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Cosmologix: Fast, accurate and differentiable distances in the universe with JAX

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Summary

Type-Ia supernovae serve as standardizable candles to measure luminosity distances in the universe. Cosmologix accelerates and simplifies cosmological parameter inference from large datasets by providing fully differentiable calculations of the distance-redshift relation as a function of cosmological parameters. This is achieved through the use of JAX (Bradbury et al., 2018), a Python library providing automatic differentiation and compilation for CPU and hardware accelerators. `Cosmologix` incorporates the density evolution of all relevant species, including neutrinos. It also provides common fitting formulae for the acoustic scale so that the resulting code can be used for fast cosmological inference from supernovae in combination with BAO or CMB distance measurements. We checked the accuracy of our computation against `CAMB`, `CCL` and `astropy.cosmology`. We demonstrated that our implementation is approximately ten times faster than existing cosmological distance computation libraries, computing distances for 1000 redshifts in approximately 500 microseconds on a standard laptop CPU, while maintaining an accuracy of 10^{-4} magnitudes in the distance modulus over the redshift range $0.01 < z < 1000$.

Statement of need

Many software are available to compute cosmological distances including `astropy` (Astropy Collaboration, 2013), `camb` (Challinor & Lewis, 2011), `class` (Lesgourgues, 2011), `ccl` (Chisari et al., 2019). To our knowledge only `jax-cosmo` (Campagne et al., 2023) and `cosmoprimo` (Mattia, 2022) provide automatic differentiation through the use of JAX. Unfortunately, at the time of writing, the computation in cosmoprimo does not seem to be jitable and distance computation in jax-cosmo is neglecting contributions to the energy density from neutrinos and photons. The accuracy of the resulting computation is insufficient for the need of the LEMAITRE analysis, a compilation of type-Ia Supernovae joining the very large sample of nearby events discovered by ZTF (Rigault et al., 2025) to higher redshift events from the SNLS (Astier et al., 2006) and HSC (Yasuda et al., 2019). The LEMAITRE collaboration is therefore releasing its internal code for computing cosmological distances. The computation follows standard methods, but our JAX implementation is optimized for speed while maintaining sufficient accuracy.

Computations of the homogeneous background evolution

The core library offers `jax` functions to compute the evolution of energy density in the universe (via the `cosmologix.densities` module) and derived quantities, such as cosmological distances (via the `cosmologix.distances` module). Details are provided in the documentation. As an example, we highlight the speed and accuracy of calculating the distance modulus (the logarithm of luminosity distance) for a large number of redshifts in the following discussion.

Accuracy

The distance computation involves the numerical evaluation of an integral. The resolution of the quadrature used for this evaluation is adjustable in `cosmologix`. To assess the numerical accuracy of our baseline computation, we compared it to the same integral evaluated at 10-fold higher resolution. The difference is displayed in Figure 1 for the baseline Planck ΛCDM model, reported in Table 1 in (Planck Collaboration et al., 2020). The difference in distance modulus between the coarse (baseline) and fine resolution computation is smaller than 10^{-4} mag over the redshift range $0.01 < z < 1000$, dominated by the interpolation error.

We also compared the results of various external codes to the fine quadrature of `cosmologix` as the reference. It demonstrates agreement within a few 10^{-5} magnitudes over the same redshift range. Residual discrepancies between libraries stem from differences in handling the effective number of neutrino species. We adopt `CAMB`'s convention, where all species share the same temperature, resulting in closer alignment with its predictions. We exclude `jax_cosmo` from this comparison because it does not account for neutrino contributions to energy density, precluding a meaningful comparison.

