Modified gravity and massive neutrinos in fast, approximate simulations of dark matter structure formation[1,2]

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[1] **B. S. Wright**, H. A. Winther, and K. Koyama. "COLA with massive neutrinos". In: **JCAP** 10, 054 (Oct. 2017), p. 054. DOI: 10.1088/1475-7516/2017/10/054. arXiv: 1705.08165.

[2] H. A. Winther K. Koyama M. Manera **B. S. Wright** G.-B. Zhao. "COLA with scale-dependent growth: applications to screened modified gravity models". In: **JCAP** 8, 006 (Aug. 2017), p. 006. DOI: 10.1088/1475-7516/2017/08/006. arXiv: 1703.00879.

Code available at: https://github.com/HAWinther/MG-PICOLA-PUBLIC

Overview

1 Context
- Testing gravity on cosmological scales
- Structure formation simulations
- COLA

2 Extending COLA
- Modified gravity
- Massive neutrinos

3 Results
- Matter power spectrum
- Degeneracy between modified gravity and neutrino mass

4 Summary

What's wrong with GR?

- GR consistent with all tests so far: solar system, weak field, gravitational waves
- But these are all small scale tests - it is a massive extrapolation to assume GR works on large scales!
- Cosmological constant (or other dark energy) required to explain cosmic acceleration
- Furthermore, we know that GR is currently incompatible with QFT - so we know we will have to go beyond GR at some stage...

Motivation

Test whether gravity modified on large scales, and whether modifications can cause the cosmic acceleration

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Testing gravity: observations

Mapping positions of galaxies on the sky + measuring redshifts allows us to study:

- Galaxy clustering (biased tracer of matter distribution)
- Weak lensing (more direct tracer of matter distribution)
- Redshift space distortions (growth rate of structure)

Both the distribution of matter and the growth rate of structure can be affected by modifications to GR

To extract cosmological parameters and test gravity, observations must be compared with theoretical predictions of the matter distribution and growth rate

Use simulations of structure formation for predictions

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Use simulations of structure formation for predictions

Simulations: *N*-body

- Typical simulation method = *N*-body: solves the Newtonian gravity equations to give full particle trajectories $\vec{x}$

$$\partial_t^2 \vec{x} = -\vec{\nabla}\Phi$$ ← gravitational potential

- However, many small timesteps required to maintain accuracy
  → *N*-body = slow
  → Expensive to produce large number of simulations
  → Expensive to test new cosmologies

- Faster methods for simulations:
  → Trade accuracy at small scales for speed
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Simulations: COLA

- COmoving Lagrangian Acceleration (COLA) method[3] solves for trajectories of particles in frame comoving with 2nd order Lagrangian perturbation theory (2LPT) observers
- i.e. computes deviations from the trajectories predicted by 2LPT

$$\vec{x} = \vec{x}_{\mathrm{2LPT}} + \vec{x}_{\mathrm{dev}}$$

$$\partial_t^2 \vec{x}_{\mathrm{dev}} = -\vec{\nabla}\Phi - \partial_t^2 \vec{x}_{\mathrm{2LPT}}$$

- Computing deviations instead of full trajectory allows fewer larger timesteps to be taken → Faster simulation

[3] S. Tassev, M. Zaldarriaga, and D. J. Eisenstein. "Solving large scale structure in ten easy steps with COLA". . In: **JCAP** 6, 036 (June 2013), p. 036. DOI: 10.1088/1475-7516/2013/06/036. arXiv: 1301.0322 [astro-ph.CO].

COLA implementation

- To implement extra physics in COLA, we need to modify:
  a) computation of trajectories predicted by 2LPT
  b) computation of deviations from these trajectories via particle-mesh (PM)
- Also may need to update initial conditions
- The version of COLA we chose to modify is L-PICOLA[4]

[4] C. Howlett, M. Manera, and W. J. Percival. "L-PICOLA: A parallel code for fast dark matter simulation". In: **Astronomy and Computing** 12 (Sept. 2015), pp. 109–126. DOI: 10.1016/j.ascom.2015.07.003. arXiv: 1506.03737.

Modified Gravity in COLA

- 2LPT updated and fifth force included in PM
- Screening implemented approximately by correcting linearised field equations[5]
- $f(R)$, DGP, and Jordan-Brans-Dicke models built-in
- Can add extra models of chameleon form using $\{m(a), \beta(a)\}$ formalism[6]
- Can add other models that use potential, gradient, or density screening

[5] H. A. Winther and P. G. Ferreira. "Fast route to nonlinear clustering statistics in modified gravity theories". In: PRD 91.12, 123507 (June 2015), p. 123507. DOI: 10.1103/PhysRevD.91.123507. arXiv: 1403.6492.

[6] P. Brax et al. "Unified description of screened modified gravity". In: PRD 86.4, 044015 (Aug. 2012), p. 044015. DOI: 10.1103/PhysRevD.86.044015. arXiv: 1203.4812 [astro-ph.CO].

