

Tests of Gravity and Dark Energy with Cosmology & Gravitational Waves

Lecture 2: the `hi_class` code in practice

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BERKELEY CENTER *for*
COSMOLOGICAL PHYSICS



Mesoamerican Center for Theoretical Physics

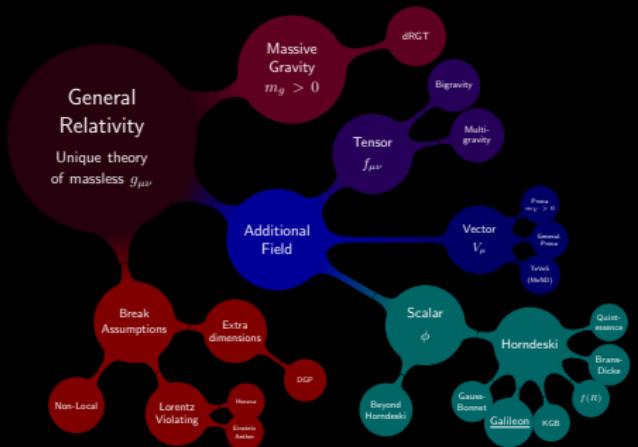
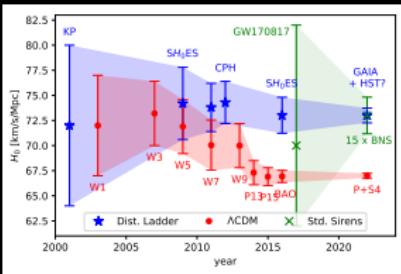
October 2018

Further reading

- “Dark Energy in light of Multi-Messenger GW astronomy” 1807.09241
- “*hi_class: Horndeski in the Cosmic Linear Anisotropy Solving System*” 1605.06102
 - “Modified Gravity and Cosmology” 1402.5031

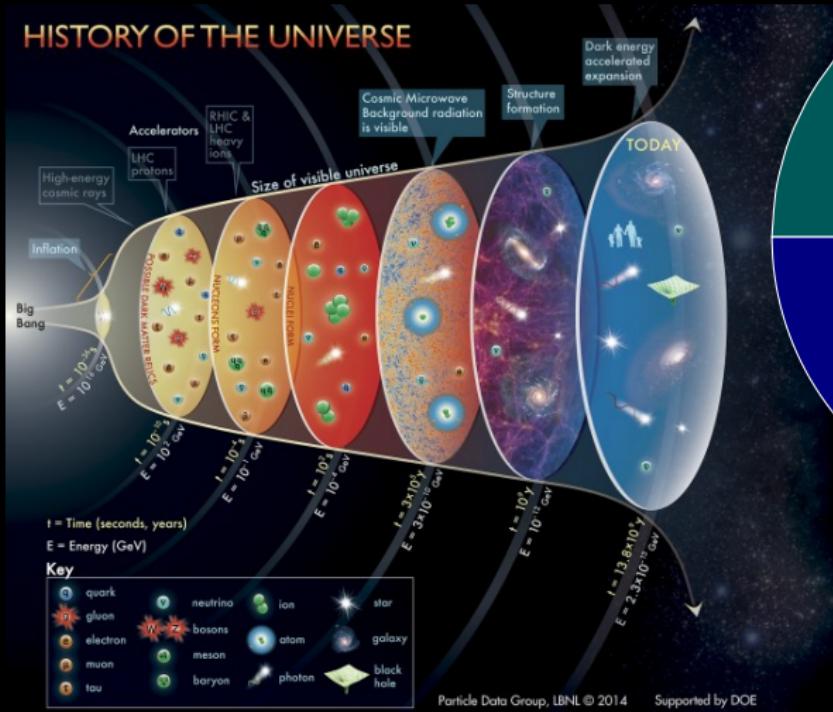
Recap from lecture 1

- Gravity is important: \exists good reasons for beyond GR
- Tensions in Λ CDM: new physics?
- Many theories available
 - general frameworks
 - flexible tools
- Most theories very predictive!
- Test theories in every regime: cosmology, local gravity, GWs...



The Dark Universe

HISTORY OF THE UNIVERSE



Dark Energy

Dark Matter

Baryons

- Dark Matter & Dark Energy
- Test gravity
- Neutrinos & relic particles...
- Inflation, initial conditions...

Well understood laws and history...

...but important unknowns

Einstein-Boltzmann Codes

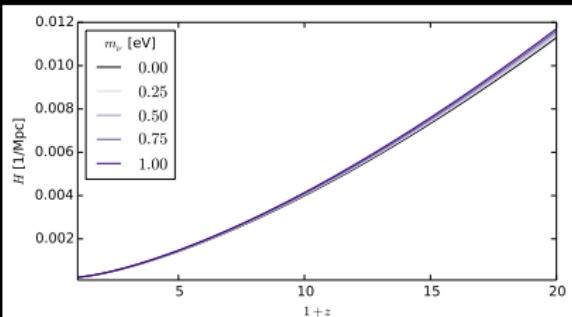
hi_class

www.hiclass-code.net

From Physics to Cosmology

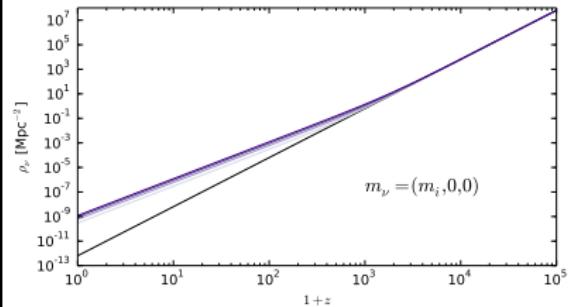
Compute predictions

- **Background evolution**
- Observables:
 - ★ $P(k, z)$
 - ★ CMB: TT, $\phi\phi$ lensing pot.
 - ★ Galaxy C_l & rel. eff.



Other intermediate results

- Thermodynamic evolution
- Initial conditions
- Transfer functions
- Perturbation evolution
- Contributions to spectra
- ...



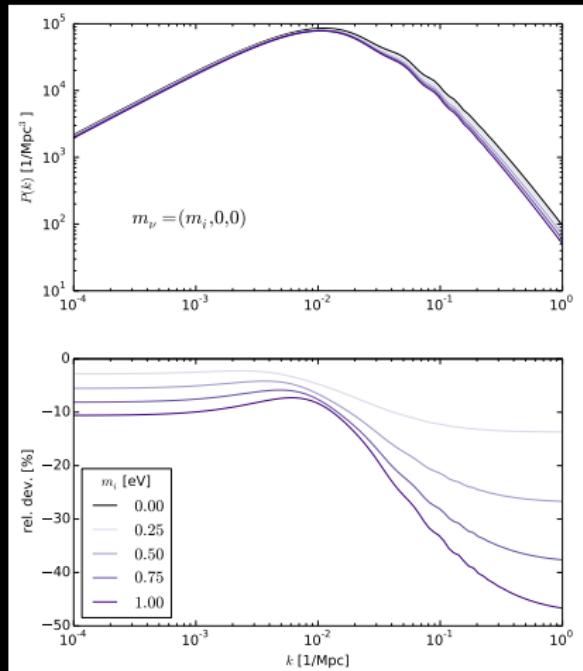
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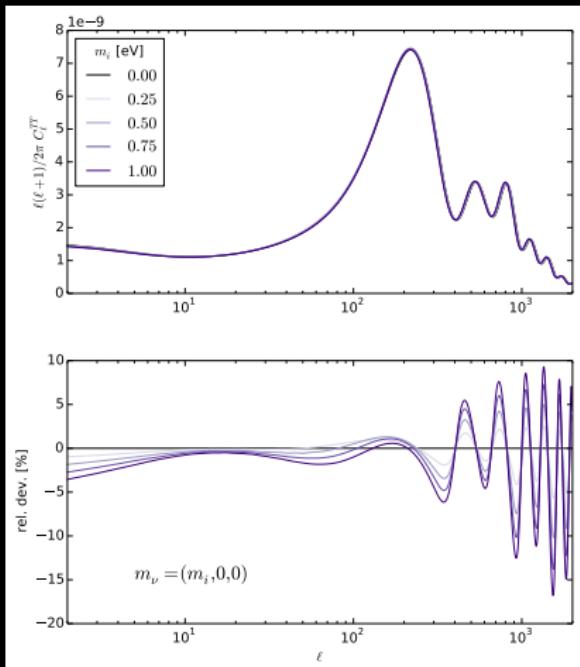
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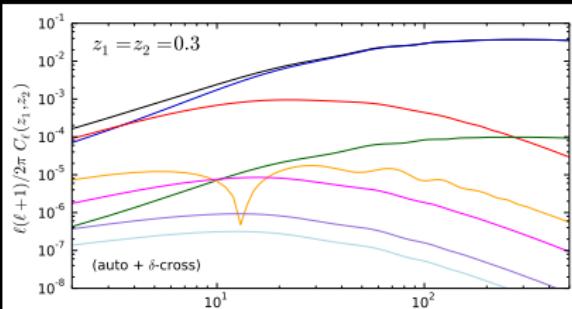
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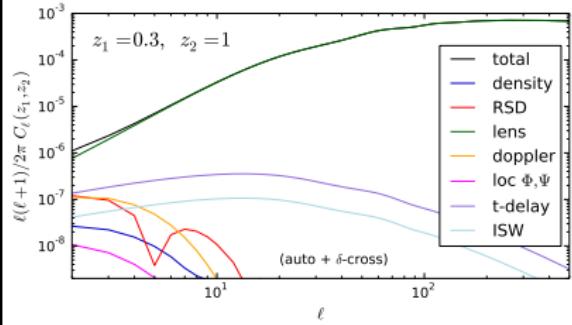
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Boltzmann Codes

- 1995: COSMICS (Bertschinger)
- 1996: CMBFAST (Seljak & Zaldarriaga)
- 1999: CAMB (Lewis): Maintained and improved
→ CAMB Sources, MGCBM, EFTCAMB...
- 2003: CMBEASY (Doran)
- 2011 CLASS (Lesgourgues & Tram)
→ CLASSGal, hi_class

CLASS

The purpose of CLASS is to simulate the evolution of linear perturbations in the universe and to compute CMB and LSS observables.

