Alternative theories of gravity

Dark Energy and cosmological tests of general relativity

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NORDITA

Cosmology in the Canary Islands

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gravity
ˈgravɪti/
noun

1. [Physics]
   the force that attracts a body towards the centre of the earth, or towards any other physical body having mass.
2. extreme importance; seriousness.
3. in the context of fermenting alcoholic beverages, refers to the specific gravity, or relative density compared to water, of the wort or must at various stages in the fermentation.

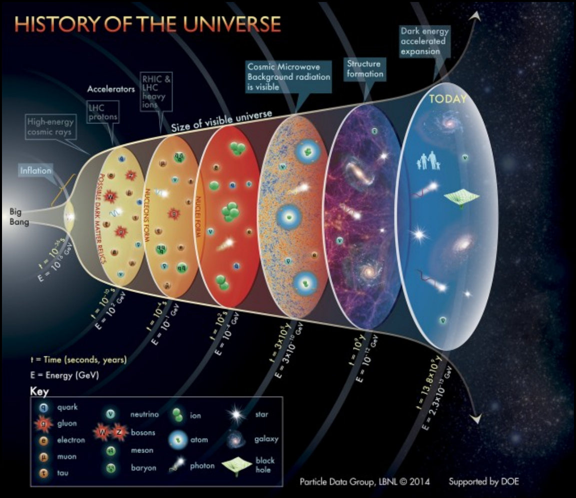
Sources: google (1,2), wikipedia (3)

Outline

- Why modify gravity?
  - $\star$ GR + ΛCDM
- Alternative Theories
  - $\star$ Scalar-tensor theories
  - $\star$ Observable Signatures
- Testing gravity
  - $\star$ Effective theory of dark energy
  - $\star$ The `hi_class` code
  - $\star$ Gravitational waves

(Short course, but happy to discuss in person or email)

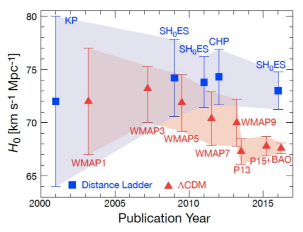
Fundamental physics and cosmology



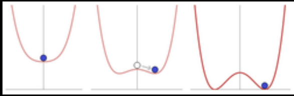
Initial conditions, Dark Matter, Neutrinos, Dark Energy, Gravity ...

The case for modified gravity

- Alternatives to Λ
  - Inflation again? $n_s \neq 1$
  - ΛCDM tensions $\longrightarrow$



- Interesting theoretical questions
  - *proxy for inflation/quantum gravity?*
  - *cosmological constant problems?*



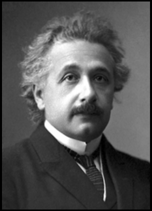
$\sim 36\%$ *of unresolved problems in physics involve gravity*

(see www.wikipedia.org/wiki/List_of_unsolved_problems_in_physics)

- Test gravity on all regimes by
  - *confirming standard predictions* ✓
  - *ruling out competing theories*

General relativity

$$S = \int d^4x \frac{1}{16\pi G}\sqrt{-g}R[\underbrace{g_{\mu\nu}}_{\text{metric}}]$$



Equations

$$\underbrace{R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R}_{\text{curvature}} = 8\pi G \underbrace{T_{\mu\nu}}_{\text{matter}}$$

Cosmology: $g_{\mu\nu} = \mathrm{diag}(-1, a(t), a(t), a(t))$ (flat FRW)

$$H \equiv \frac{\dot a}{a} = \left(\frac{8\pi G}{3}\sum \rho_i\right)^{\frac{1}{2}} \longrightarrow \rho_i \supset \text{matter+light}, \nu, \text{DM, DE}$$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}\sum(\rho_i + 3p_i) \rightarrow \text{acceleration} \Leftrightarrow p < \rho/3$$

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How to modify gravity

Lorentz + QM $\Rightarrow$ restrictions on massless graviton interactions!

(Weinberg '64)

Einstein gravity: only covariant metric theory with 2^{nd} order eqs.

