Introduction to hi_class

CLASSy Tests of Gravity and Dark Energy

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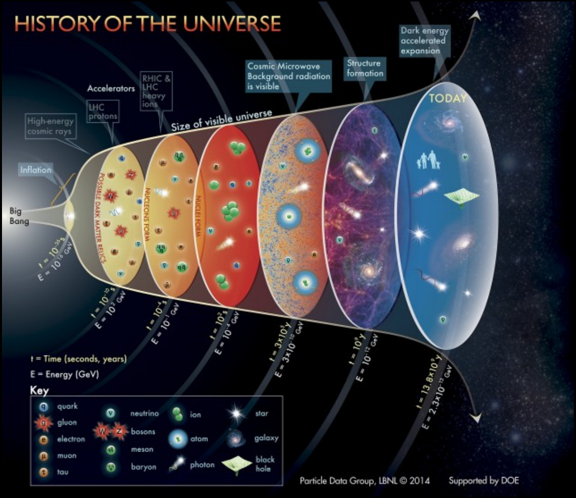
NORDITA

Cosmology in Theory and Practice

September 2017

Fundamental physics and cosmology



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

The case for modified gravity

- Alternatives to Λ?

  Inflation again? $n_s \neq 1$

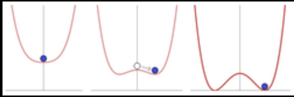
- Interesting theoretical questions

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

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

  proxy for inflation/quantum gravity?

  cosmological constant problems?



- Test gravity on all regimes by

  - *confirming standard predictions* ✓
  - *ruling out competing theories*

ΛCDM very successful *but*...

H_0 in tension

- Cepheids+SNe (distance ladder)

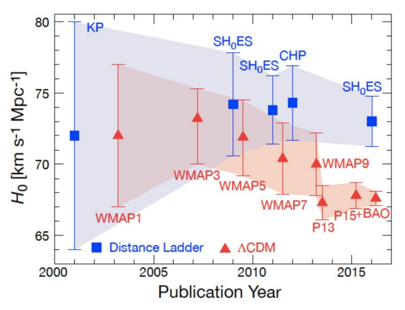
  $$H_0 = 73.24 \pm 1.74$$

  (Riess *et al.* '16)

- CMB+BAO+ΛCDM

  $$H_0 = 66.93 \pm 0.62$$

  (Planck '15)



(W. Freedman - Nature '17)

- 3.4σ tension $\Rightarrow$ Either systematic effects or new physics
- Also tension between Planck + Weak Lensing surveys

Scalar-Tensor gravity

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

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

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⋆ 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, $X \equiv -(\partial\phi)^2/2$

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

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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)

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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Standard kinetic term $\rightarrow c_S^2$

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M_p running: α_M

Variation rate of effective M_p

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Standard kinetic term $\to c_S^2$

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Variation rate of effective M_p

Tensor speed excess: α_T

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

Horndeski in the Cosmic Linear Anisotropy Solving System

hi_class

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

www.hiclass-code.net

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

hi_class in practice

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

a) Full theory + IC *

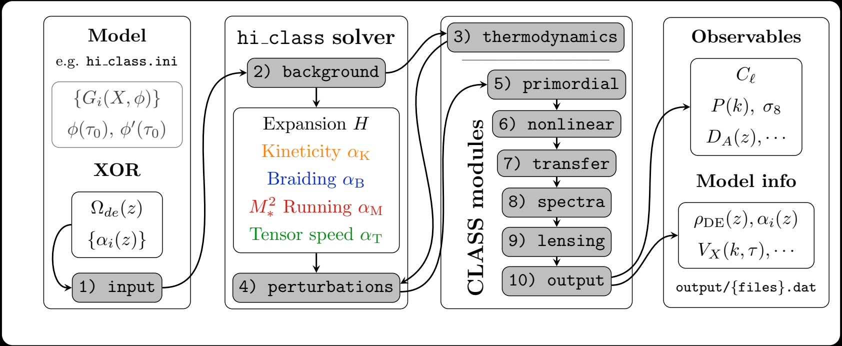
b) *or* Parameterize $w(z), \alpha_i(z)$

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 $\longrightarrow$ 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

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

- 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)