<http://class-code.net/>

The Cosmic Linear Anisotropy Solving System (CLASS)

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- **Friendly and flexible**: should be easy to compile, to pass input parameters, to understand the code, and to modify it

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- **Accurate**: need more and more precision. Analysing Planck and WMAP data require very different accuracy settings. Before, CAMB precision could only be calibrated w.r.t itself. CLASS played important role in pushing precision to Planck level. Similar efforts in the future (LSS, next CMB satellite, 21cm, etc.)

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CLASS vs CAMB:

- More modern (C vs Fortran, Python interfaced,...)
- Easy to modify —→ less cursing!

some Coding Principles

The CLASS Commands

- Notation from Ma & Bertschinger
(astro-ph/9506072)

some Coding Principles

- input.c
- background.c
- thermodynamics.c
- perturbations.c
- primordial.c
- nonlinear.c
- transfer.c
- spectra.c
- lensing.c
- output.c

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- All precision variables grouped in one single place (`input.c`)

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- No duplicate equations

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$\rho_b \rightarrow \text{vec}[\text{index_bg_rho_b}]$

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- No hard-coding: dynamical indexing
 $\rho_b \rightarrow \text{vec}[\text{index_bg_rho_b}]$
- Component-specific blocks
`if (has_xxx) { (xxx physics) }`
- Easy to add new components:
 - Search for inspirational ingredient
 - Copy, paste & adapt to:
 - interpret parameters (`input.c`)
 - implement equations
(`background.c`, `perturbations.c`)

CLASS flexibility (see explanatory.ini)

Coding principles greatly simplify implementation of new models:

Dark Matter

- Ultra relativistic (ur)
- Warm (ncdm)
- Cold (cdm)
- Decaying into dark radiation (dcdm)

Initial conditions

- Analytic $P(k)$
- Isocurvature perturbations
- Inflationary potential $V(\phi)$
- Correlated, Axion, Curvaton
- External ...

Neutrinos (ncdm)

- Masses (Ω_ν, m_ν)
- Chemical potential
- Phase space distribution
- Flavor mixing ...

Dark Energy and Gravity

- Perfect fluid (fld)
- Quintessence (scf)
- MG-class (by P. Bull)
- Horndeski Gravity (smg)

Plus curvature, relativistic effects, Newt/Synchr. Gauges...

Horndeski in the Cosmic Linear Anisotropy Solving System

Goals: $\left\{ \begin{array}{l} \star \text{DE/MG predictions in as much detail as } \Lambda\text{CDM} \\ \star \text{public tool, valid for a large class of theories} \end{array} \right.$

$$\begin{aligned} \Omega &= \sqrt{-g} \quad L_H \quad a_H \quad \dot{\Psi} \quad \rho \quad p \quad \phi \quad \Omega &= \sqrt{-g} \quad L_H \quad a_H \quad \Psi \quad \rho \quad \dot{x} \quad R_{\mu\nu} \quad \partial_\mu \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ G_0 &= \Phi \quad \alpha_H \quad \dot{\phi}_H \quad P \quad \alpha_R \quad \Gamma_{\mu\nu}^R \quad G_5 &= G_0 \quad \alpha_M \quad \dot{\delta} \quad P \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ \delta &= R_{\mu\nu} \quad \partial_\mu^2 \quad \dot{\phi}_H \quad h_0 \quad \dot{\phi}_H^2 \quad R_{\mu\nu} \quad \partial_\mu^2 \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ H &= \dot{\phi} \quad \Psi \quad h_0 \quad \alpha_R \quad R_{\mu\nu} \quad \Gamma_{\mu\nu}^R \quad \dot{\phi}_H^2 &= H \quad \dot{\phi} \quad h_0 \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ \alpha_R &= \alpha_H \quad \dot{\phi}_H^2 \quad \sqrt{-g} \quad \square_T \quad \alpha_R &= \alpha_H \quad \alpha_R \quad \dot{\phi}_H^2 \quad P \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ \Phi &= \Gamma_{\mu\nu}^R \quad \Pi \quad \eta \quad \mathcal{E} \quad \Pi &= \Phi \quad \Gamma_{\mu\nu}^R \quad \Pi \quad \dot{\phi} \quad \mathcal{E} \quad \Gamma_{\mu\nu}^R \quad \omega \quad \dot{\phi}^2 \quad X \quad G_5 \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ X &= G_5 \quad \mathcal{L}_H \quad \dot{\phi} \quad \Psi \quad G_5 \quad \Psi &= X \quad G_5 \quad \mathcal{L}_H \quad \dot{\phi} \quad X \quad G_5 \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ \omega &= G_5 \quad \dot{\phi}_H \quad \dot{\phi}_H^2 \quad \Psi \quad G_5 \quad \Psi &= X \quad G_5 \quad \mathcal{L}_H \quad \dot{\phi} \quad X \quad G_5 \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ \psi_5 &= G_5 \quad \square_R \quad H \quad R \quad \alpha_H &= \psi_5 \quad G_5 \quad \square_R \quad G_5 \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ G_5 &= \square_R \quad G_5 \quad G_5 \quad \alpha_H &= \Psi \quad G_5 \quad \square_R \quad G_5 \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ \alpha_R &= G_5 \quad \dot{\phi}_H^2 \quad \Psi \quad V_5 &= G_5 \quad \alpha_H \quad \square_R \quad \dot{\phi}_H^2 \quad R \quad R_{\mu\nu} \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ G_5 &= G_5 \quad \dot{\phi}_H^2 \quad \Psi \quad V_5 &= G_5 \quad \alpha_H \quad \square_R \quad \dot{\phi}_H^2 \quad R \quad R_{\mu\nu} \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ \alpha_B &= \dot{\phi}_H^2 \quad M_*^2 &= \alpha_B \quad \alpha_K \quad \square_R \quad \dot{\phi}_H^2 \quad R \quad R_{\mu\nu} \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ \delta &= \dot{\phi} \quad \Psi \quad \alpha_R \quad X &= \alpha_B \quad \alpha_K \quad \square_R \quad \dot{\phi}_H^2 \quad R \quad R_{\mu\nu} \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \\ \alpha_B &= h_0 \quad \dot{\phi}_H^2 &= \delta \quad \dot{\phi} \quad \alpha_R \quad X &= \alpha_B \quad \alpha_K \quad \square_R \quad \dot{\phi}_H^2 \quad R \quad R_{\mu\nu} \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \quad R \quad \alpha_H \quad \dot{\phi}_H \quad \dot{\phi}_{\mu\nu} \quad h_0 \end{aligned}$$