(Lovelock '71)

Need to give up some of the assumptions:

- Add degrees of freedom:
  - Massive gravity: $\rightarrow$ 5 d.o.f. $\rightarrow$ very tough!
  - Scalar-tensor: $\rightarrow$ 2+1 d.o.f.
  - vector-tensor, tensor-vector-scalar (TeVeS), $\cdots$
- Lorentz violation, Non-local interactions, $\cdots$

Quintessence (Wetterich '88, Rathra and Peebles '88)

$$S = \int d^4x\sqrt{-g}\Big\{\frac{1}{16\pi G}R[\underbrace{g_{\mu\nu}}_{\text{metric}}] + \underbrace{\frac{1}{2}(\partial\phi)^2}_{\text{kinetic}} - \underbrace{V(\phi)}_{\text{potential}}\Big\}$$

Modifies cosmic expansion:

- $\rho_q = \frac{1}{2}\dot\phi^2 + V(\phi) \qquad p_q = \frac{1}{2}\dot\phi^2 - V(\phi)$

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Modifies cosmic expansion:

- $\rho_q = \frac{1}{2}\dot\phi^2 + V(\phi) \qquad p_q = \frac{1}{2}\dot\phi^2 - V(\phi)$
- Acceleration equation:

$$\frac{\ddot a}{a} \propto -(\rho_m + 3p_m) - 2\dot\phi^2 + 2V(\phi)$$

- Slow roll $\dot\phi \ll \sqrt{V} \Rightarrow$ effective Λ

$$w \equiv \rho_q/p_q \approx -1 + \dot\phi^2/V \quad \Rightarrow \quad \underline{w > -1}$$

$\Rightarrow$ Probed by SNe, H_0, BAO, CMB scales...

Brans-Dicke theory (Jordan '59, Brans & Dicke '61)

$$S = \int d^4x\sqrt{-g}\left\{ \underbrace{\frac{\phi}{16\pi G}}_{\text{effective } G} R[g_{\mu\nu}] + \underbrace{\frac{\omega_{\rm BD}}{\phi}}_{\text{coefficient}} \underbrace{\frac{1}{2}(\partial\phi)^2}_{\text{kinetic}} \right\}$$

Modifies expansion and growth:

$$g_{\mu\nu} \to -(1+\Psi)dt^2 + (1-\Phi)d\vec{x}^2,$$
$$\phi \to \phi_0 + \delta\phi$$

- Scalar force: $\vec{\partial}^2\delta\phi = \frac{8\pi G}{2\omega_{\rm BD}+3}(\rho - 3p) + \cdots$

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- Newtonian potential → Probed by Clustering & RSD

$$\vec{\partial}^2\Psi = \frac{8\pi G}{\phi_0}\rho + \vec{\partial}^2\delta\phi + \cdots$$

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- Newtonian potential $\to$ Probed by Clustering & RSD

$$\vec{\partial}^2\Psi = \frac{8\pi G}{\phi_0}\rho + \vec{\partial}^2\delta\phi + \cdots$$

- Anisotropic stress $\to$ Probed by Gravitational Lensing

$$\vec{\partial}^2(\Psi - \Phi) = \vec{\partial}^2\delta\phi + \frac{8\pi G}{\phi_0}\sigma + \cdots$$

Galileon gravity (Nicolis+ '08, de Rham Tolley '10...)

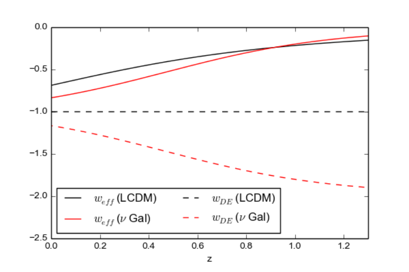
Limit of massive gravity, DGP/extra-dimensions:

$$S = \int d^4x\sqrt{-g}\Big\{\frac{1}{16\pi G}R[g_{\mu\nu}] - \underbrace{\frac{1}{2}(\partial\phi)^2}_{\text{kinetic}} + \underbrace{c_3(\partial\phi)^2\Box\phi}_{\text{deriv. int.}} + \cdots\Big\}$$