Gravity model → choice of $\{\alpha_i(t)\}$ functions

background.c → background_gravity_functions

```
if (pba->gravity_model_smg == propto_omega) { //name of model

   //friendly notation
   double c_k = pba->parameters_2_smg[0];
   double c_b = pba->parameters_2_smg[1];
   double c_m = pba->parameters_2_smg[2];
   double c_t = pba->parameters_2_smg[3];

   //write the alpha functions
   pvecback[pba->index_bg_kineticity_smg] = c_k*Omega_smg;
   pvecback[pba->index_bg_braiding_smg] = c_b*Omega_smg;
   pvecback[pba->index_bg_tensor_excess_smg] = c_t*Omega_smg;
   pvecback[pba->index_bg_mpl_running_smg] = c_m*Omega_smg;
   pvecback[pba->index_bg_M2_smg] = M_pl;
}
else if (pba->gravity_model_smg == propto_scale) {
      //...
```

Expansion model → choice of ρ_{smg}, p_{smg} → $H(z)$

background.c → background_gravity_functions

```
if (pba->expansion_model_smg == wowa){

   //friendly notation
   double Omega_const_smg = pba->parameters_smg[0];
   double w0 = pba->parameters_smg[1];
   double wa = pba->parameters_smg[2];

   //DE density and pressure
   pvecback[pba->index_bg_rho_smg] = Omega_const_smg *
       pow(pba->H0,2)/pow(a,3.*(1. + w0 + wa)) *
       exp(3.*wa*(a-1.));
   pvecback[pba->index_bg_p_smg] = (w0+(1-a)*wa) *
       Omega_const_smg * pow(pba->H0,2)/pow(a,3.*(1.+w0+wa)) *
       exp(3.*wa*(a-1.));
}
```

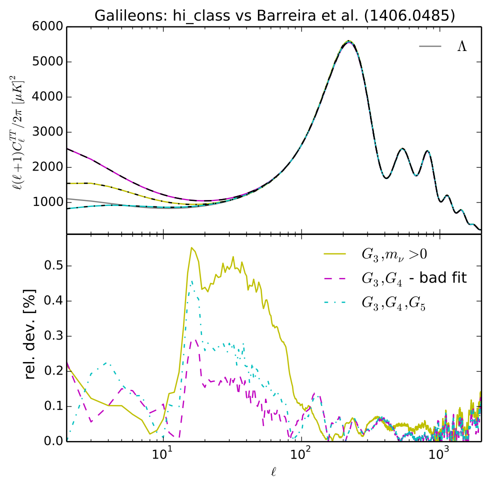
Example: Galileons

$$G_2 = -X$$
$$G_3 = c_3 X / M^3$$
$$G_4 = \frac{M_p^2}{2} + c_4 X^2 / M^6$$
$$G_5 = c_5 X^2 / M^9$$

Tested against Barreira+ '14 & EFTCAMB

- $\delta C_\ell \lesssim 0.5\%$
- $\delta P(k) \lesssim 0.1\%$
- $\delta w(z) \lesssim 0.01\%$

fully independent implementations



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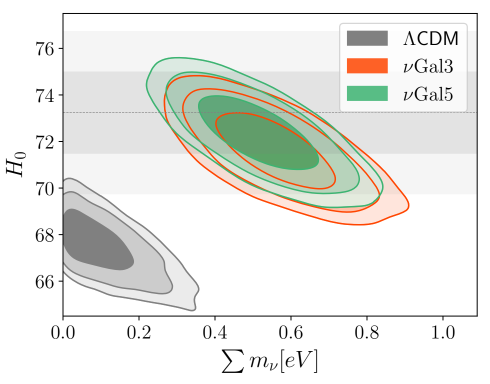

- Viable model (with $m_\nu \sim 0.6$eV)!
- H_0 solution?

(Renk+ 1707.02263)

hi_class: status and prospects

Public (www.hiclass-code.net)

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

   ☛ your model here!

2. Iterface with MontePython (parameter estimation)

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Prospects

1. beyond Horndeski:

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

Conclusions

- Flexibility, accuracy and speed
- Many physics already implemented
  - Inflation/primordial: $V(\phi)$/external, isocurvature...
  - Dark Matter and ν: warm, decaying, chemical pot.
  - Dark Energy: perfect fluid, quintessence
  - Modified Gravity: Horndeski → `hi_class`
- Very easy to add your own stuff!
- Exciting avances underway!

(See more resources in www.hiclass-code.net)