CMB **An**alysis with a **D**ifferentiable **L**ikelihood

L. Balkenhol with C. Trendafilova, K. Benabed, S. Galli, E. Hivon, E. Camphuis, F. Guidi, A. R. Khalifeh, A. Vitrier

CMB France #5, 04/12/2023, Institut d'Astrophysique de Paris

Many Thanks To My Collaborators!

C. Trendafilova (UIUC)

S. Galli (IAP)

K. Benabed (IAP)

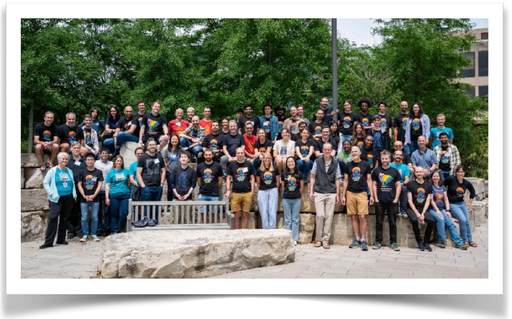
E. Hivon (IAP)

F. Guidi (IAP)

A. R. Khalifeh (IAP)

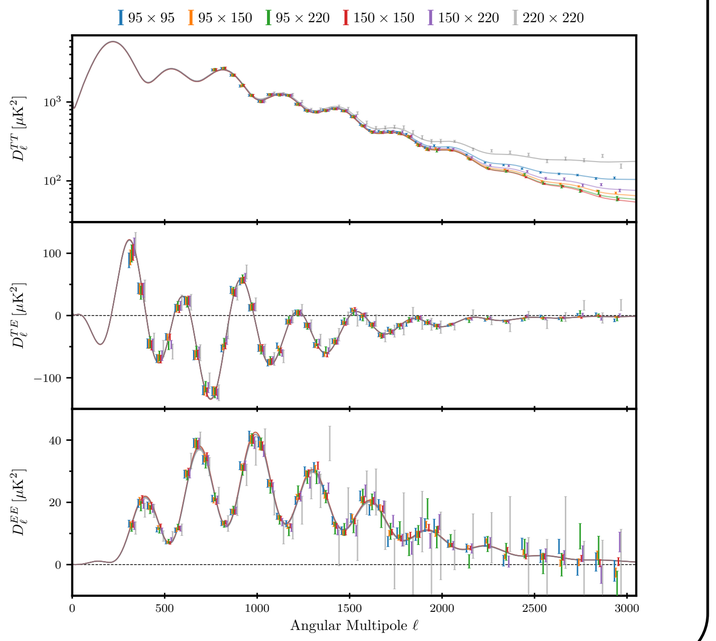
E. Camphuis (IAP)