Self-acceleration

- $\rho_{gal} = \dfrac{\Omega_{gal}H_0^2}{H(t)^2} \Rightarrow \boxed{w < -1}$
- $H^4 = H^2\rho_m(t) + \Omega_{gal}H_0^4$

  accelerates with $\Lambda = 0$



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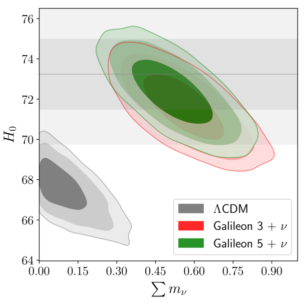
  accelerates with $\Lambda = 0$
- No Λ+GR limit
  $\rightarrow$ very predictive



- Cosmologically viable (CMB+BAO) (Renk+ 1707.02263)
- Modified gravity effects hidden on small scales (screening)

Scalar-Tensor gravity

⋆ First-generation: $f(\phi)R + K[(\partial\phi)^2, \phi]$

$\supset$ quintessence, $f(R)$, Brans-Dicke (Jordan '59, Brans & Dicke '61)

⋆ Horndeski's Theory (1974)

$g_{\mu\nu}$ + $\boxed{\phi}$ + Local + 4-D + Lorentz theory with $\boxed{2^{nd}\text{ order Eqs.}}$

4× functions $G_i(X, \phi)$ of ϕ, $X \equiv -(\partial\phi)^2/2$

$$\mathcal{L}_H = G_2 - G_3\nabla^2\phi + G_4 R + G_{4,X}\left[\nabla\nabla\phi\right]^2 + G_5 G_{\mu\nu}\phi^{;\mu\nu} - \frac{G_{5,X}}{6}\left[\nabla\nabla\phi\right]^3$$

$\supset$ GR, quint/k-essence, Brans-Dicke, $f(R)$, chameleons...

kinetic gravity braiding, covariant Galileon, Gauss-Bonnet...

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⋆ Beyond Horndeski → *discovered by accident!*

(MZ & Garcia-Bellido '13, Gleyzes *et al.* '14, Langlois & Noui '15)

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  - ⋆ Gravitational waves

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Effective theory of Dark Energy (Gubitosi+, Bloomfield+ '13)

- Too many gravity theories $\Rightarrow$ systematic approach
- Background: $w(z) \rightarrow$ complete description

$$p_{DE} = w(z)\rho_{DE} \,, \qquad \dot{\rho}_{DE} + 3H(1+w)\rho_{DE} = 0$$

$\rightarrow w(z)$ with data (parameterization, binning, principal components...)

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- EFT-DE $\rightarrow$ Most general theory of gravity with:
  - $\star$ Only background + linear perturbations
  - $\star$ Tensor + scalar field $\cdots$

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- EFT-DE $\rightarrow$ Most general theory of gravity with:
  - $\star$ Only background + linear perturbations
  - $\star$ Tensor + scalar field $\cdots$
  - $\star$ FRW Symmetries: homogeneity + isotropy
  - $\star$ Theory symmetries: coordinate transformations

$\Rightarrow$ Finite set of $\alpha_i(z)$ functions $\leftrightarrow$ describes any theory

(Review: Gleyzes, Langlois, Vernizzi '14)

Horndeski in four words (Bellini & Sawicki '14)

$$\underbrace{\ddot{h}_{ij} + 3H(1 + \alpha_M)\dot{h}_{ij}}_{\delta(\sqrt{-g}M_*^2\dot{h}_{ij}^2)} + \underbrace{(1 + \alpha_T)}_{c_T^2,\ \text{GW}} k^2 h_{ij} = 0 \qquad \text{(tensors)}$$

$$\underbrace{\alpha_K}_{\text{diagonal}} \delta\ddot{\phi} + 3H \underbrace{\alpha_B}_{\text{mixing}} \ddot{\Phi} + \underbrace{\left(\quad \cdots \quad \right)}_{\alpha_K, \alpha_B, \alpha_M, \alpha_T} = 0 \qquad \text{(scalar field)}$$

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Kineticity: α_K

Standard kinetic term $\rightarrow c_S^2$

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Kinetic Mixing of $g_{\mu\nu}$ & ϕ