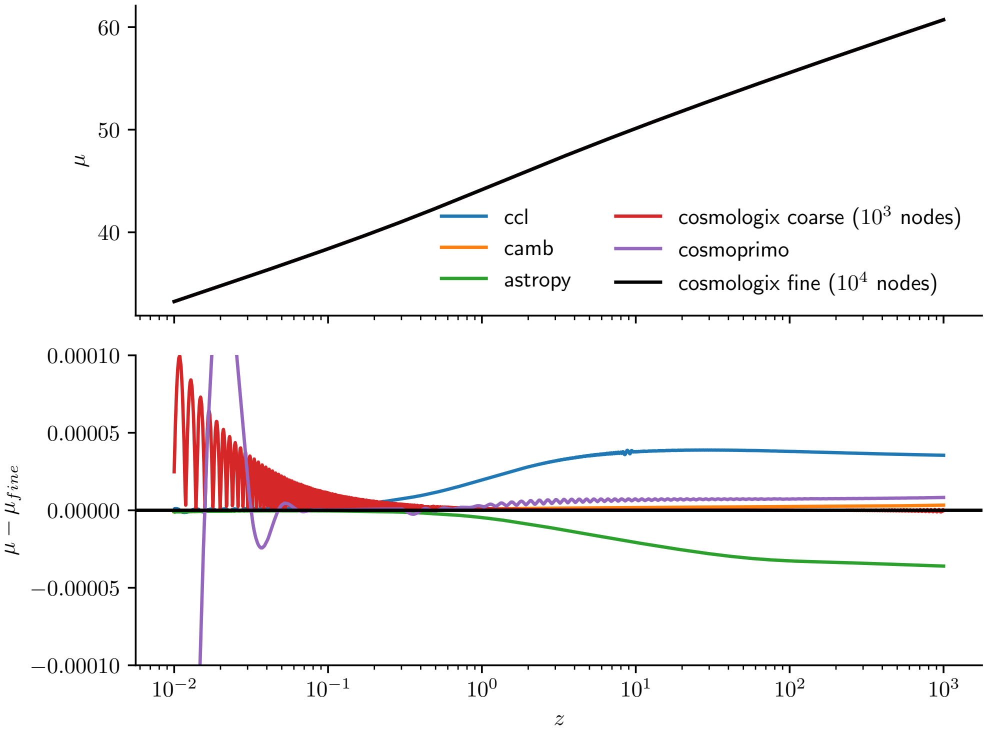

Figure 1: Difference in distance modulus for the Planck best-fit ΛCDM model with respect to the higher resolution quadrature computation in cosmologix.

Computation speed

The computation time for a vector of distance moduli across various redshifts is plotted in Figure 2 as a function of the number of redshifts requested. We differentiate between the first call and subsequent calls, as the initial call may involve specific overheads. For `cosmologix`, this includes JIT-compilation times, which introduces a significant delay. In subsequent calls, cosmologix overperforms all other tested codes by a significant margin.

In addition we also timed the computation of the jacobian matrix of the distance modulus with respect to the 9 cosmological parameters. It is evaluated as `jax.jacfwd(mu)`. The computation time for the Jacobian is roughly 5 times larger than the function itself. This is faster than finite differences, which require 10 function evaluations, reducing computation time by approximately 50%.

