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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, 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 baryon acoustic oscillation or cosmic microwave background 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} mag in the distance modulus over the redshift range $0.01 < z < 1000$.

Statement of need

Many software packages are available to compute cosmological distances including Astropy (Astropy Collaboration, 2013), `CAMB` (Challinor & Lewis, 2011), `CLASS` (Lesgourgues, 2011) or `CCL` (Chisari et al., 2019). To our knowledge only `jax-cosmo` (Campagne et al., 2023) and `cosmoprimo` (de Mattia, 2022) provide automatic differentiation through the use of JAX (Bradbury et al., 2018). Unfortunately, at the time of writing, the computation in `cosmoprimo` does not seem to be jittable 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 needs of the LEMAITRE analysis, a compilation of type Ia Supernovae joining the very large sample of nearby events discovered by the Zwicky Transient Facility (Rigault et al., 2025) to higher redshift events from the Supernova Legacy Survey (Astier et al., 2006) and the Subaru Strategic Program (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

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(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 $0.01 < z < 1000$ and 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} mag 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.

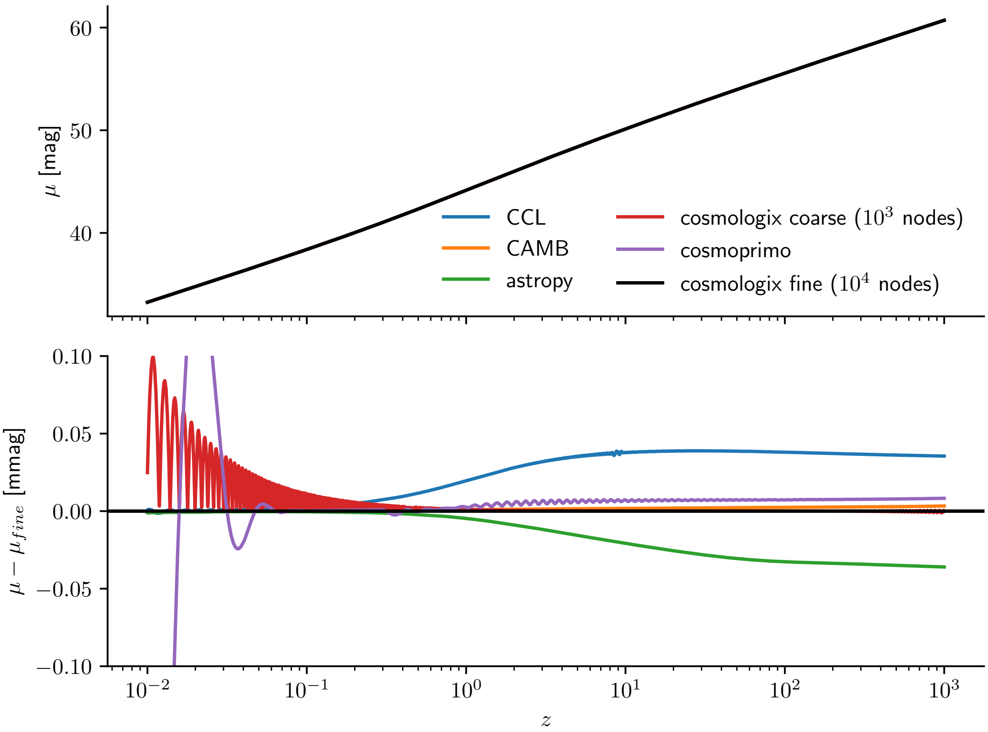

Figure 1: Top: Distance modulus for the Planck best-fit ΛCDM model as a function of redshift computed using two different accuracy settings in Cosmologix, and compared to four other numerical libraries. Bottom: Difference in the above numerical results with respect to the higher resolution quadrature 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

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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 outperforms all other tested codes by a significant margin, typically 10 times faster or more on the tested CPU architecture for 2000 redshifts (corresponding to the current number of supernovae in Hubble diagrams).

We also timed the computation of the Jacobian matrix ($\vec{\nabla}\mu$) 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%.