A. Vitrier (IAP)

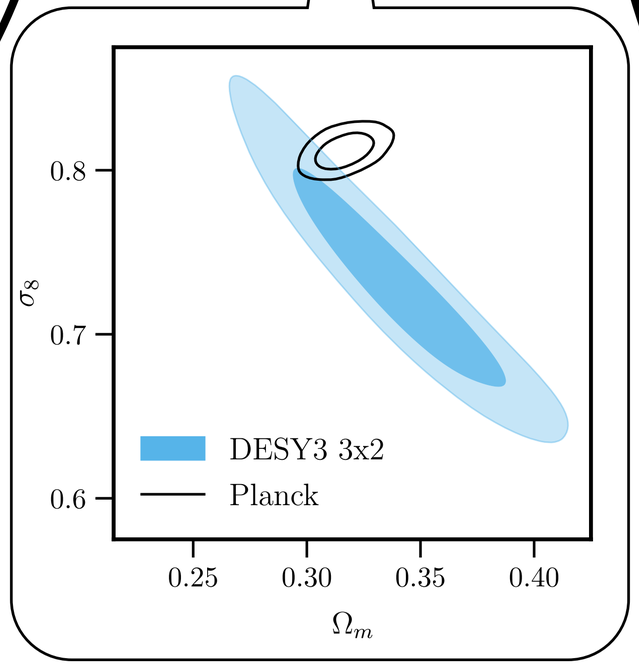


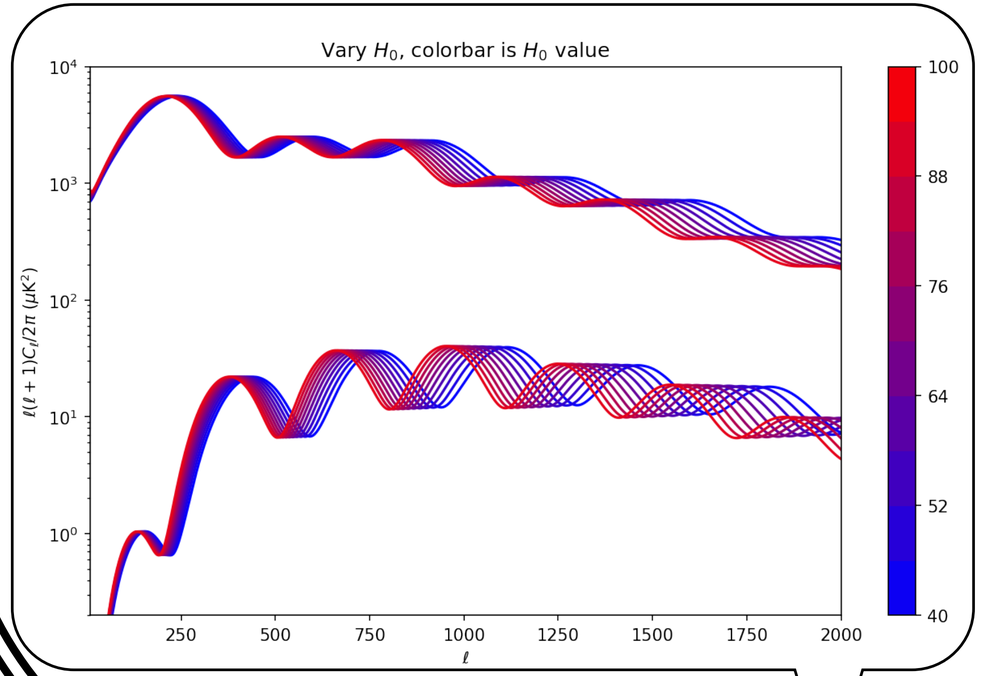
Feedback from the SPT-3G Collaboration

Cosmological Inference



Likelihood Code & MCMC sampler





Data

Read in by Code

Predictions

xO(100k)

Theory Code

Image Credit: Z. Pan (private communication)

The Traditional Approach

- Boltzmann Code - supplies CMB theory spectra
  - CAMB (arXiv:9911177), CLASS (arXiv:1408.4788)
- Likelihood - adapts theory spectra for data model and compares to data
  - Custom code in fortran or python
- Sampler - explores the parameter space
  - CosmoMC (arXiv:0205436), Cobaya (arXiv:2005.05290), MontePython (arXiv:1804.07261)

Inference is rigid and takes O(days) for a given model!

New CMB Data Deserves Better

- Ground-based CMB experiments (SPT-3G ’20 and ACT DR6 data) achieving Planck precision imminently

“With great data comes great responsibility”

- **Need**: light, flexible pipeline to power consistency checks and robustness tests
  - Unchartered territory: claims of new physics need confidence
  - Distribution: Data and tools need to be as accessible to the community as possible
- **Opportunity:**
  - Field is transitioning to Python
  - Field is embracing differentiable emulators: CosmoPower (arXiv:2106.03846), Capse (arXiv:2307.14339), Günther 2023 (arXiv:2307.01138), …
  - Increased use of JAX: Campagne et al. 2023 (arXiv:2302.05163), Piras & Spurio Mancini 2023 (arXiv:2305.06347)

New CMB Data Deserves Better

- Ground-based CMB experiments (SPT-3G ’20 and ACT DR6 data) achieving Planck precision imminently

“W

- **Need**: light, flexible pipeline to p
  - Unchartered territory: claims
  - Distribution: Data and tools n ossible
- **Opportunity:**
  - Field is transitioning to Pytho
  - Field is embracing differen , Capse (arXiv:2307.14339), Gün 023 (arXiv:2307.01138), …
  - Increased use of JAX: Campagne et al. 2023 (arXiv:2302.05163), Piras & Spurio Mancini 2023 (arXiv:2305.06347)