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Massive Neutrinos in COLA

- Neutrinos shown to have mass by flavour oscillation experiments[7,8]
- Specifically, at least 1 mass eigenstate with $m_\nu \gtrsim 0.06$eV
- Neutrinos have high thermal velocities at late times so can't cluster at scales < $\lambda_{\rm fs}$

$\rightarrow$ Growth of dark matter density perturbations suppressed on scales < $\lambda_{\rm fs}$

- Structure formation simulations need to account for massive neutrinos

- Treat neutrinos as only a linear perturbation throughout
- In PM, neutrinos described as local density on grid evolved forward in time using linear Boltzmann theory[9]

[7] Y. Fukuda et al. "Measurements of the Solar Neutrino Flux from Super-Kamiokande's First 300 Days". In: **Physical Review Letters** 81 (Aug. 1998), pp. 1158–1162. DOI: 10.1103/PhysRevLett.81.1158. eprint: hep-ex/9805021.

[8] Q. R. Ahmad et al. "Measurement of the Rate of $\nu_e + d \rightarrow p + p + e^-$ Interactions Produced by ^8B Solar Neutrinos at the Sudbury Neutrino Observatory". In: **Phys. Rev. Lett.** 87 (July 2001), p. 071301. DOI: 10.1103/PhysRevLett.87.071301. URL: https://link.aps.org/doi/10.1103/PhysRevLett.87.071301.

[9] J. Brandbyge and S. Hannestad. "Grid based linear neutrino perturbations in cosmological N-body simulations". In: **JCAP** 5, 002 (May 2009), p. 002. DOI: 10.1088/1475-7516/2009/05/002. arXiv: 0812.3149.

$f(R)\ P_{\delta\delta}(k)$

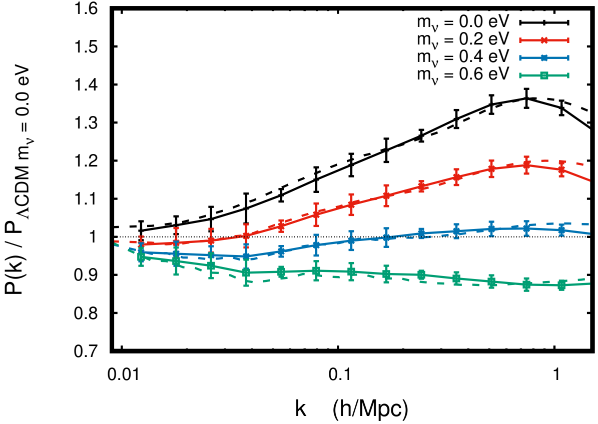

Figure: $f(R)$ CDM power spectrum at $z = 0$ computed with COLA (solid) and N-body[10] (dashed).

[10] M. Baldi et al. "Cosmic degeneracies - I. Joint N-body simulations of modified gravity and massive neutrinos". In: **MNRAS** 440 (May 2014), pp. 75–88. DOI: 10.1093/mnras/stu259. arXiv: 1311.2588.

f_{R0} vs m_ν degeneracy

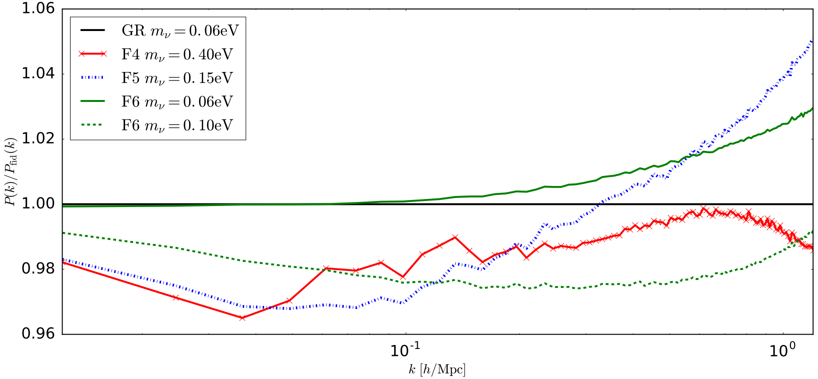

Figure: $f(R)$ non-linear CDM power spectrum at $z = 0$ computed with COLA for a variety of $|f_{R0}|$ and m_ν values.

Summary

- COLA is a fast, approximate structure formation simulation method
- To extend COLA, must modify:
  a) computation of 2LPT trajectories
  b) computation of deviations from 2LPT trajectories via PM
- Due to its speed, extended COLA useful for investigating degeneracy between enhancement of structure formation due to MG and suppression due to massive neutrinos
- Ongoing work to distinguish MG + massive neutrino case from ΛCDM using redshift space distortions which measure the growth rate of structure
- Potential to use modified COLA to create pipeline for mock galaxy catalogues that include massive neutrino effects

Thank you for listening!

Based on arXiv:1703.00879 and arXiv:1705.08165

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