hi_class

$$\begin{aligned} h_0 &= \frac{\dot{\phi}}{\dot{\phi}_H} \quad \Psi &= \frac{R_{\mu\nu}}{h_0} \quad \frac{k^2}{X} \quad \frac{R_{\mu\nu}}{h_0} \\ H &= \frac{\dot{\phi}_H}{\dot{\phi}} \quad \alpha_H &= \frac{\alpha_H}{\dot{\phi}_H} \quad \alpha_R &= \frac{\alpha_R}{\dot{\phi}_H} \quad \alpha_B &= \frac{\alpha_B}{\dot{\phi}_H} \quad \alpha_K &= \frac{\alpha_K}{\dot{\phi}_H} \quad \alpha_M &= \frac{\alpha_M}{\dot{\phi}_H} \\ \mathcal{L}_H &= \frac{\Phi}{\dot{\phi}_H} \quad \alpha_H &= \frac{\alpha_H}{\dot{\phi}_H} \quad \alpha_R &= \frac{\alpha_R}{\dot{\phi}_H} \quad \alpha_B &= \frac{\alpha_B}{\dot{\phi}_H} \quad \alpha_K &= \frac{\alpha_K}{\dot{\phi}_H} \quad \alpha_M &= \frac{\alpha_M}{\dot{\phi}_H} \\ R &= \frac{\alpha_H}{\dot{\phi}_H} \quad V_5 &= \frac{\mathcal{L}_H}{\dot{\phi}_H} \quad \sqrt{-g} &= \frac{\delta}{\dot{\phi}_H} \quad X &= \frac{\sqrt{-g}}{\dot{\phi}_H} \quad \alpha_H &= \frac{\alpha_H}{\dot{\phi}_H} \quad \alpha_R &= \frac{\alpha_R}{\dot{\phi}_H} \quad \alpha_B &= \frac{\alpha_B}{\dot{\phi}_H} \quad \alpha_K &= \frac{\alpha_K}{\dot{\phi}_H} \quad \alpha_M &= \frac{\alpha_M}{\dot{\phi}_H} \\ \sqrt{-g} &= \frac{\alpha_H}{\dot{\phi}_H} \quad \alpha_R &= \frac{\alpha_R}{\dot{\phi}_H} \quad \alpha_B &= \frac{\alpha_B}{\dot{\phi}_H} \quad \alpha_K &= \frac{\alpha_K}{\dot{\phi}_H} \quad \alpha_M &= \frac{\alpha_M}{\dot{\phi}_H} \\ \dot{\phi} &= \frac{\dot{\phi}_H}{\dot{\phi}} \quad \dot{\phi}_H &= \frac{\dot{\phi}_H}{\dot{\phi}} \quad \dot{\phi}_R &= \frac{\dot{\phi}_R}{\dot{\phi}_H} \quad \dot{\phi}_B &= \frac{\dot{\phi}_B}{\dot{\phi}_H} \quad \dot{\phi}_K &= \frac{\dot{\phi}_K}{\dot{\phi}_H} \quad \dot{\phi}_M &= \frac{\dot{\phi}_M}{\dot{\phi}_H} \\ \dot{\phi}_H &= \frac{\dot{\phi}_H}{\dot{\phi}} \quad \dot{\phi}_{\mu\nu} &= \frac{\dot{\phi}_{\mu\nu}}{\dot{\phi}_H} \quad h_0 &= \frac{h_0}{\dot{\phi}_H} \quad R &= \frac{R}{\dot{\phi}_H} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{\dot{\phi}_H} \quad \alpha_R &= \frac{\alpha_R}{\dot{\phi}_H} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{\dot{\phi}_H} \quad \dot{\phi} &= \frac{\dot{\phi}}{\dot{\phi}_H} \\ \dot{\phi}_R &= \frac{\dot{\phi}_R}{\dot{\phi}} \quad \dot{\phi}_{\mu\nu} &= \frac{\dot{\phi}_{\mu\nu}}{\dot{\phi}_H} \quad h_0 &= \frac{h_0}{\dot{\phi}_H} \quad R &= \frac{R}{\dot{\phi}_H} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{\dot{\phi}_H} \quad \alpha_R &= \frac{\alpha_R}{\dot{\phi}_H} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{\dot{\phi}_H} \quad \dot{\phi} &= \frac{\dot{\phi}}{\dot{\phi}_H} \\ \dot{\phi}_B &= \frac{\dot{\phi}_B}{\dot{\phi}} \quad \dot{\phi}_K &= \frac{\dot{\phi}_K}{\dot{\phi}} \quad \dot{\phi}_M &= \frac{\dot{\phi}_M}{\dot{\phi}} \\ \dot{\phi}_M &= \frac{\dot{\phi}_M}{\dot{\phi}} \quad \dot{\phi}_{\mu\nu} &= \frac{\dot{\phi}_{\mu\nu}}{\dot{\phi}_H} \quad h_0 &= \frac{h_0}{\dot{\phi}_H} \quad R &= \frac{R}{\dot{\phi}_H} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{\dot{\phi}_H} \quad \alpha_R &= \frac{\alpha_R}{\dot{\phi}_H} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{\dot{\phi}_H} \quad \dot{\phi} &= \frac{\dot{\phi}}{\dot{\phi}_H} \\ \dot{\phi}_K &= \frac{\dot{\phi}_K}{\dot{\phi}} \quad \dot{\phi}_M &= \frac{\dot{\phi}_M}{\dot{\phi}} \quad \dot{\phi}_{\mu\nu} &= \frac{\dot{\phi}_{\mu\nu}}{\dot{\phi}_H} \quad h_0 &= \frac{h_0}{\dot{\phi}_H} \quad R &= \frac{R}{\dot{\phi}_H} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{\dot{\phi}_H} \quad \alpha_R &= \frac{\alpha_R}{\dot{\phi}_H} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{\dot{\phi}_H} \quad \dot{\phi} &= \frac{\dot{\phi}}{\dot{\phi}_H} \\ k^2 &= \frac{k^2}{X} \quad H &= \frac{H}{X} \quad \alpha_R &= \frac{\alpha_R}{X} \quad \alpha_B &= \frac{\alpha_B}{X} \quad \alpha_K &= \frac{\alpha_K}{X} \quad \alpha_M &= \frac{\alpha_M}{X} \\ \dot{\phi}_H &= \frac{\dot{\phi}_H}{X} \quad \dot{\phi}_{\mu\nu} &= \frac{\dot{\phi}_{\mu\nu}}{X} \quad h_0 &= \frac{h_0}{X} \quad R &= \frac{R}{X} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{X} \quad \alpha_R &= \frac{\alpha_R}{X} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{X} \quad \dot{\phi} &= \frac{\dot{\phi}}{X} \\ \dot{\phi}_B &= \frac{\dot{\phi}_B}{X} \quad \dot{\phi}_K &= \frac{\dot{\phi}_K}{X} \quad \dot{\phi}_M &= \frac{\dot{\phi}_M}{X} \quad \dot{\phi}_{\mu\nu} &= \frac{\dot{\phi}_{\mu\nu}}{X} \quad h_0 &= \frac{h_0}{X} \quad R &= \frac{R}{X} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{X} \quad \alpha_R &= \frac{\alpha_R}{X} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{X} \quad \dot{\phi} &= \frac{\dot{\phi}}{X} \\ \dot{\phi}_K &= \frac{\dot{\phi}_K}{X} \quad \dot{\phi}_M &= \frac{\dot{\phi}_M}{X} \quad \dot{\phi}_{\mu\nu} &= \frac{\dot{\phi}_{\mu\nu}}{X} \quad h_0 &= \frac{h_0}{X} \quad R &= \frac{R}{X} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{X} \quad \alpha_R &= \frac{\alpha_R}{X} \quad R_{\mu\nu} &= \frac{R_{\mu\nu}}{X} \quad \dot{\phi} &= \frac{\dot{\phi}}{X} \end{aligned}$$

www.hiclass-code.net (MZ, Bellini, Sawicki, Lesgourgues, Ferreira '16)