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M_p running: α_M

Variation rate of effective M_p

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Kineticity: α_K

Standard kinetic term $\to c_S^2$

Braiding: α_B

Kinetic Mixing of $g_{\mu\nu}$ & ϕ

M_p running: α_M

Variation rate of effective M_p

Tensor speed excess: α_T

GW at $c_T^2 = 1 + \alpha_T$

Theory-specific relations

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Kineticity: α_K

kinetic term $\to c_S^2$

Braiding: α_B

Mixing of $g_{\mu\nu}$ & ϕ

scalar & tensor

M_p running: α_M

Variation of eff. M_p

Tensor speed excess: α_T

GW speed $c_T^2 = 1 + \alpha_T$

tensor only

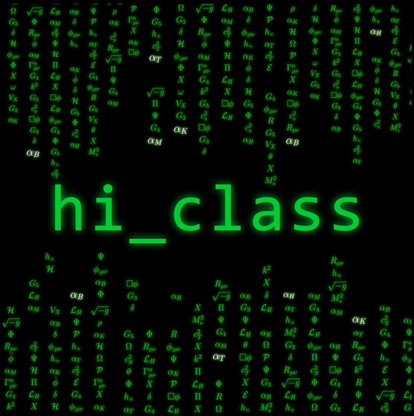
Theory-specific relations, e.g.

- Quintessence: $\alpha_K \propto (1+w)\Omega_{\rm DE}$
- Brans-Dicke: α_K, $\alpha_B = -\alpha_M$
- Galileon $G_3 \to \alpha_K, \alpha_B \neq \alpha_M$
  $G_4, G_5 \to \alpha_M$, α_T

Measure α's $\leftrightarrow$ Properties of gravity & underlying theory

Horndeski in the Cosmic Linear Anisotropy Solving System

Goal: compute general DE/MG models in as much detail as ΛCDM



www.hiclass-code.net

1. Flexibility:
   - ⋆ New models trivially added
   - ⋆ Compatible massive ν's, etc...
2. Accuracy:
   - ⋆ Full linear dynamics + ICs
   - ⋆ Tested - Bellini+ (in prep.)
3. Speed:
   - ⋆ $2\times$ QS approx. $\rightarrow$ speed up

(MZ, Bellini, Sawicki, Lesgourgues, Ferreira '16)

`hi_class` in practice

$$\left.\begin{array}{c} G_2,\, G_3,\, G_4,\, G_5 \\ \phi(t_0),\, \dot\phi(t_0) \end{array}\right\} \longrightarrow \left\{\begin{array}{c} \text{Kineticity } \alpha_K \\ \text{Braiding } \alpha_B \\ M_p \text{ running } \alpha_M \\ \text{Tensor speed } \alpha_T \end{array}\right\} \longrightarrow \left\{\begin{array}{c} D_A(z) \\ C_\ell \\ P(k) \\ \ldots \end{array}\right.$$

a) Full theory + IC*

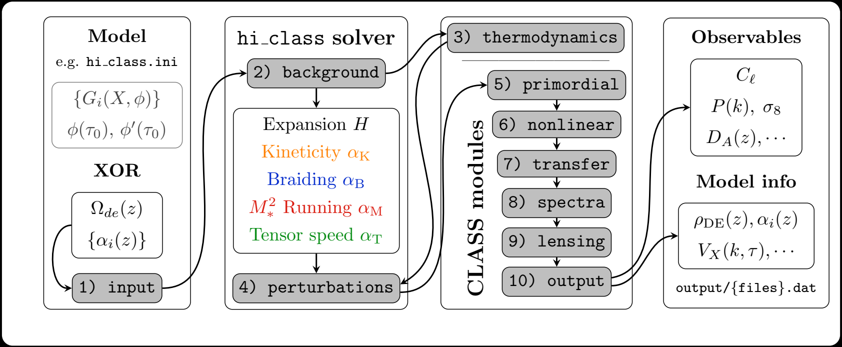
b) *or* Parameterize $w(z), \alpha_i(z)$

Full theory has more info

- Background $\longrightarrow$ often very constraining
- Non-linear effects
- Other regimes: GWs, strong gravity, Solar System, QM, Lab...

