The Cosmic Linear Anisotropy Solving System:
a most *classy* way from Fundamental Physics to Cosmology

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NORDITA

IFT School on Cosmology Tools

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DISCLAIMER: Short time!

$\lesssim 2h$ course $\Rightarrow$ overview and basic usage

Learn further:

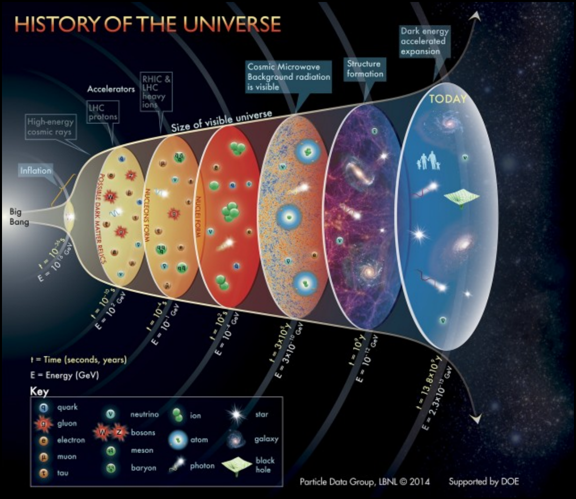
- CLASS lecture by Julien Lesgourgues ($\sim 4h$)
  `https://lesgourg.github.io/class-tour/Narbonne.pdf`
- CLASS course by J. Lesgourgues and T. Tram ($\sim 13h$)
  `https://lesgourg.github.io/class-tour-Tokyo.html`
- Links to extra resources in exercise sheet

Acknowledgements

Extra help from:

Thejs Brinckmann, Carlos Garcia, Deanna Hooper & Vivian Poulin

Fundamental physics and cosmology



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

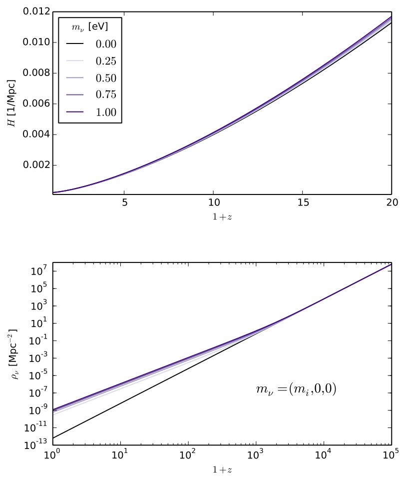
From Physics to Cosmology

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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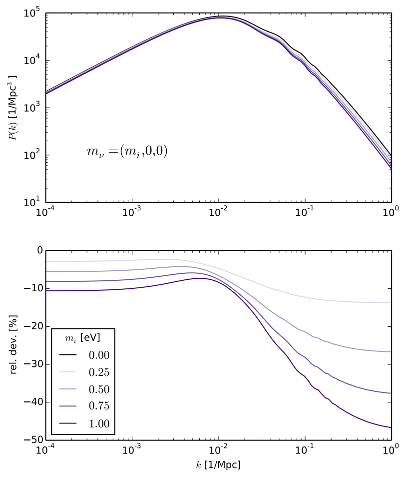

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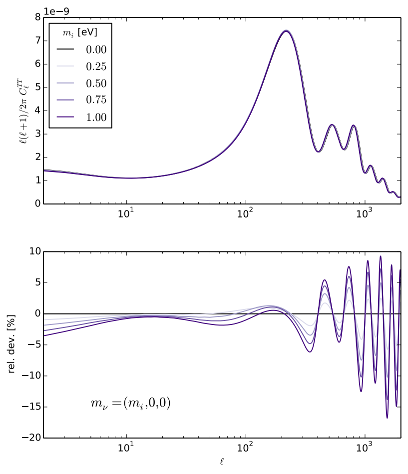

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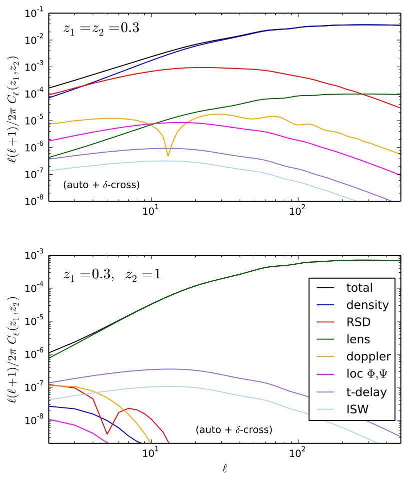