hi_class in practice

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

a) Full theory + IC*

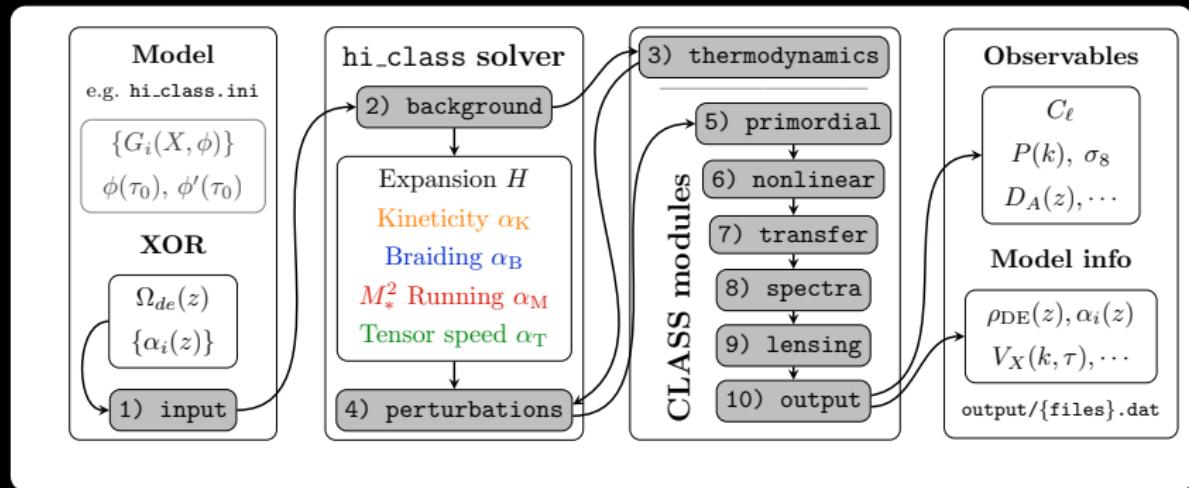
b) or Parameterize $w(z), \alpha_i(z)$

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

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

hi_class use

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

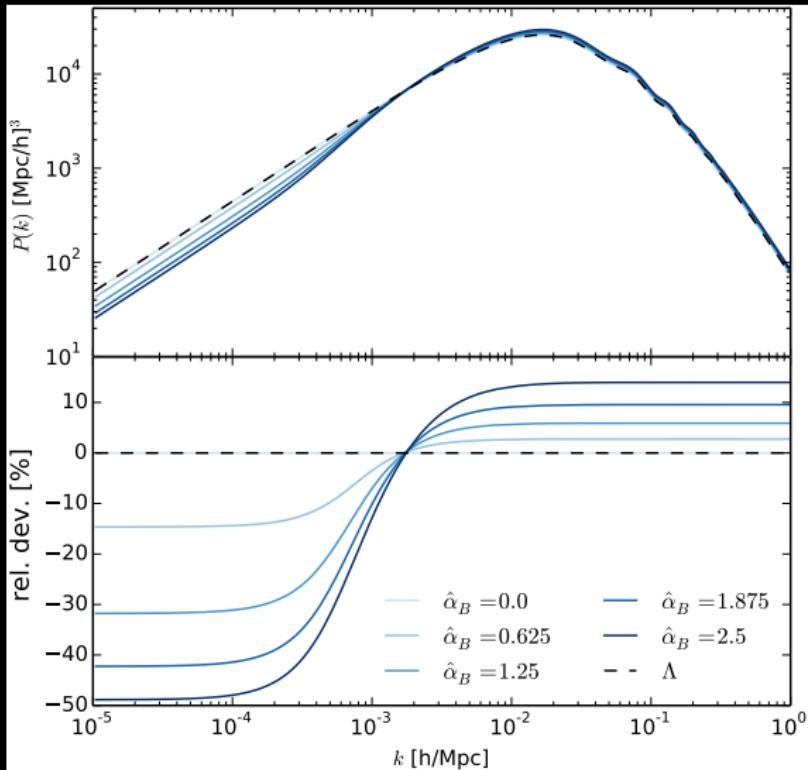
- Choose model + parameters (expansion and gravity/ α 's)

```
"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)

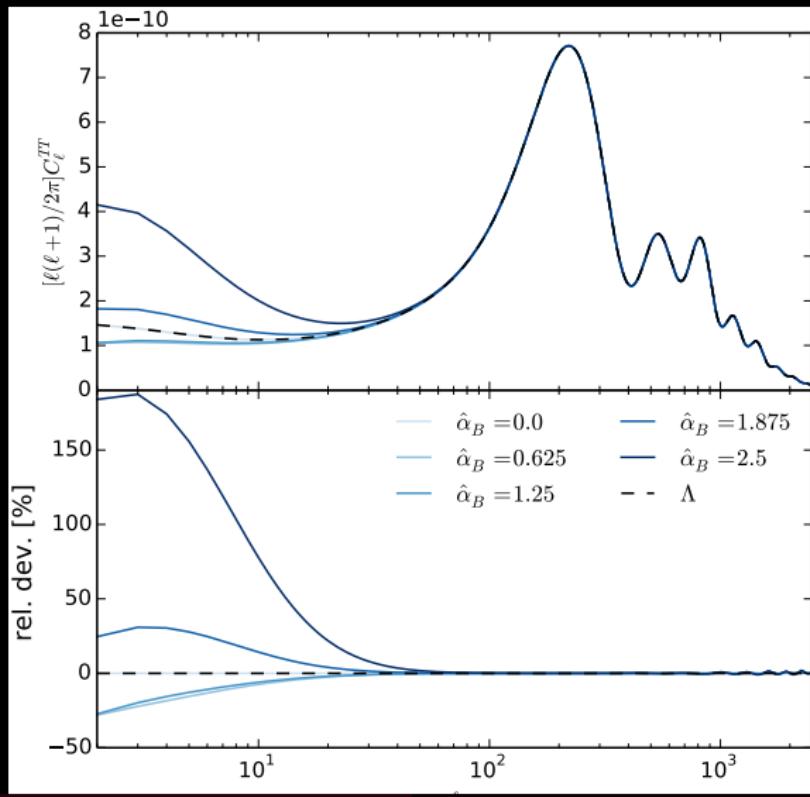
hi_class output

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



hi_class output

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



hi_class: status and prospects

Public (www.hiclass-code.net)

- Parameterized H, α
 $\alpha \propto \Omega$, Planck param...
➡ your model here!
- Interface with MontePython
(parameter estimation)
- Tested: $\delta C_\ell \lesssim 0.5\%$, $\delta P_k \lesssim 0.1\%$

Private (coming soon)

- Theories with $G_2 - G_5$:
Brans-Dicke, Galileons...
➡ your model here!
- Early Modified Gravity



hi_class

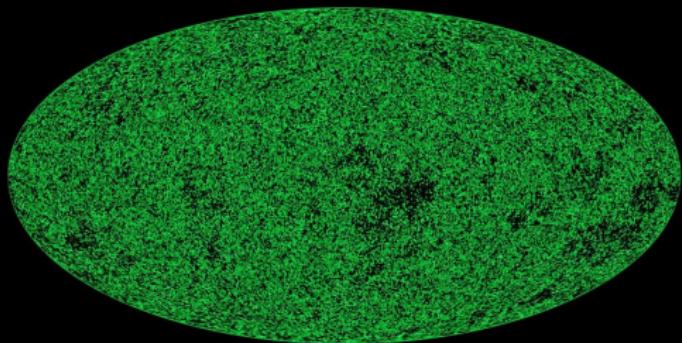
Development/test

- Self consistent from Lagrangian
- Quasi-static approximation
- MG initial conditions

Prospects

- beyond Horndeski:
 G^3 , EST, massive gravity
- Non-linear (PT, N-body)
- Curvature, Newt. gauge...

Galileon as Dark Energy



A fully worked example with `hi_class`

PLANCK

hi_class in practice

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

a) Full theory + IC

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

Full theory has more info

- Background \rightarrow often very constraining \rightarrow H_0 tension
- Non-linear effects
- Other regimes: GWs, strong gravity, Solar System, QM, Lab...

Horndeski's Theory, with

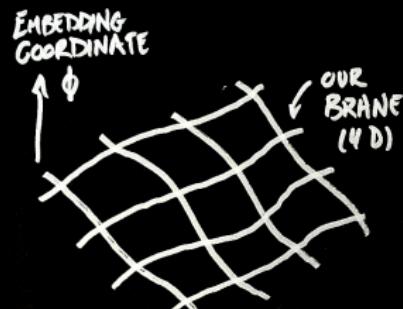
$\boxed{\Lambda = 0}$ + simple choice of $G_i(X, \phi)$: $(X \equiv -(\partial\phi)^2/2)$

$$\frac{M_p^2}{2}R - X - c_3 \frac{X}{M^3} \nabla^2 \phi \rightarrow \text{Gal3: 0 extra params}$$

