Toward Fast BSM Physics with Bolt

CMB-S4 Meeting 2023

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Motivation: Theoretical Progress

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In the Astro2010 decadal survey, the Panel on Cosmology and Fundamental Physics presented four questions—(1) How did the universe begin? (2) Why is the universe accelerating? (3) What is dark matter? (4) What are the properties of neutrinos?—as well as a discovery area in gravitational wave astronomy.[1] Progress on observational and experimental data sets to study these topics has been tremendous.

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These are familiar questions

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Current data makes model extensions *hard*!

How do we facilitate new model development?

1. Remove standard assumptions
2. Make BSM extensions easy (Julia code, gradients)
3. Aim for (nuanced) “model discovery” with ML

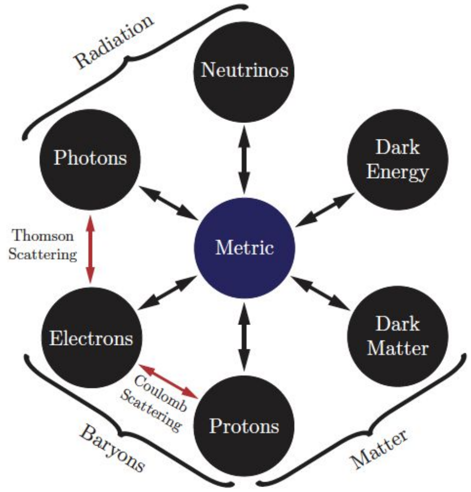
E-B Solver - the Cornerstone of Cosmology

LSS and the CMB models evolve perturbations described by GR and the Boltzmann eqn. (Einstein-Boltzmann system)

Accurate modeling requires solving this (stiff) ODE system

Can address stiffness in two ways:

- Approximations
- Smart ODE solver



Ma&Bertschinger95, Baumann (adapted)

Beyond State of the Art

SOTA codes CAMB & CLASS are incredible feats of scientific software engineering

However:

- both rely on approximations
- neither is differentiable
- navigating the source is a time commitment

The future is differentiable and easy to modify

-> Bolt.jl

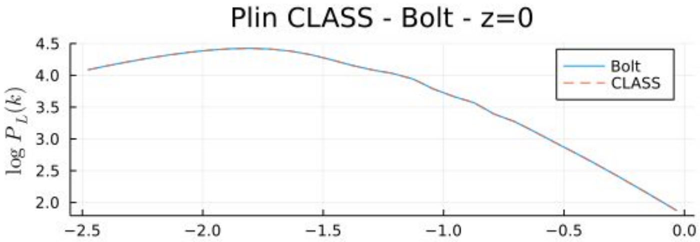
Blas++11, Lewis++00

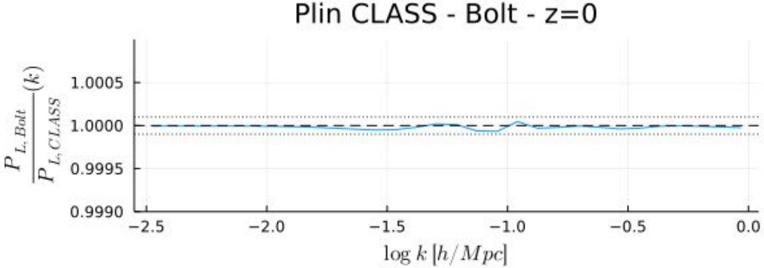
Agreement at the 0.1% Level

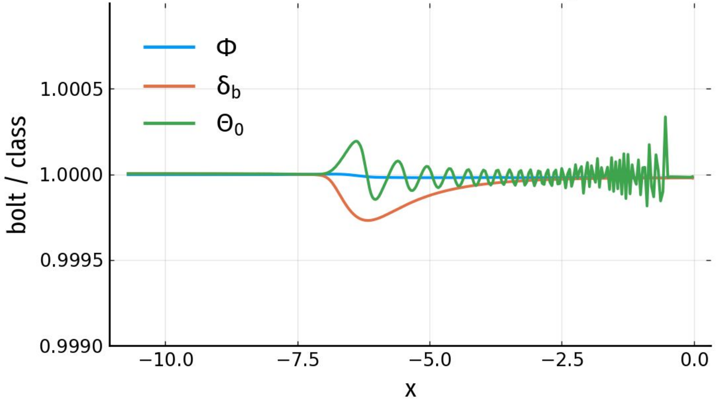
CLASS/CAMB are consistent at the 0.1% level in CMB and matter power spectra

Bolt joins* this exclusive club!

We agree on the perturbations for individual k-modes too







*see also, Moser++22

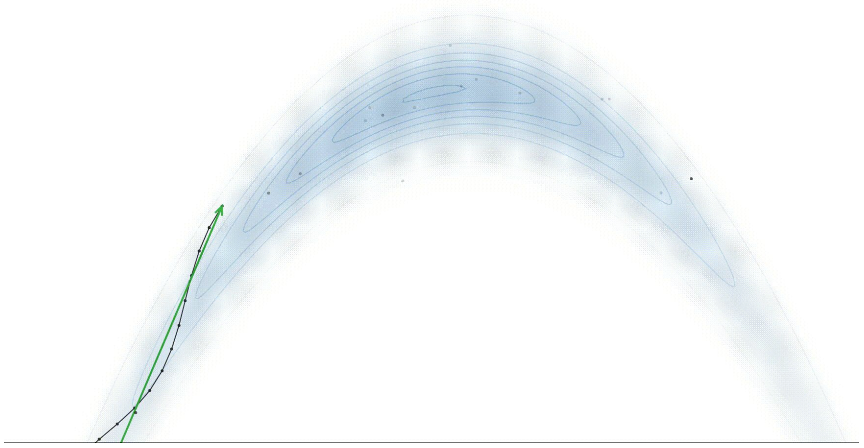
A Need for Differentiable Models

More parameters means high-dimensional inference

Gradient-based methods make this tractable

Must use model gradients, even when not analytic!