- Google-developed Python library
- *“JAX is Autograd and XLA, brought together for high-performance numerical computing”* [1]
- Automatic differentiation

candl

- CMB TT/TE/EE/ΦΦ Likelihood code
- Stand-alone python package
- JAX-friendly (optional, but encouraged)
- Comes with the latest SPT-3G and ACT data releases
- Easy interface (Cobaya, MontePython, CosmoPower, …)
- Auxiliary tools (Fisher matrices, mock data generation, …)

candl

Stand-alone

```
import candl
import candl.data

candl_like = candl.Like(candl.data.SPT3G_2018_TTTEEE)
# candl_like.data_bandpowers, candl_like.covariance, …

import candl.interface
cobaya_dict = {‘likelihood':
  candl.interface.get_cobaya_info_dict_for_like(candl_like)}
```

Easy access to data

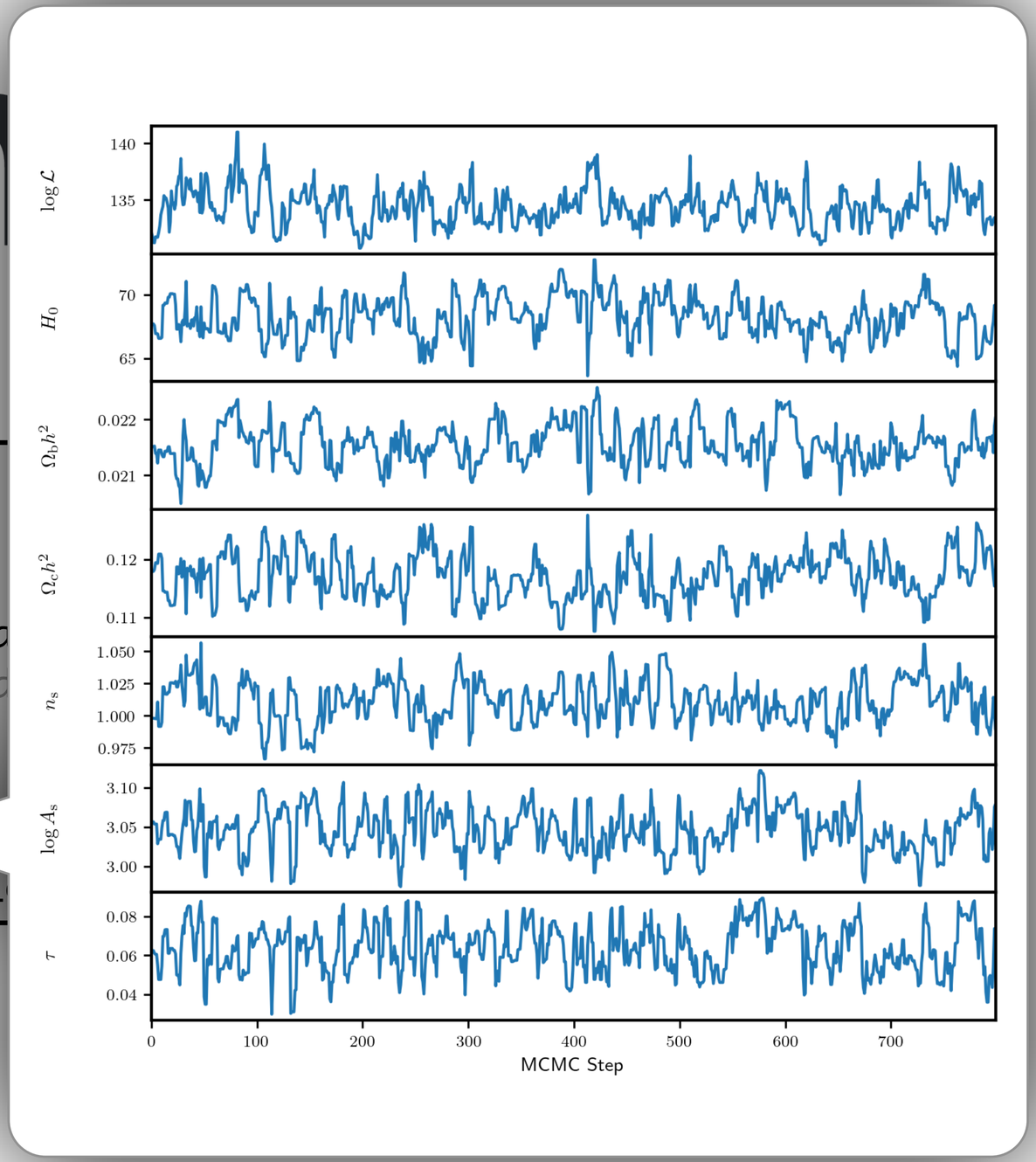
Straightforward interface

can

Stand-alone

Straightforward interface

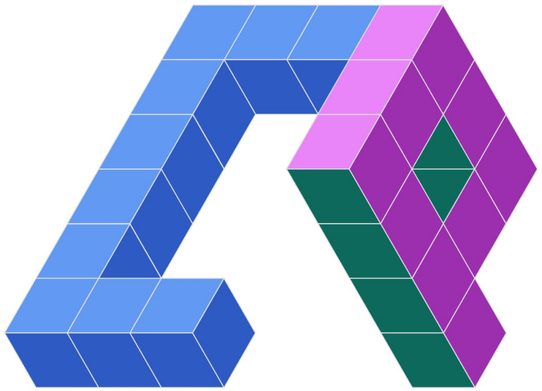
```
import candl
import candl.data

candl_like = candl.Like(candl.data
# candl_like.data_bandpowers, cand

import candl.interface
cobaya_dict = {'likelihood':
  candl.interface.get_cobaya_info_
```



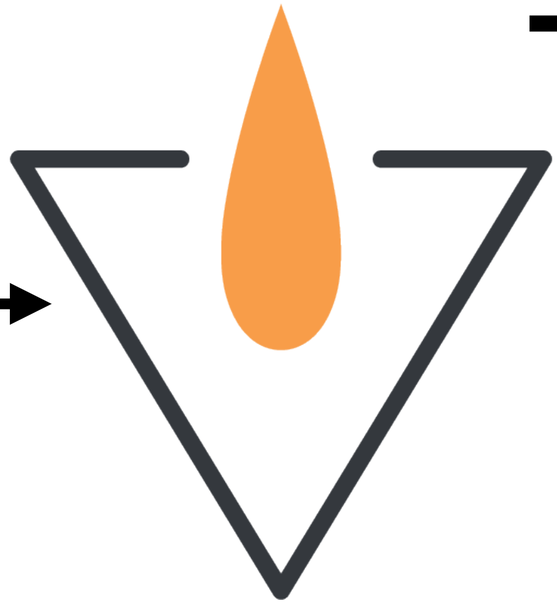
Differentiable

candl

H_0,
ω_c,
ω_b,
n_s,
A_s,
τ,
...



$-\left(D_\ell^{CMB}\right)\rightarrow$



$\rightarrow \chi^2$

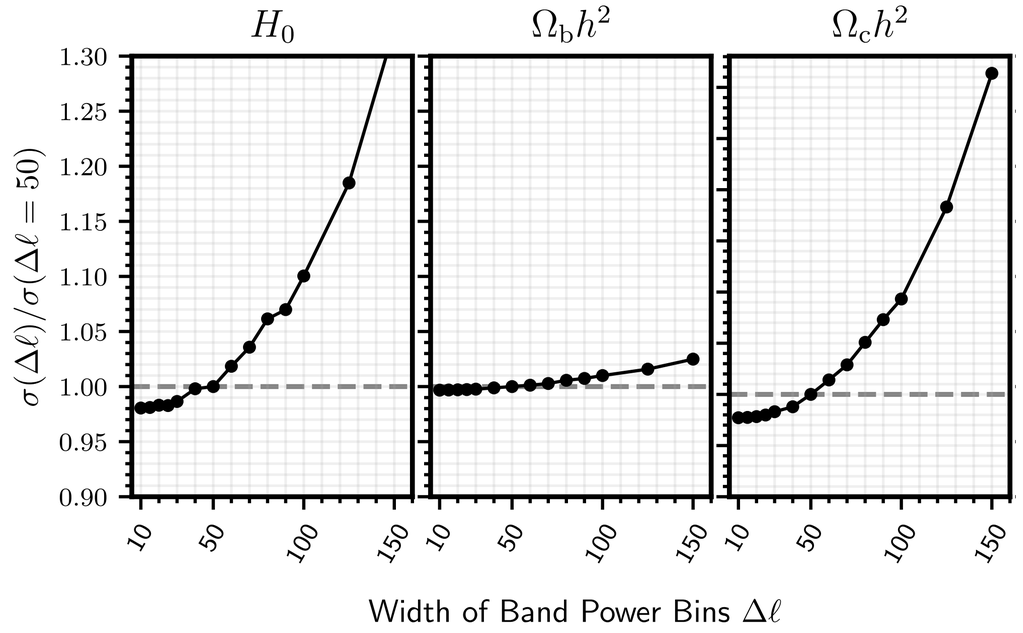
CosmoPower-JAX
(Piras and Spurio Mancini 2023)