$$+ c_4 \frac{X^2}{M^6} \left(\frac{M_p^2}{2}R + \frac{2}{X} [\nabla \nabla \phi]^2 \right) \rightarrow \text{Gal4: 1 extra params}$$

$$+ c_5 \frac{X^2}{M^9} \left(G_{\mu\nu} \phi^{;\mu\nu} - \frac{1}{3X} [\nabla \nabla \phi]^3 \right) \rightarrow \text{Gal5: 2 extra params}$$

- Related to
 - ★ Massive Gravity: $\phi \rightarrow$ helicity 0
 - ★ DGP/extra dim: $\phi \leftrightarrow x^5$ coord.
- Vainshtein: $\Rightarrow \sim \text{GR}$ on small scales
- Self-accelerating solutions ($\Lambda = 0$)



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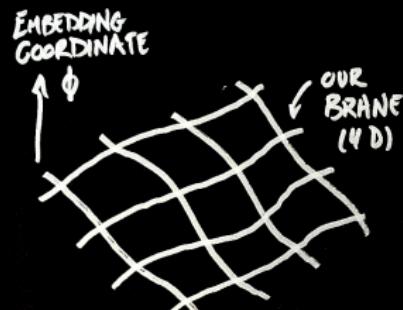
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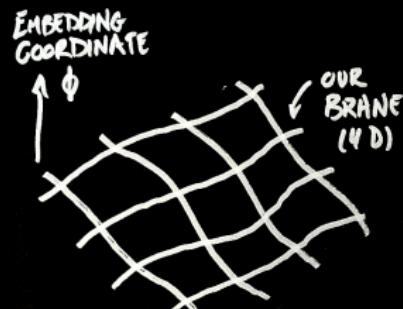
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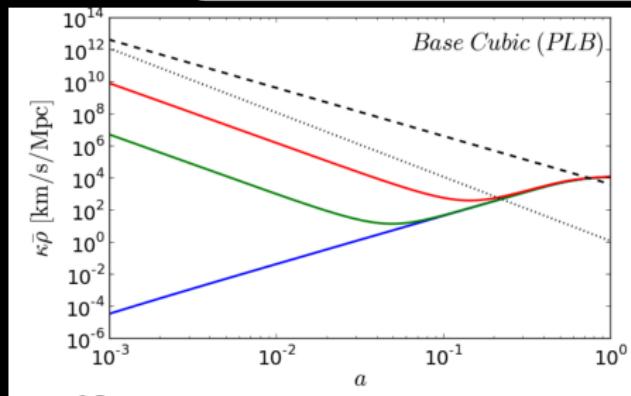
Galileon gravity: symmetries & tracker

(Barreira+ '14)

Shift Symmetry $\phi \rightarrow \phi + C$ (Galilean symmetry $\delta\phi = b_\mu x^\mu + C$)

\Rightarrow conserved $\mathcal{J}^\mu \quad \Rightarrow \mathcal{J}^0 \propto a^{-3} \rightarrow 0$

$$\boxed{\dot{\phi}(t)H(t) = \xi \cdot H_0^2 M_P = \text{constant}}$$



- Evolution to tracker: no fine tuning
- Tracker by $z_T \sim \infty$, $z_T \approx 6$,
 $z_T \approx 2.5$ (Ω_{de} small but relevant)

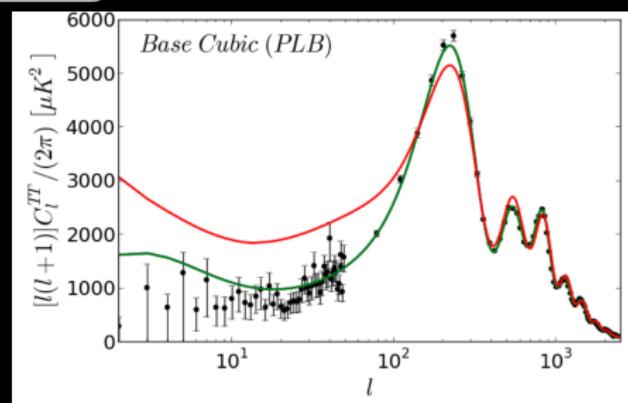
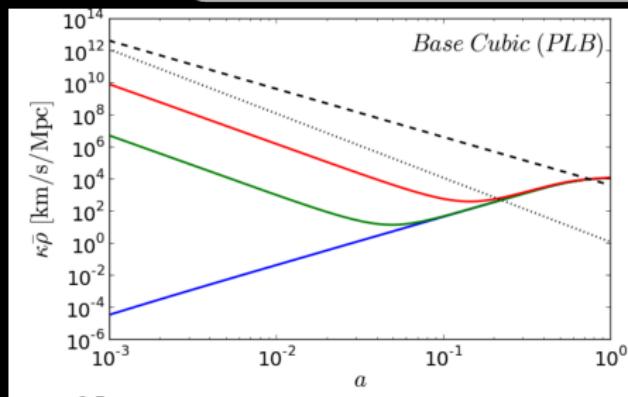
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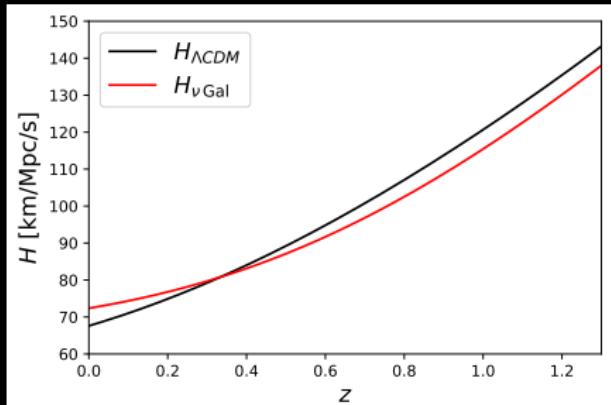
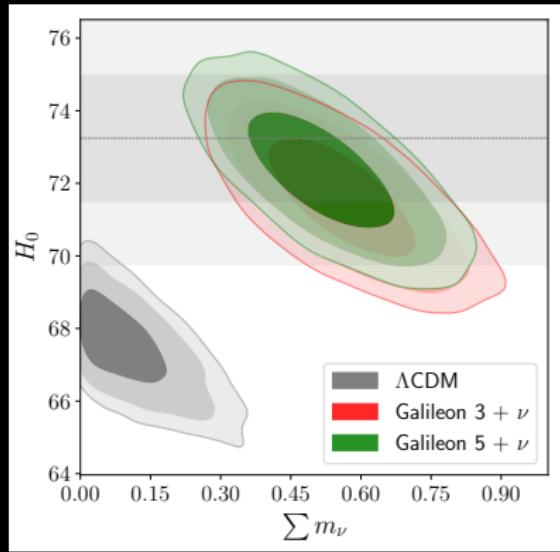
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 $z_T \approx 2.5$ (Ω_{de} small but relevant)
- Inviable if out of tracker late
(i.e. while Ω_{de} significant)
- Indistinguishable if reached earlier

$\Lambda = 0$ Galileon cosmologically viable! (Barreira+ '14, Renk+ '17)

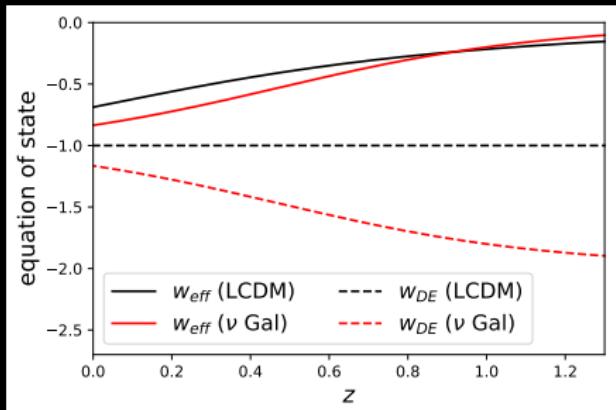
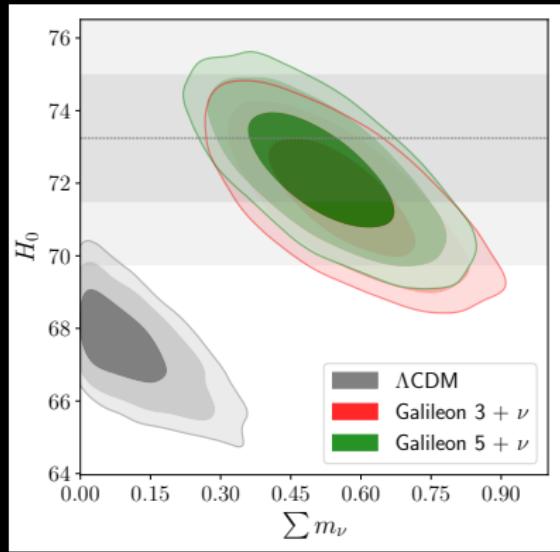
Planck(w. lensing)+BAO:



- H_0 compatible (Λ CDM $3.4\sigma!$)
 - $\Sigma m_\nu \approx 0.6$ eV
 - tension with current BAO data
- Negative equation of state
 - Heavy neutrinos
 - Modified gravity (growth \uparrow)
(different Ω_c but $\Omega_c h^2$ fixed by CMB)