$*$ Available soon

hi_class structure



changes in 3 modules

- input: read/interpret model parameters
- background: compute α-functions and $\rho_{DE}(t)$
- perturbations: solve modified Einstein eqs

New model $\longrightarrow$ modify input & background only

hi_class use

- All modifications labeled `_smg` ⟶ scalar modified gravity

```
grep '_smg' /source/background.c # -> shows modif. in back.
```

- all details in hi_class.ini (equiv. to explanatory.ini)

hi_class use

- All modifications labeled **_smg ⟶ scalar modified gravity**

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```

- Add a DE component (in params or .ini file)

```
params = {
"Omega_fld" : 0,
"Omega_Lambda" : 0,
"Omega_smg" : -1, #find as 1-Omega_m - Omega_r
```

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```

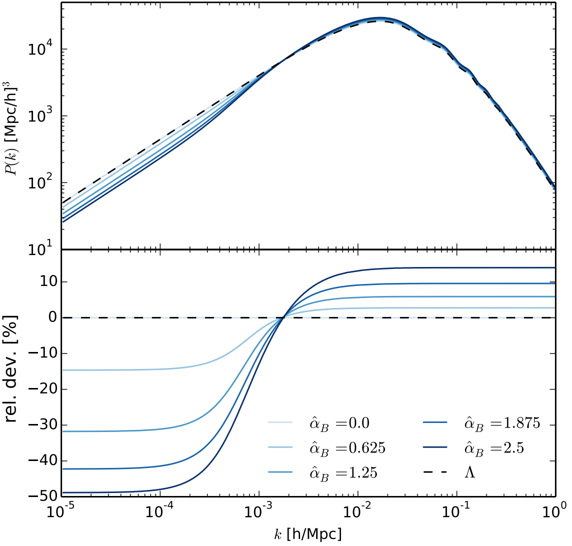
- Choose model + parameters (expansion and gravity/α's)

```
"gravity_model" : "propto_omega", #alpha_i = c_i Omega_smg
#  gravity params -> c_K, c_B, c_M,  c_T,  M_0^2
"parameters_smg" : " 1,  -0.1,   0,    0,  1.0",
"expansion_model" : "w0wa", #usual parameterization
# expansion params -> Omega_smg, w_0, w_a
"expansion_smg" :   "0.75,   -1,   0", #Omega_smg set by code
}
```

- all details in hi_class.ini (equiv. to explanatory.ini)

hi_class output

$$\alpha_B = \hat{\alpha}_B \cdot \Omega_{de},\ \alpha_K = 1 \cdot \Omega_{de}, \quad w = -1$$



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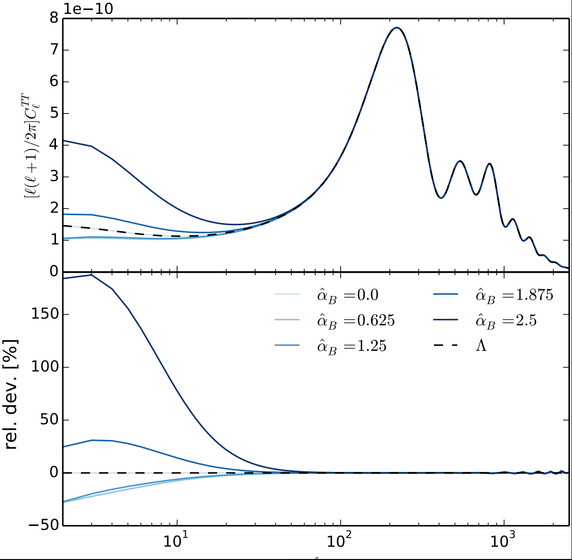


Testing gravity with Gravitational Waves

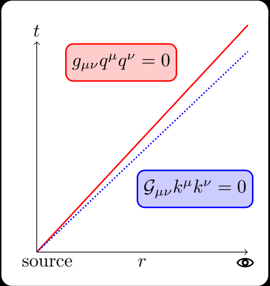
$$G_2 - G_3\Box\phi + G_4 R + G_{4,X}\left[\nabla\nabla\phi\right]^2 + G_5 G_{\mu\nu}\phi^{;\mu\nu} - \frac{G_{5,X}}{6}\left[\nabla\nabla\phi\right]^3$$