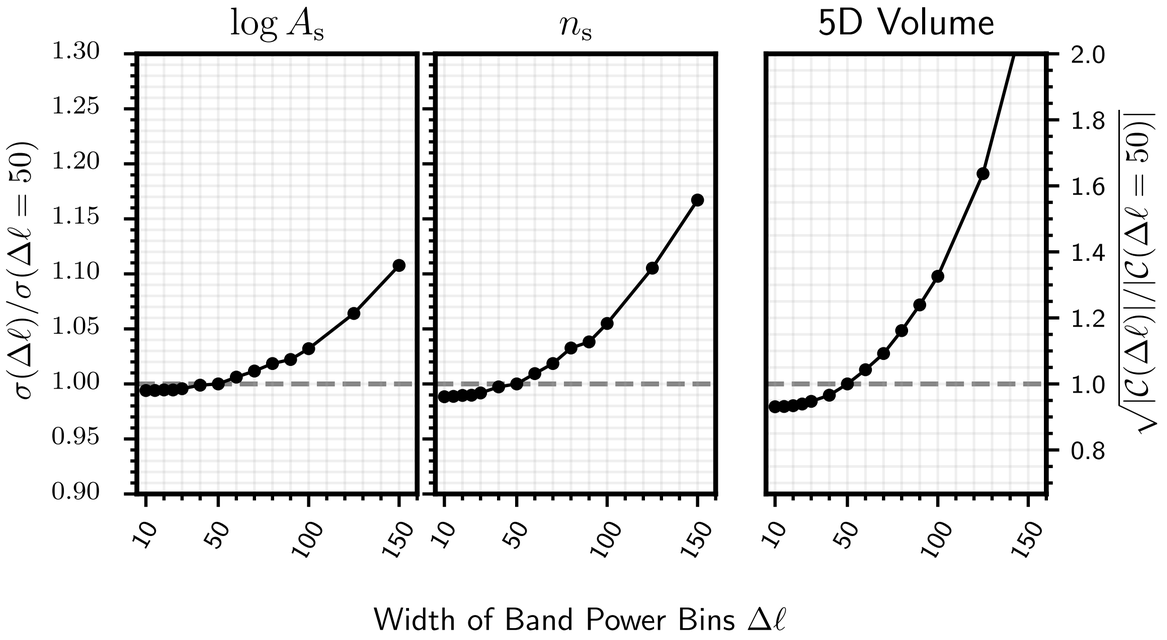
```
import candl.tools
cp_emus = {"TT": "cmb_spt_TT_NN", "TE": "cmb_spt_TE_PCAplusNN", "EE": "cmb_spt_EE_NN"}
pars_to_theory_specs = candl.interface.get_CosmoPowerJAX_pars_to_theory_specs_func(cp_emus)
pars_to_chisq = candl.tools.get_params_to_chi_square_func(candl_like, pars_to_theory_specs)
pars_to_chisq_deriv = jax.jacfwd(pars_to_chisq)
```

Applications

w/ CosmoPower-JAX

- **<u>Quick, easy, reliable Fisher matrices:</u>**
  - Forecasting
  - Correlation between subsets
- **<u>Smart exploration of the likelihood:</u>**
  - Gradient-based minimisers
  - HMC/NUTS sampling