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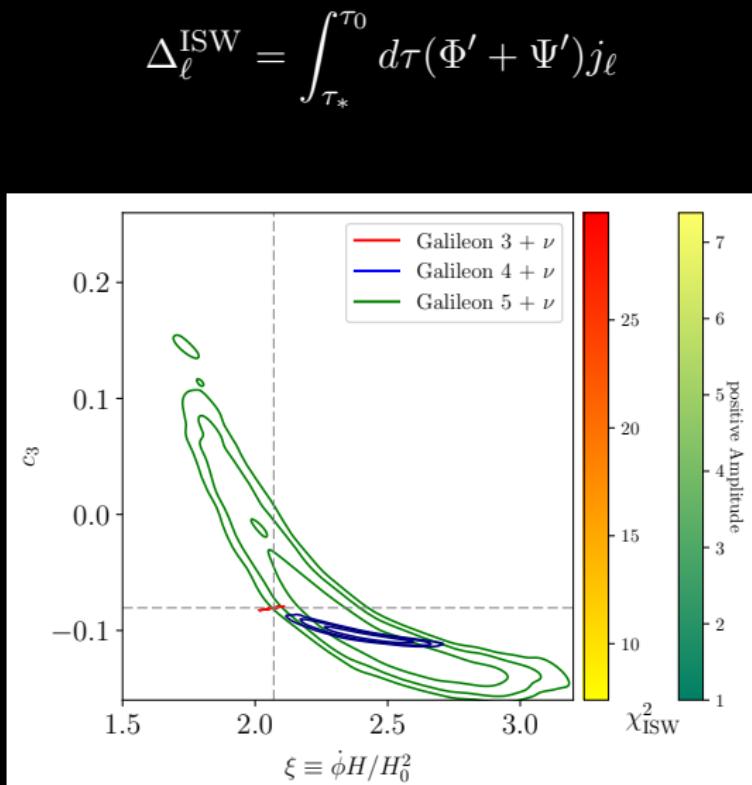
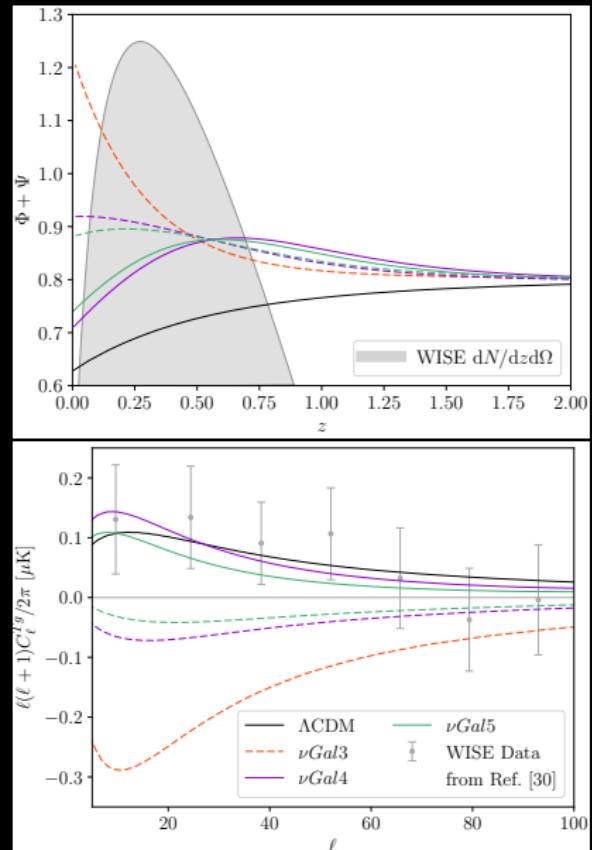
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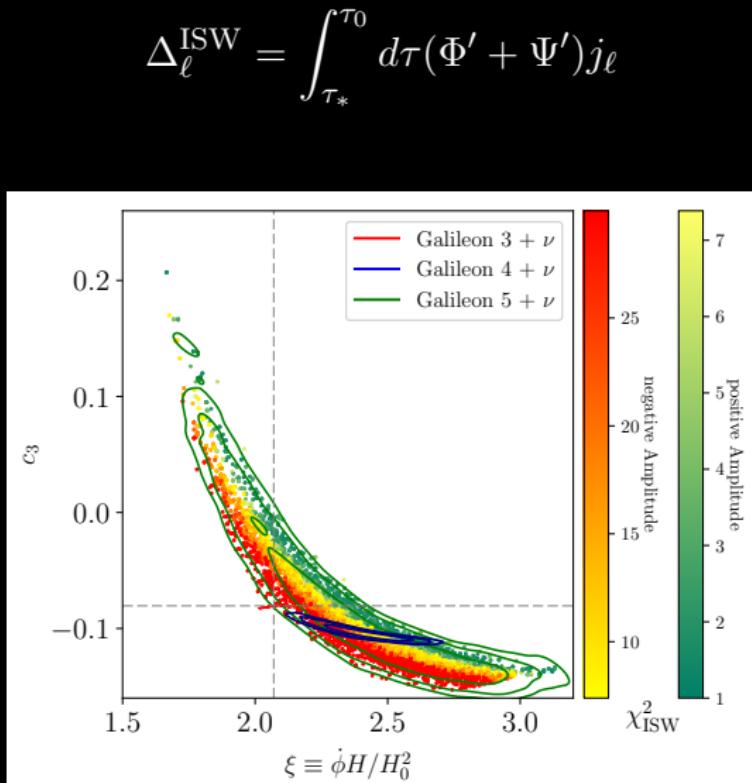
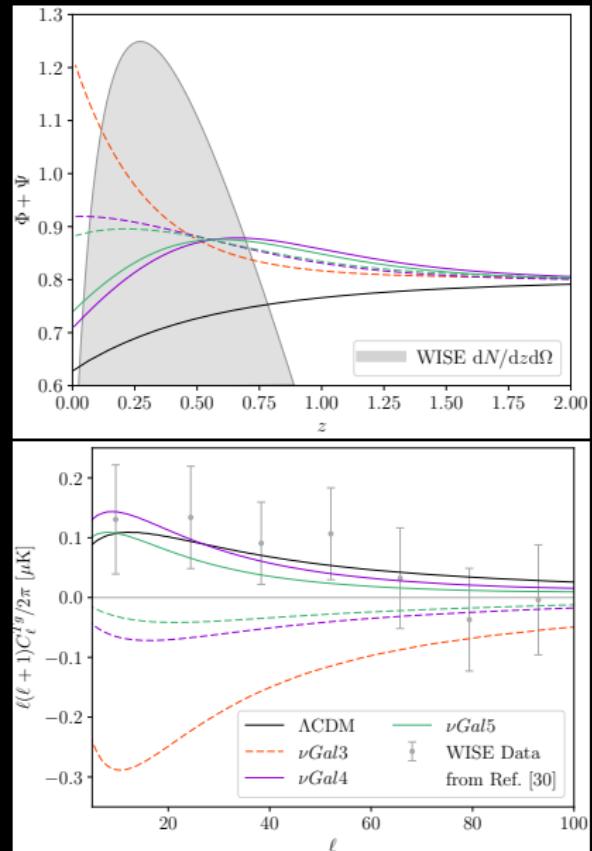
Galileon and Integrated Sachs-Wolfe effect

(Renk+ '17)



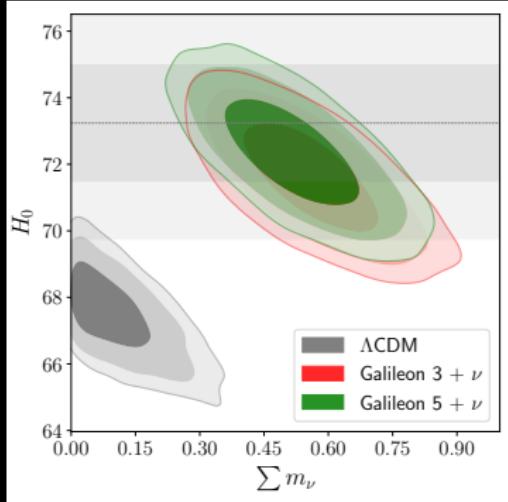
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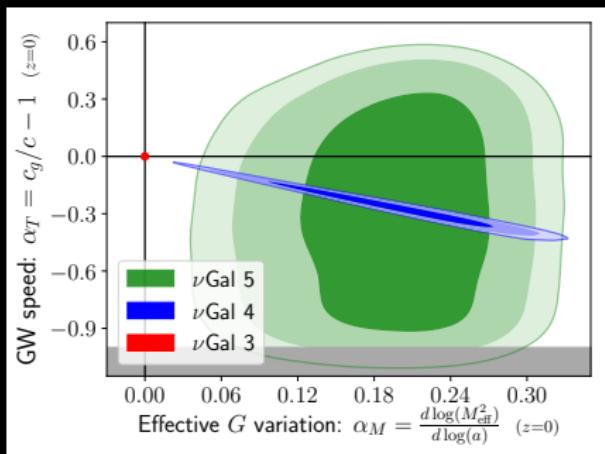


Self-accelerating Galileon \longrightarrow modifies GW propagation

Planck(w. lensing)+BAO:



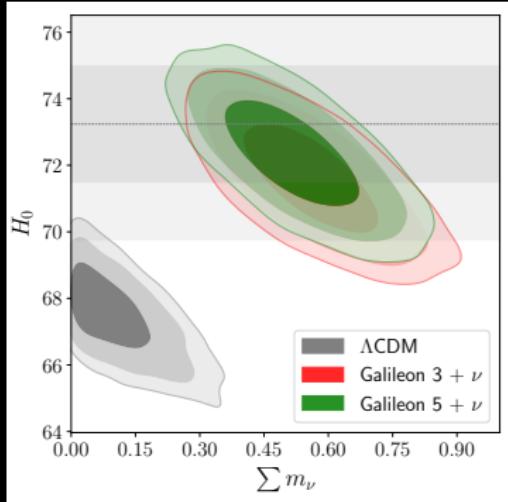
$$\ddot{h}_{ij} + \underbrace{(1 + \alpha_T)}_{c_g^2, \text{ GW}} \vec{\nabla}^2 h_{ij} + 3H(1 + \alpha_M)\dot{h}_{ij} = 0$$



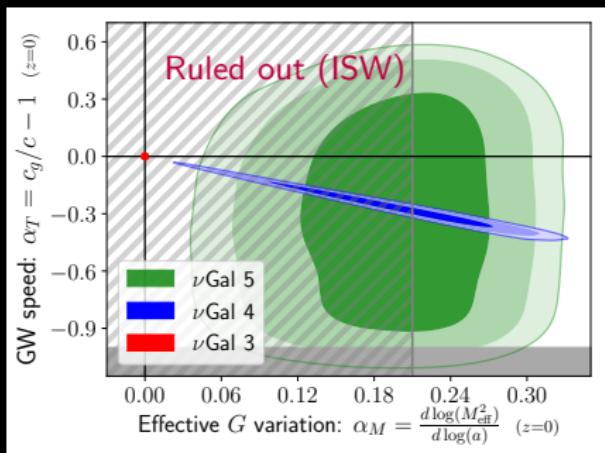
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- H_0 compatible (Λ CDM 3.4σ !)
- if $\sum m_\nu \approx 0.6$ eV
- slight tension with other data

- ISW effect (from Planck×WISE):
 - kills ν Gal3 (8.2σ)
 - non-standard GW propagation

Backup Slides

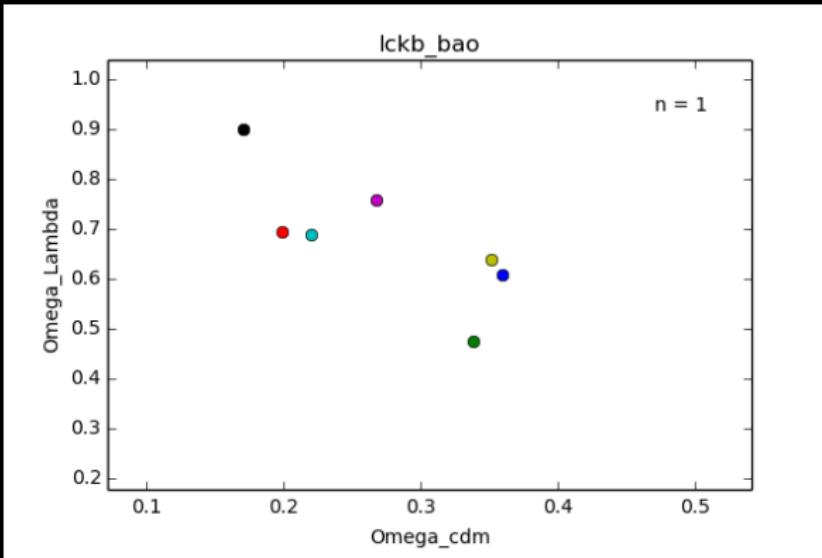
$$\begin{array}{cccccccccc}
\Omega & \sqrt{-g} & \mathcal{L}_H & \alpha_B & \Psi & P & \Phi & \Omega & \sqrt{-g} & \mathcal{L}_H & \alpha_B & \Psi & \rho & \delta & R_{\mu\nu} & \partial_t & \phi_{\mu\nu} & h_+ \\
G_2 & \Phi & \alpha_M & \delta & P & \alpha_K & G_3 & G_2 & \Phi & \alpha_M & \delta & P & \alpha_K & \mathcal{H} & \delta & \partial_\mu & \Psi & h_+ & \alpha_T \\
\delta & R_{\mu\nu} & c_T^\mu & \phi_{\mu\nu} & h_+ & c_T^\mu & X & h_+ & \delta & R_{\mu\nu} & c_T^\mu & \phi_{\mu\nu} & h_+ & \mathcal{H} & \phi_{\mu\nu} & \alpha_M & R & \alpha_H & c_T^\mu \\
\mathcal{H} & \delta & \Psi & h_+ & \alpha_T & R_{\mu\nu} & \square \phi & \mathcal{H} & \delta & \bar{\phi} & \Psi & h_+ & \alpha_T & \Omega & \Phi & X & G_1 & L_H & G_3 \\
\phi_{\mu\nu} & \alpha_M & \mathcal{H} & \delta & \bar{\phi} & \square \phi & \square \phi & \mathcal{H} & \delta & \bar{\phi} & \Psi & h_+ & \alpha_T & \Omega & \Phi & X & G_1 & L_H & G_3 \\
\Phi & \Gamma_{\mu\nu}^\rho & \Pi & \alpha_K & \mathcal{E} & \Pi & \alpha_M & \Phi & \Gamma_{\mu\nu}^\rho & \Pi & \alpha_K & \mathcal{E} & \Pi & \rho & w & \Gamma_{\mu\nu}^\rho & k^2 & X & \alpha_X & \phi_{\mu\nu} & \mathcal{E} \\