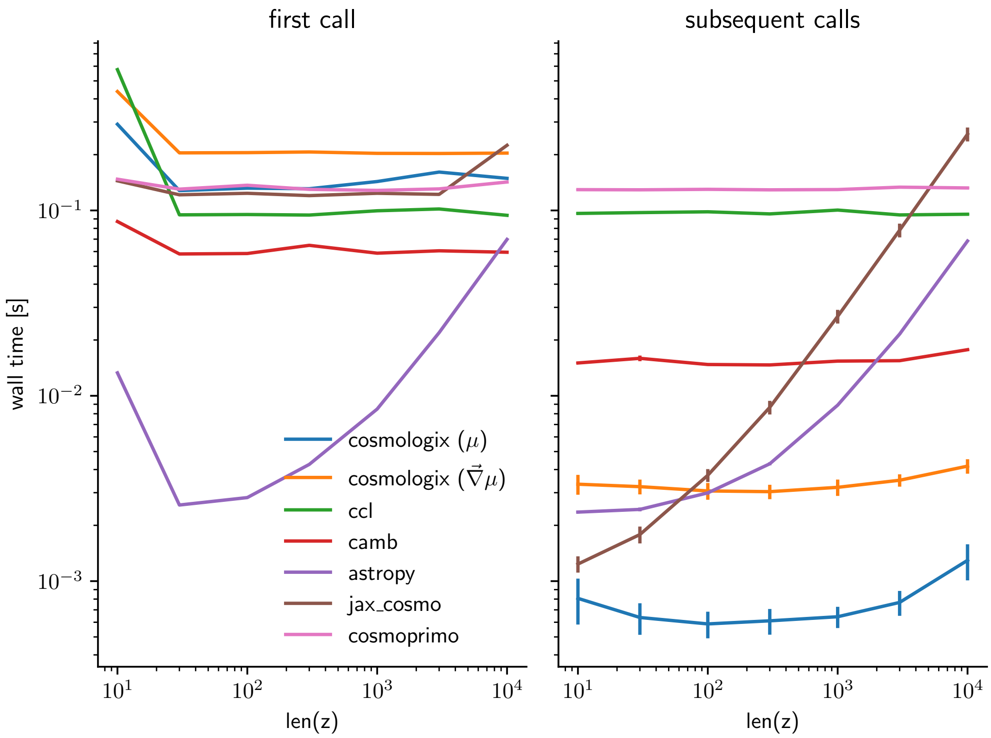

Figure 2: Computation speed of the distance modulus for various cosmological codes. The left panel displays the measured time for the first call which integrates pre-computation and in the case of jax codes overhead associated with jit compilation. The right panel displays the average time measured over 10 subsequent calls. The measurements were obtained on an Intel(R) Core(TM) i7-1165G7 CPU clocked at 2.80GHz, without GPU acceleration.

Differentiability and likelihood maximization

Last, the code provides a framework to efficiently build frequentist confidence contours for cosmological parameters for all measurements whose likelihood can be expressed as a chi-square. Figure 3 provides an example 2-dimensionnal confidence region in the plane (Ω_{bc}, w) for a flat w-CDM model as probed by the Union3 supernovae compilation (Rubin et al., 2023). The full computation took 3.86s on an Intel(R) Core(TM) i7-1165G7 at 2.80GHz without GPU acceleration.

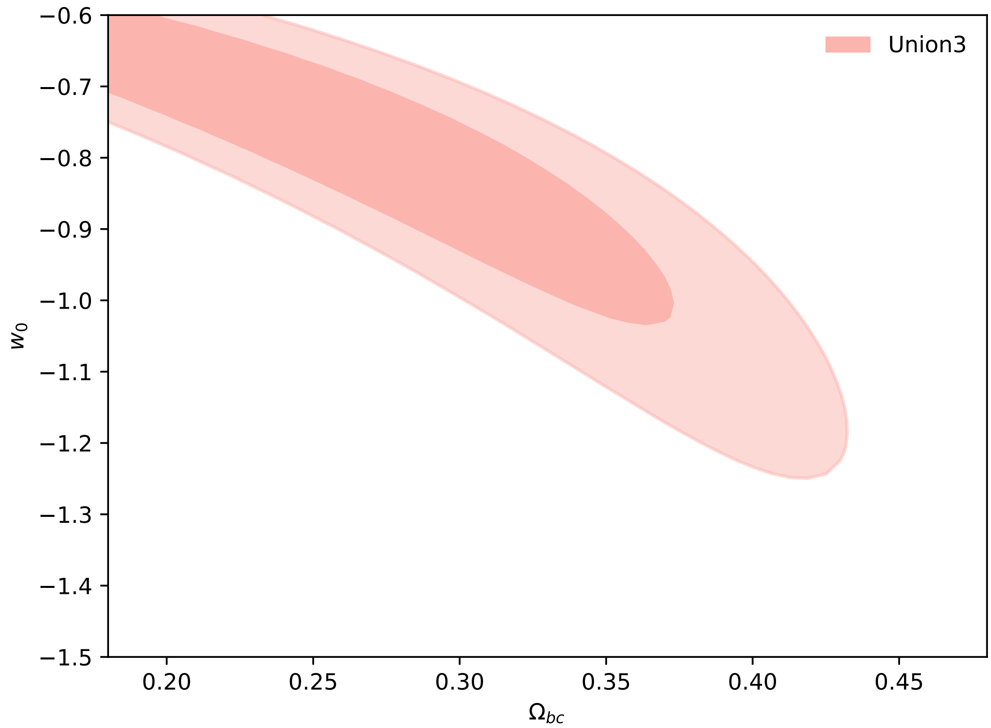

Figure 3: Confidence region at 68 and 95 percent for the w and Ω_{bc} parameters probed by the Union3 compilation.

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