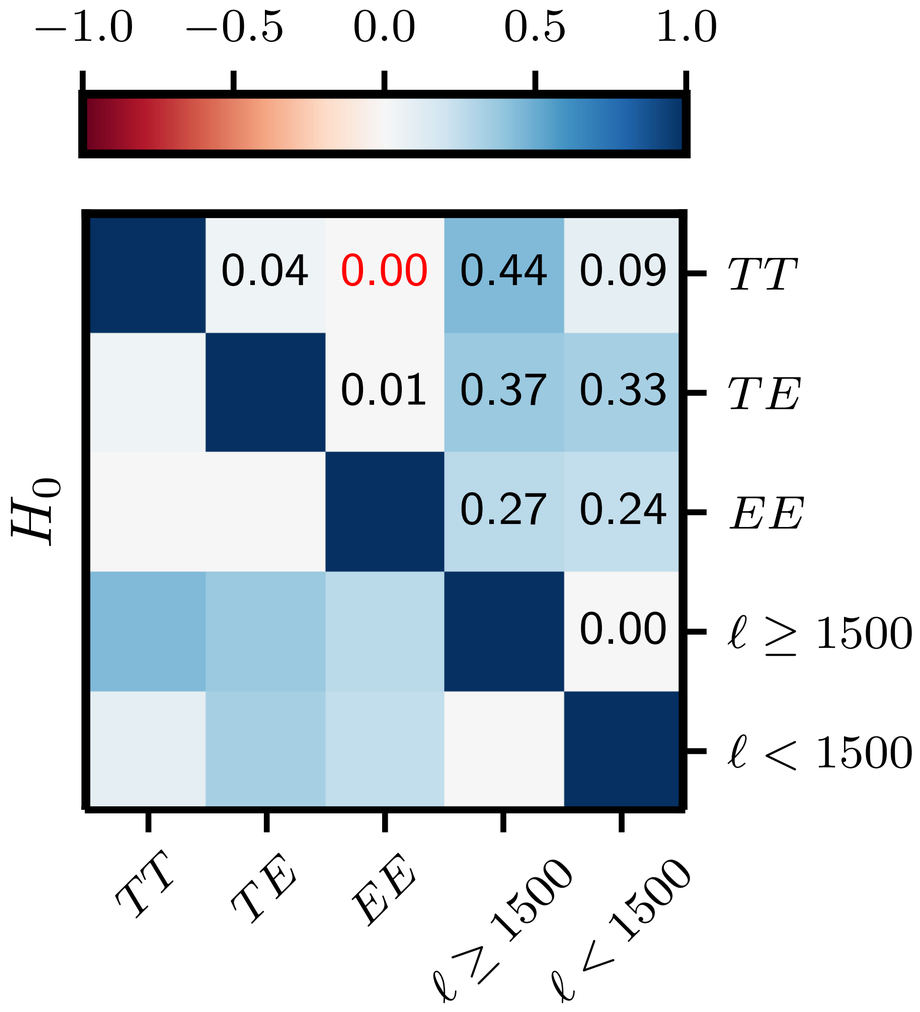




Applications

w/ CosmoPower-JAX

- **<u>Quick, easy, reliable Fisher matrices:</u>**
  - Forecasting
  - Correlation between subsets
- **<u>Smart exploration of the likelihood:</u>**
  - Gradient-based minimisers
  - HMC/NUTS sampling

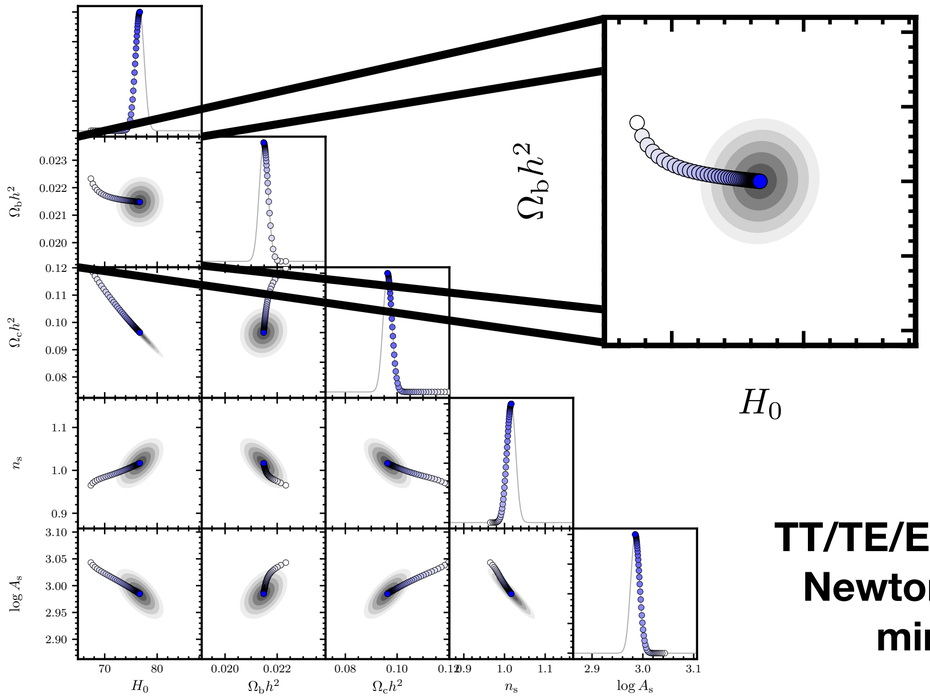


For background see Kable, Addison, Bennett 2019 (arXiv:1908.01626)