X & G_1 & \mathcal{L}_H & \alpha_K & G_1 & \Psi & X & G_1 & \mathcal{L}_H & \delta & \mathcal{E} & X & V_N & G_2 & c_T^\mu & L_H & \delta & G_3 & \phi & R \\
w & k^2 & X & \delta & \phi_{\mu\nu} & G_1 & \sqrt{-g} & w & k^2 & X & \mathcal{H} & G_2 & \alpha_K & \alpha_K & \square \phi & G_2 & G_1 & G_3 & \phi & X & M_2^2 \\
V_N & G_2 & \square \phi & \mathcal{H} & R & \alpha_M & \Pi & V_N & G_2 & \square \phi & G_2 & \phi_{\mu\nu} & c_T^\mu & R & R_{\mu\nu} & \alpha_B & G_3 & G_1 & G_3 & \phi & V_N \\
G_2 & c_T^\mu & \mathcal{L}_H & G_0 & G_0 & \Psi & G_2 & G_1 & \mathcal{L}_H & \Phi & c_T^\mu & G_3 & \delta & \Phi & R_{\mu\nu} & \alpha_B & G_3 & G_1 & G_3 & \Phi & X \\
\alpha_K & \square \phi & \phi_{\mu\nu} & \Phi & V_N & & G_1 & \alpha_K & \square \phi & G_1 & \alpha_B & G_3 & \alpha_B & R_{\mu\nu} & \alpha_B & G_3 & G_1 & G_3 & \phi & M_2^2 \\
G_0 & G_2 & \phi & \theta & & & G_1 & \alpha_K & \square \phi & G_1 & \alpha_B & G_3 & \alpha_B & R_{\mu\nu} & \alpha_B & G_3 & G_1 & G_3 & \phi & M_2^2 \\
\delta & \Phi & c_T^\mu & \theta & X & \alpha_M & G_1 & \alpha_B & \delta & \theta & & & & & & & & & & & & h_+ \\
\alpha_B & G_3 & \alpha_B & M_2^2 & \partial_t \\
& h_+ & & c_T^\mu & M_2^2 \\
\end{array}$$

hi_class

$$\begin{array}{cccccccccc}
h_+ & \Psi & & & & k^2 & & & & R_{\mu\nu} \\
\mathcal{H} & \phi_{\mu\nu} & & & & X & & & & h_+ \\
G_0 & \alpha_B & \Pi & \square \phi & & & & & & \sqrt{-g} \\
\mathcal{L}_H & \alpha_B & \Phi & G_1 & & & & & & M_2^2 \\
& & & & & & & & & \\
\mathcal{H} & \alpha_M & V_N & \mathcal{L}_H & \sqrt{-g} & & & & & \\
& \sqrt{-g} & \alpha_B & \Psi & \rho & & & & & \\
& \Phi & \delta & P & \alpha_K & G_0 & \Phi & R & c_T^\mu & G_1 & \mathcal{L}_H & \alpha_T & G_4 & \alpha_M & \alpha_B \\
& R_{\mu\nu} & c_T^\mu & \phi_{\mu\nu} & h_+ & \mathcal{H} & R_{\mu\nu} & \phi_{\mu\nu} & h_+ & \Omega & R_{\mu\nu} & \alpha_K & M_2^2 & \mathcal{L}_H & \alpha_T & G_4 & \alpha_M & \alpha_B \\