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Boltzmann Codes

- 1995: COSMICS (Bertschinger)
- 1996: CMBFAST (Seljak & Zaldarriaga)
- 1999: CAMB (Lewis): Manteined and improved

  $\longrightarrow$ CAMB Sources, MGCAMB, EFTCAMB...
- 2003: CMBEASY (Doran)
- 2011 CLASS (Lesgourgues & Tram)

  $\longrightarrow$ 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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- 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 $\longrightarrow$ less cursing!

some Coding Principles

The CLASS Commandments

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

some Coding Principles

1. input.c
2. background.c
3. thermodynamics.c
4. perturbations.c
5. primordial.c
6. nonlinear.c
7. transfer.c
8. spectra.c
9. lensing.c
10. output.c

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

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  $\rho_b \rightarrow$ `vec[index_bg_rho_b]`

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  `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`)

Neutrinos (`ncdm`)

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

Initial condtitions

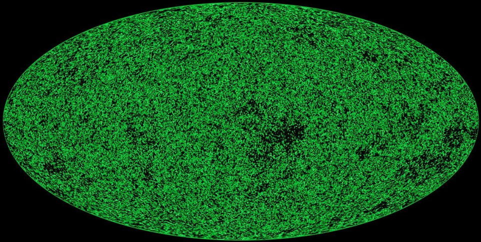
- Analytic $P(k)$
- Isocurvature perturbations
- Inflationary potential $V(\phi)$
- Correlated, Axion, Curvaton
- External ...

Dark Energy and Gravity

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

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

Modified Gravity with CLASS



with

E. Bellini, J. Lesgourgues, I. Sawicki

PLANCK

The case for modified gravity

- Alternatives to Λ?

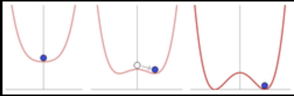
  Inflation again? $n_s \neq 1$

- Interesting field-theoretical questions

  proxy for inflation/quantum gravity?

  viable massive spin-2 particles?

  cosmological constant problems?



- Test gravity on all regimes by

  - *confirming standard predictions* ✓

  - *ruling out competing theories*

Scalar-Tensor gravity

$\star$ First-generation: $f(\phi)R + K(X,\phi)$ $\quad X \equiv -(\partial\phi)^2/2$

$\supset$ 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 $\boxed{2^{nd} \text{ order Eqs.}}$

$$G_2(X,\phi) - G_3(X,\phi)\Box\phi + G_4(\phi,X)R + G_{4,X}\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]$$

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

$\supset$ all Old-school,

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⊃ all Old-school, kin. grav. braiding, covariant Galileon

⊃ proxy for DGP & massive grav. (de Rham & Heisenberg '11)

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- $\star$ Beyond Horndeski $\rightarrow$ *discovered by accident!*

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

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
3. Speed:
   - ⋆ $2\times$ QS approx. $\rightarrow$ speed up

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

Horndeski in four words (Bellini & Sawicki '14)

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

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

Theory specific relations:

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

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 $c_T^2 = 1 + \alpha_T$

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

Galileons

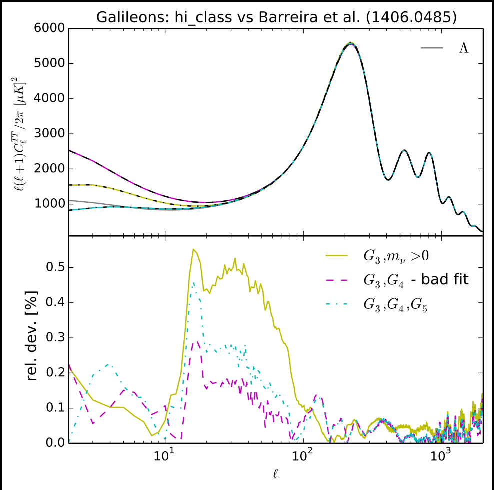
$$G_2 = -X$$
$$G_3 = c_3 X / M^3$$
$$G_4 = \frac{M_p^2}{2} + c_4 X^2 / M^6$$
$$G_5 = c_5 X^2 / M^9$$

Best fit models (Barreira+ '14)

Tested!

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

fully independent implementation



Similar agreement with EFTCAMB and Brans-Dicke.

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: $\delta C_\ell \lesssim 0.5\%$, $\delta P_k \lesssim 0.1\%$

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Prospects

1. beyond Horndeski:

   G^3, EST, massive gravity
2. Non-linear (PT, N-body)
3. 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 $\rightarrow$ `hi_class`
- Very easy to add your own stuff!
- This just scratches the surface, many more options!

(See also J. Lesgourgues and T. Tram's slides)