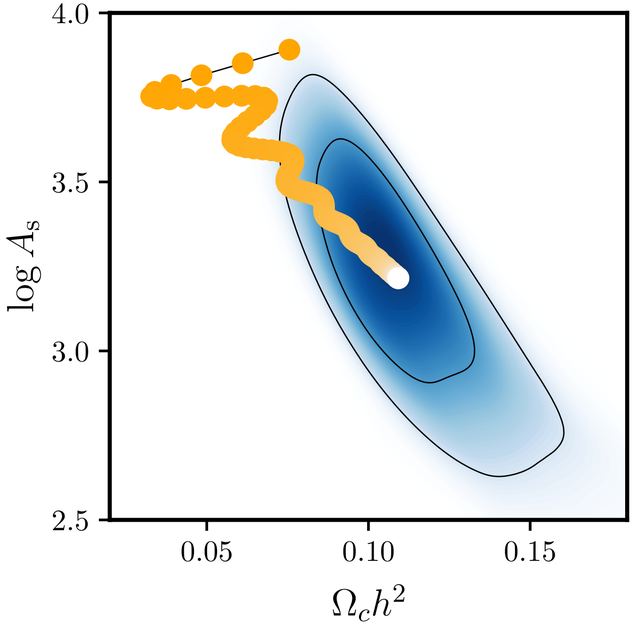
Applications

w/ CosmoPower-JAX

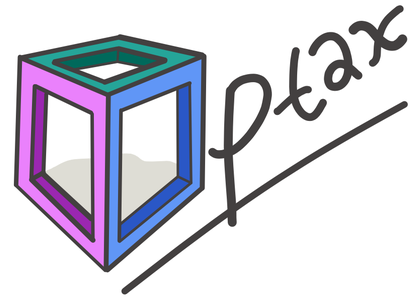
- **Quick, easy, reliable Fisher matrices:**
  - Forecasting
  - Correlation between subsets
- **Smart exploration of the likelihood:**
  - Gradient-based minimisers
  - HMC/NUTS sampling



TT/TE/EE Likelihood
Newton-Raphson minimiser



ΦΦ Likelihood
ADAM minimiser
(arXiv:1412.6980)