& \bar{\phi} & \Psi & h_+ & \alpha_T & \Omega & c_T^\mu & \mathcal{L}_H & \Psi & k^2 & \alpha_T & \square \phi & P & \delta & \Pi & \Psi & G_5 & h_+ & \Psi \\
& \alpha_M & \mathcal{H} & \alpha_K & c_T^\mu & \mathcal{P} & \theta & \Gamma_{\mu\nu}^\rho & \alpha_K & \Pi & & & & & & & & & & & \\
& \Gamma_{\mu\nu}^\rho & \Pi & \delta & \mathcal{E} & \Gamma_{\mu\nu}^\rho & \Phi & X & \mathcal{P} & \mathcal{L}_H & \Phi & X & G_3 & \sqrt{-g} & \Phi & G_3 & R & X & \theta \\
& G_4 & \mathcal{L}_H & \delta & G_3 & X & h_+ & \delta & \square \phi & \Pi & R & \mathcal{E} & \alpha_B & \mathcal{L}_H & \phi_{\mu\nu} & \delta & \Psi & \sqrt{-g} & \mathcal{L}_I \\
& k^2 & \mathcal{H} & \phi_{\mu\nu} & \alpha_K & \alpha_T & G_1 & \mathcal{L}_H & X & \Omega & h_+ & M_2^2 & h_+ & \Omega & G_2 & \mathcal{L}_H & c_T^\mu & G_1 &
\end{array}$$

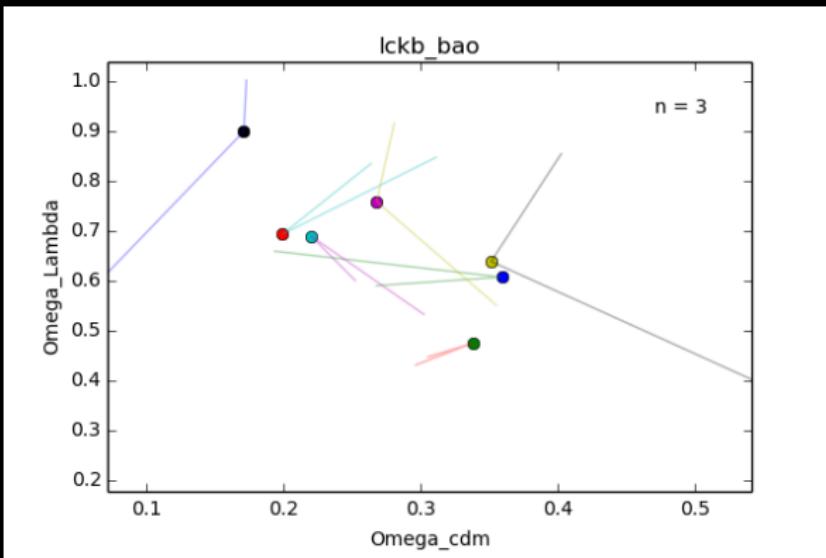
www.hiclass-code.net

Scan space of parameters



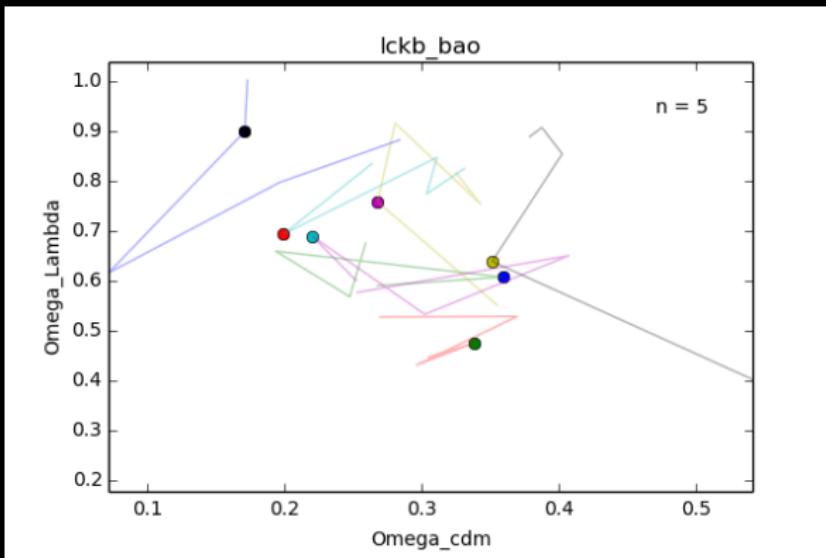
(using MontePython)

Scan space of parameters



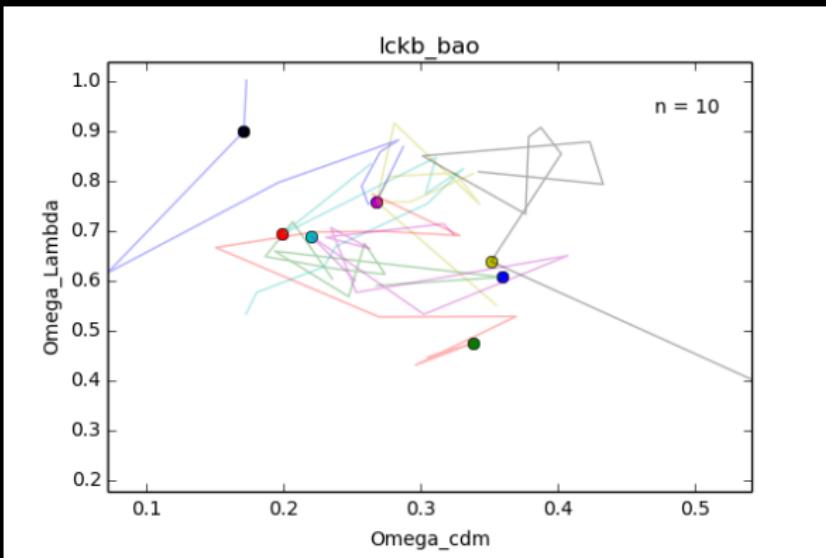
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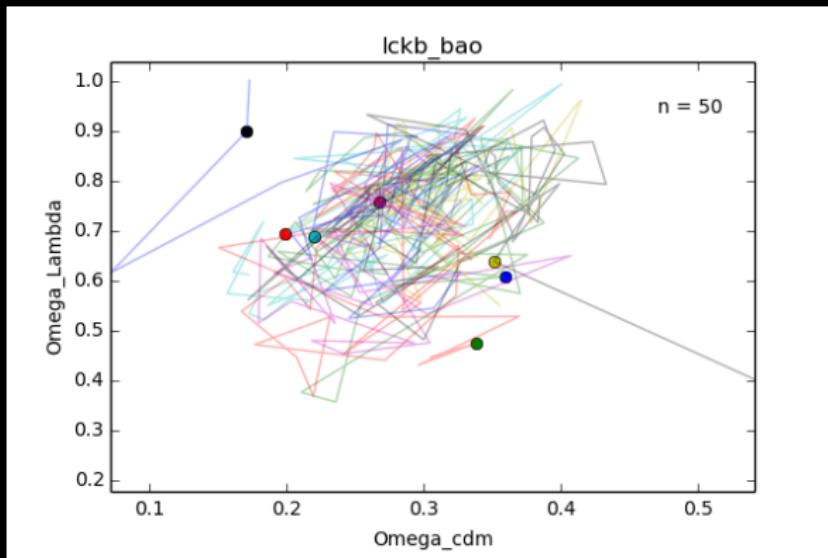
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Scan space of parameters



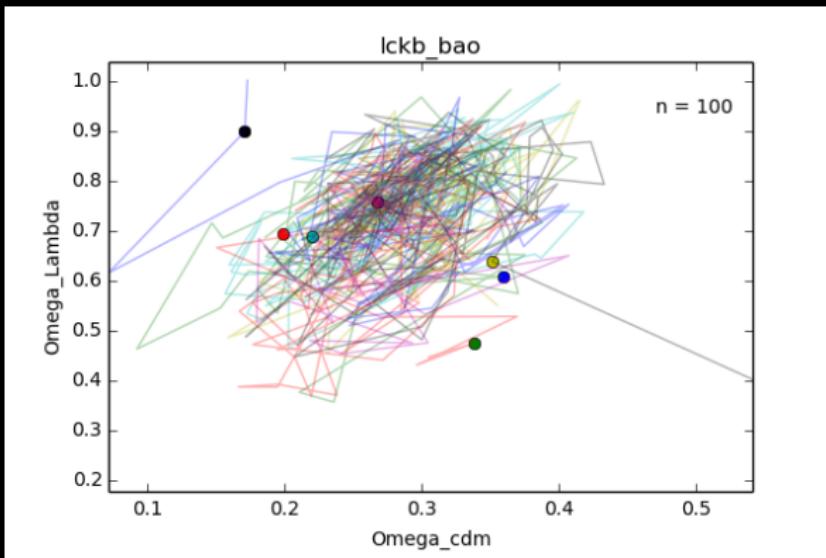
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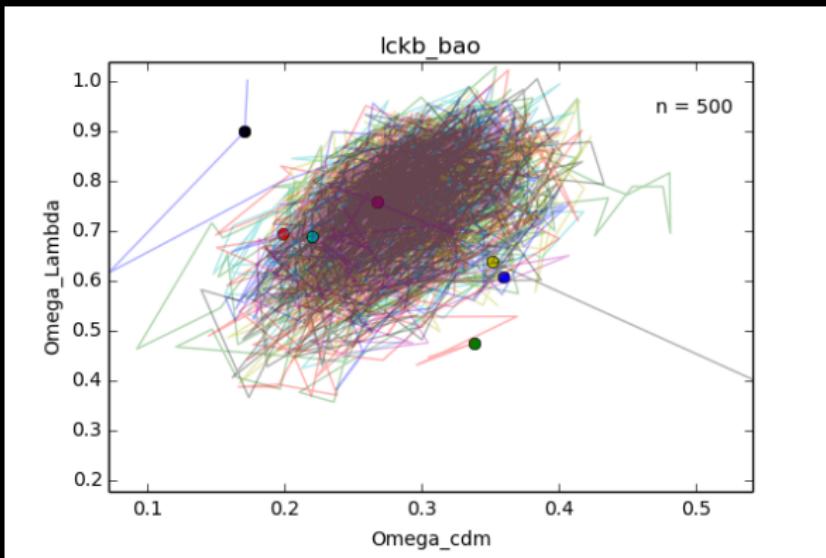
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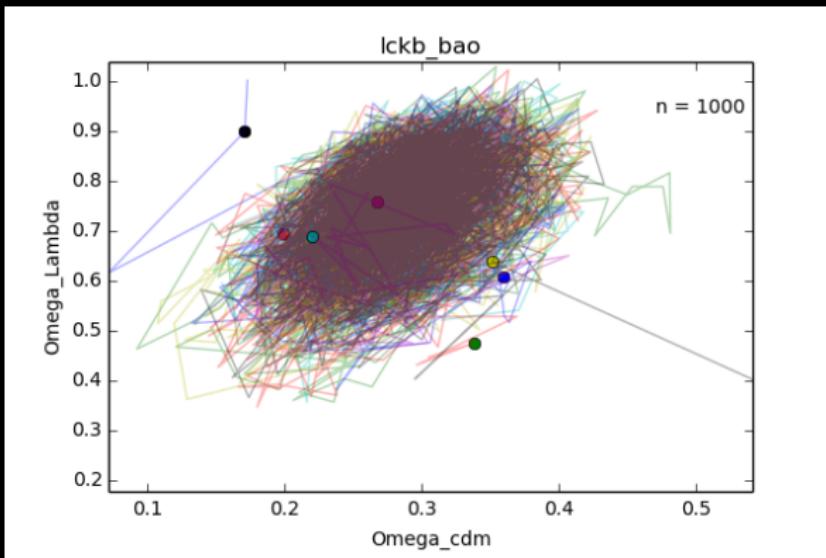
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Effective theory of Dark Energy (Gubitosi+, Bloomfield+ '13)

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

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

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

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 - ★ Only background + linear perturbations
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★ Only background + linear perturbations

★ Tensor + scalar field ...

★ FRW Symmetries: homogeneity + isotropy

★ Theory symmetries: coordinate transformations

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

(Review: Gleyzes, Langlois, Vernizzi '14)