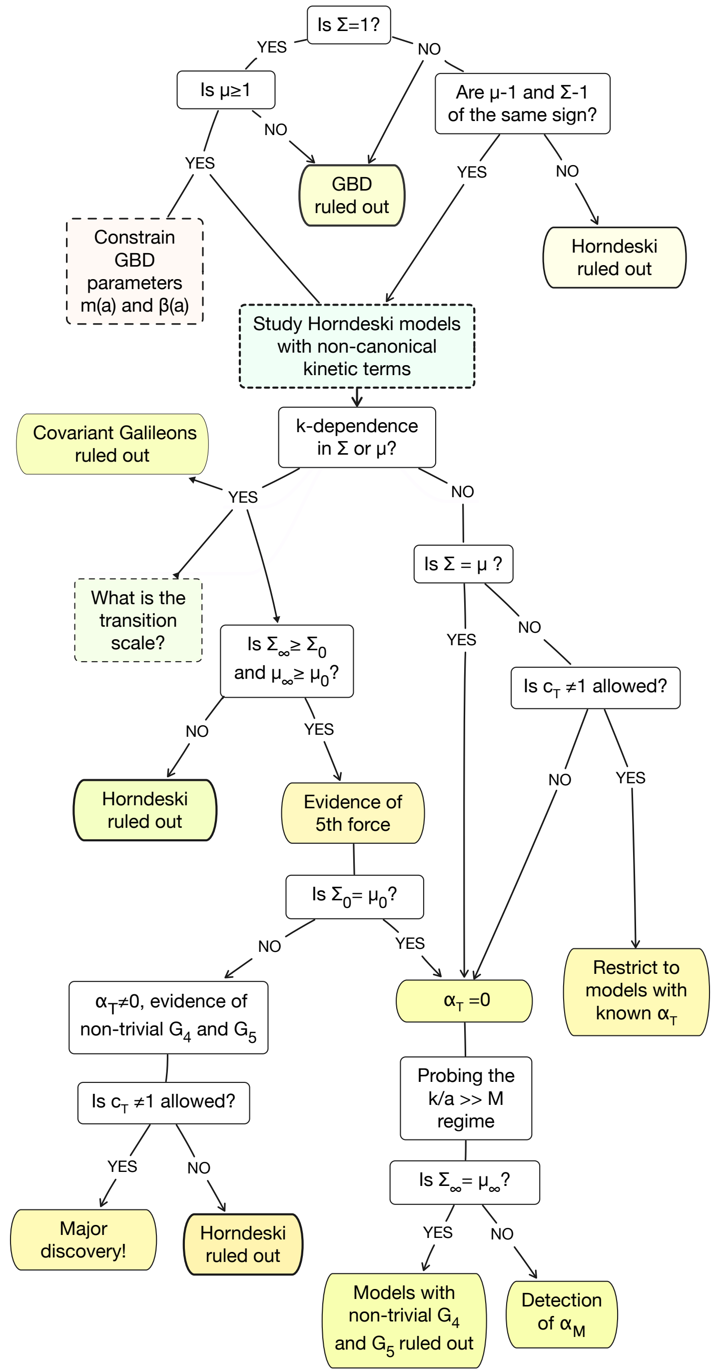
Pulsars constrain $\boldsymbol{\alpha}_T$ today <0.02, but it can, in principle, vary in the past

Jimenez, Piazza, Velten, 1507.05047

Evolution of the Planck constant is constrained by BBN and CMB (at 10% level)

Different signs of $\boldsymbol{\mu}$-1 and $\boldsymbol{\Sigma}$-1 would effectively rule out all Horndeski models

LP & Silvestri, 1606.05339



LP & Silvestri, 1606.05339

Summary

<u>Key observational tests</u>:

Is w_{DE}=-1?
Are the Newtonian and the Weyl potentials the same?
Is the speed of gravitational waves the same as the speed of light?

It is possible to constrain large classes of modified gravity models using a few phenomenological functions

Future surveys, such as Euclid and LSST, will measure a lot of numbers

The challenge for theorists is to find meaningful questions they can answer