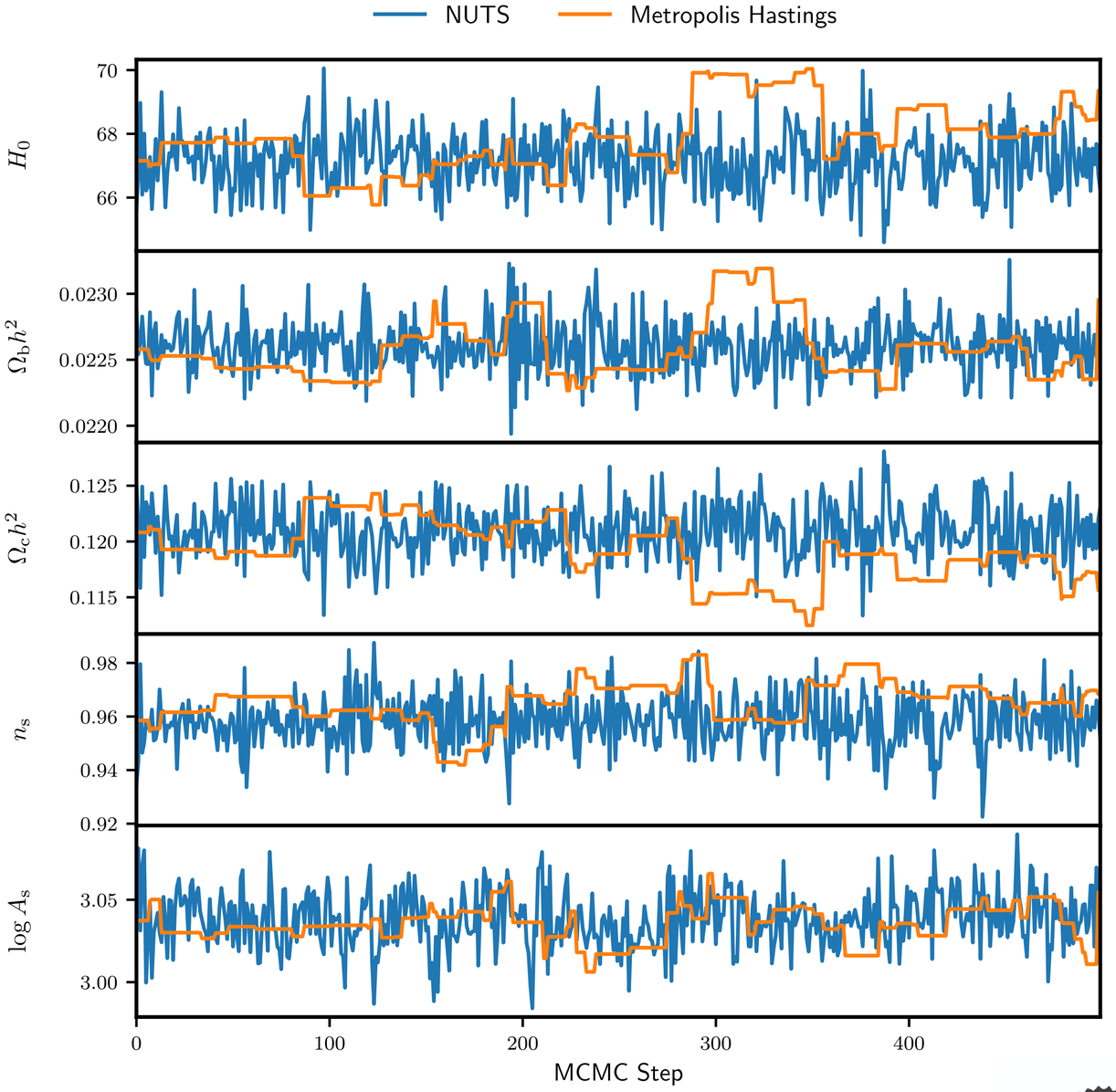


https://github.com/deepmind/optax

Applications

w/ CosmoPower-JAX

- **Quick, easy, reliable Fisher matrices:**
  - Forecasting
  - Correlation between subsets
- **Smart exploration of the likelihood:**
  - Gradient-based minimisers
  - HMC/NUTS sampling



Using BlackJAX: https://github.com/blackjax-devs/blackjax

Conclusions

- Upcoming CMB data need fast, efficient, robust tools
- **candl** is a python-based stand-alone, TT/TE/EE/ΦΦ likelihood
- **candl** is JAX-friendly and differentiable
- **candl** can easily be interfaced with Cobaya, Montepython, CosmoPower, Optax, BlackJAX, …

Coming to arxiv & pip soon!

Lennart Balkenhol, IAP, lennart.balkenhol@iap.fr

BACKUP SLIDES

What is JAX?

- *“JAX is Autograd and XLA, brought together for high-performance numerical computing”* [1]
- Google-developed Python library with:
  - Just-in-time compilation
  - CPU, GPU, and TPU optimisation
  - Automatic differentiation
  - Automatic vectorisation
  - Numpy API compliance
- Increasing use in Cosmology:
  - JAX-Cosmo paper has great examples and discussion [2]
- **JAX is optional**

[1] https://jax.readthedocs.io/en/latest/index.html
[2] https://arxiv.org/abs/2302.05163

Related Work

- Increasing use of JAX and differentiable likelihoods more generally in Cosmology:
  - **Campagne et al 2023, JAX-COSMO, arXiv:2302.05163:**
    Library of different cosmological calculations.
    Examples showing the power of differentiable theory code and likelihood.
    Part of differentiable universe initiative.
  - **Piras and Spurio Mancini 2023, CosmoPower-JAX, arXiv:2305.06347:**
    Differentiable emulator written in JAX.
    Compatible with vanilla CosmoPower models.
  - Implicit likelihood inference (arXiv:2104.12992), MUSE (arXiv:2112.09354), …