GWs on FRW (Bellini+Sawicki, Gleyzes+ '14)

$$\ddot{h}_{ij} + \underbrace{(1+\alpha_T)}_{c_g^2 \neq c} k^2 h_{ij} + \cdots = 0$$

- Speed of GW varies in ST theories
- Measure with GW-EM source

Bettoni, Ezquiaga, Hinterbichler, MZ '16



Multi-messenger event GW+EM (Will '14, Lombriser+Taylor '15)

$$\frac{\Delta t}{s} \sim 10^{17}\left(\frac{c_g}{c} - 1\right)\left(\frac{D}{200\text{Mpc}}\right)$$

$\Rightarrow$ strong constraints on theories with G_4, G_5!

Conclusions

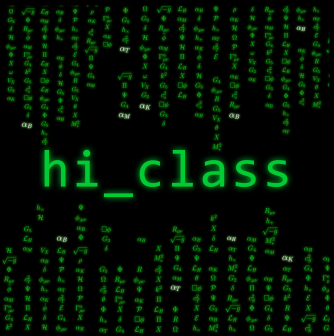
Thanks!

- Scalar-tensor cosmology well understood
  - ⋆ Specific Theories
  - ⋆ General Parameterizations
- hi_class code
  - ⋆ Flexible: add your own models
  - ⋆ Accurate and fast
- Many tests of gravity
  - ⋆ Cosmology: expansion, growth...
  - ⋆ Gravitational wave speed

www.hiclass-code.net

The hi_class academy

Coming soon!



www.hiclass-code.net

- Set of interrelated projects:
  - ⋆ Theory & model building
  - ⋆ Implementation and phenomenology
  - ⋆ Compare with data
- Collaboration → Publishable results
  - ⋆ Review of models
  - ⋆ Observational constaints
- Stay tuned for more info!

Backup Slides

hi_class

www.hiclass-code.net

hi_class: status and prospects

Public (www.hiclass-code.net)

1. Parameterized H, α_i

   $\alpha_i \propto \Omega, a$, Planck param...

   ☛ your model here!
2. Iterface with MontePython (parameter estimation)
3. Tested: $\delta C_\ell \lesssim 0.5\%$, $\delta P_k \lesssim 0.1\%$

Private (coming soon)

1. Theories with $G_2 - G_5$:

   Brans-Dicke, Galileons...

   ☛ your model here!
2. Early Modified Gravity

Development/test

1. Quasi-static approximation
2. MG initial conditions

Prospects

1. beyond Horndeski:

   G^3, EST, massive gravity
2. Non-linear (PT, N-body)
3. Automatic code generator
4. Curvature, Newt. gauge...

Screening Mechanisms

$\rho \gg \rho_0$ Chameleon Screening - Khoury & Weltman (PRL 2004)

Yukawa force: $\phi \propto \frac{1}{r} e^{-\phi/m_\phi}$ with $m_\phi(\rho)$ increases with ρ

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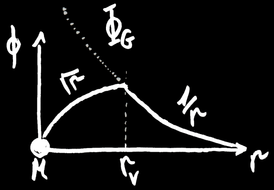
$\mathcal{L} \supset (\partial\phi) + \Box\phi X/m^2 + \alpha\phi T_m$ Non-linear derivative interactions

$$\Rightarrow\ \Box\phi + m^{-2}\left((\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right) = \alpha M \delta(r)$$

$$\phi \propto \begin{cases} r^{-1} & \text{if } r \gg r_V \\ \sqrt{r} & \text{if } r \ll r_V \end{cases}$$

Vainshtein radius $r_V \propto (GM/m^2)^{1/3}$



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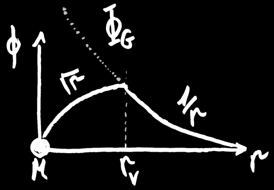

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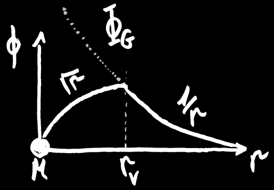