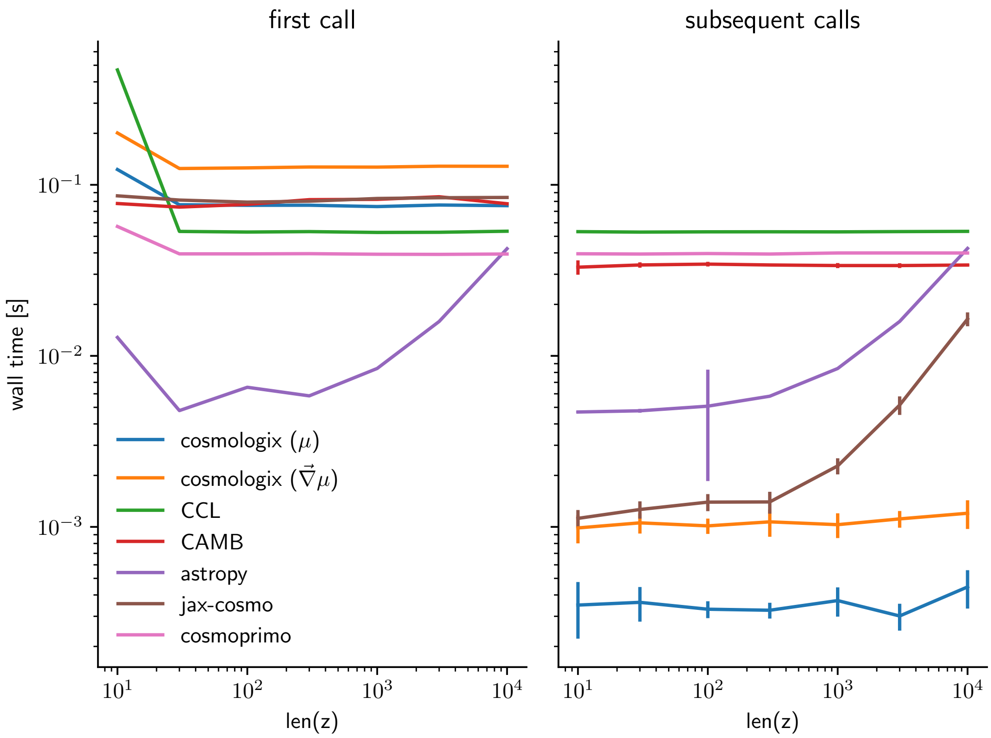

Figure 2: Computation speed of the distance modulus for various cosmological codes. Left: the measured time for the first call which integrates pre-computation and in the case of JAX codes overhead associated with JIT compilation. Right: the median time measured over 10 subsequent calls. The error bar is the rms over 10 measurements. The measurements were obtained on an AMD RYZEN AI MAX+ 395, 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-dimensional confidence region in the plane (Ω_{bc}, w) for a flat w-CDM model as probed by the Union3 supernovae compilation (Rubin et al., 2025). Ω_{bc} is the combined density parameter of baryonic and cold dark matter. The full computation took 3.86s on an Intel(R) Core(TM) i7-1165G7 at 2.80GHz without GPU acceleration.

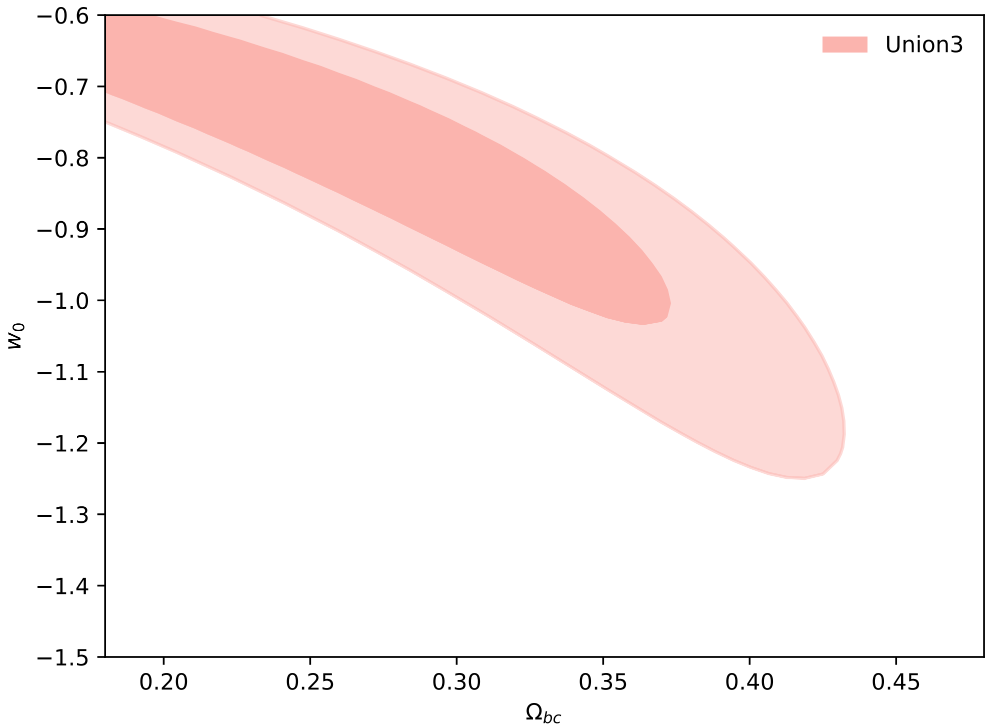

Figure 3: Confidence region at 68 and 95 percent for the w and Ω_{bc} parameters probed by the Union3 compilation.

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