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Systematic approaches to test gravity

1 - Model from Lagrangian

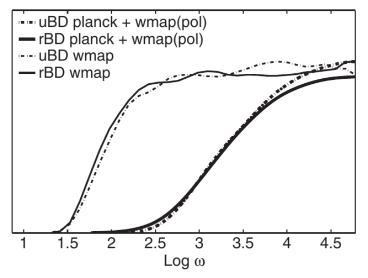
$$\mathcal{L}[g_{\mu\nu}, \cdots] = \frac{R}{16\pi G} + \text{modifications}$$

- Very specific, self-consistent
- Variable freedom: parameters + ICs $\rightarrow$ several free functions
- Predictions for any regime, consistent expansion history

Example: Brans-Dicke theory

$$\mathcal{L} \propto \phi R - 2\Lambda - \frac{\omega}{\phi}(\partial\phi)^2$$

(Avilez & Skordis '14)



Systematic approaches to test gravity

2 - Parameterize the solutions

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

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

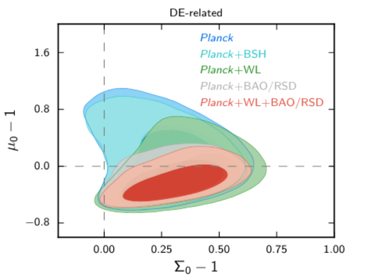
- Most general / model independent
- Vast functional freedom: 2 functions 2 variables
- No info from other regimes, no expansion history

Example: pure time dependence

$$\mu = 1 + \mu_0 \Omega_{de}(a)$$

$$\Sigma = 1 + \Sigma_0 \Omega_{de}(a)$$

(Planck '15 DE paper)



Systematic approaches to test gravity

3 - Effective theory approaches

$$\mathcal{L} = \sum_i \alpha_i(t)\mathcal{O}_i$$

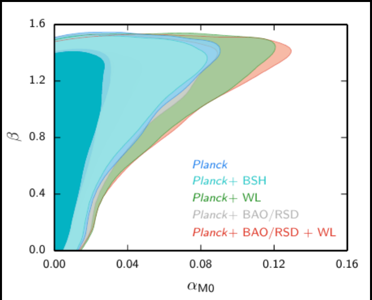
- Rather general: locality, covariance, d.o.f. # & type
- Large functional freedom $\mathcal{O}$(few) functions, 1 variable
- Limited info from other regimes (GWs) no expansion history

Example: Simple EFT-DE

$$\alpha_M = \frac{a}{\Omega+1}\frac{d\Omega}{da} = -\alpha_B$$

$$\Omega(a) = \exp\left[\frac{\alpha_{M,0}}{\beta}a^\beta\right] - 1$$

(Planck '15 DE paper)



Massive Gravity (Reviews: de Rham 2014, Hinterbichler 2011)

- $\star$ Very difficult problem: $\sim 1939 - 2010$ to "solve"!
- $\star$ Degrees of freedom:

  $g_{\mu\nu} \rightarrow 10$ components $\rightarrow 2s+1 = 5$ d.o.f. $+$ ghosts!

- $\star$ dRGT massive gravity (de Rham, Gabadadze, Tolley 2010)

  5 d.o.f. $\rightarrow \checkmark$

  flat FRW $\Rightarrow \dot{a}(t) = 0$:(

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⋆ Bigravity (Hasan, Rosen 2011)

$g_{\mu\nu}$, $f_{\mu\nu}$: 5+2 d.o.f $\rightarrow$ ✓

Cosmic evolution + acceleration :)

But unstable (Könnig '15) or

too close to Λ (Akrami *et al.* '15)

⋆ Multigravity (Hinterbichler, Rosen '12), Lorentz-violating (Blas, Sibiryakov '14)

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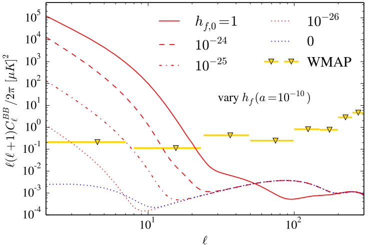

(Amendola, Könnig, Martinelli, Pettorino, MZ '15)

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