Can make an approximation*,
or use a differentiable model**



*e.g. Mancini++21, DeRose++21, Colas++20, Wibking++20 **e.g. Modi++20, Modi++21, Hearin++22

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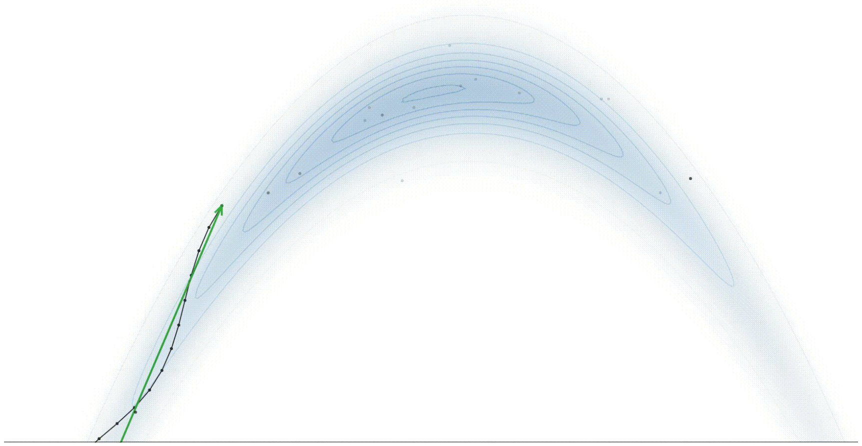

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Gradients on Computers

Symbolic Differentiation

(aka Diff by grad student…or Mathematica)

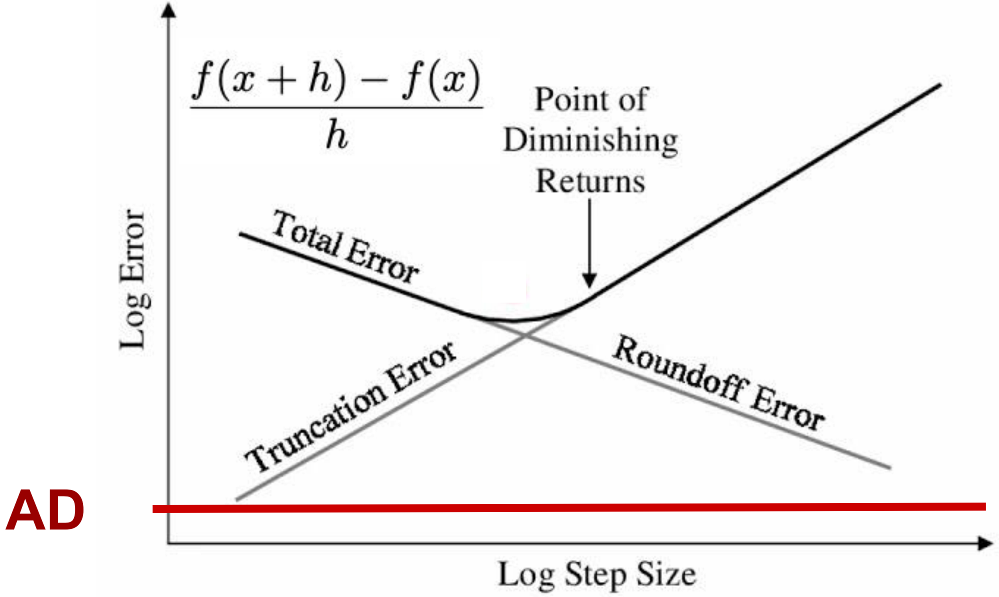
Doesn't work for complex models

Finite Difference

(frequently used for Fisher forecasts)

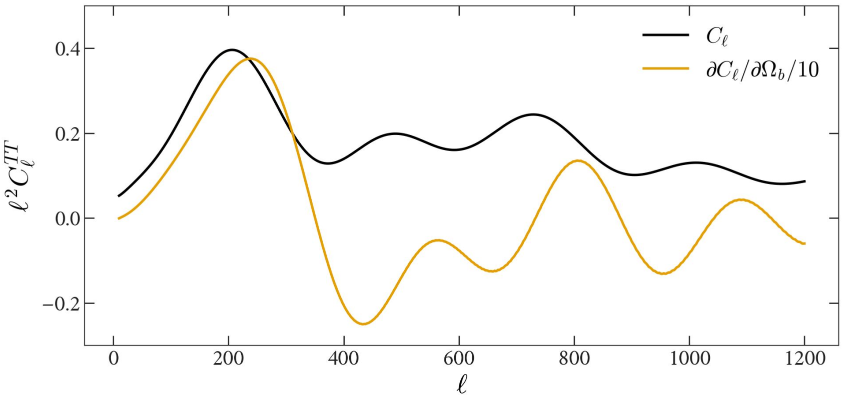
But what is the step?!

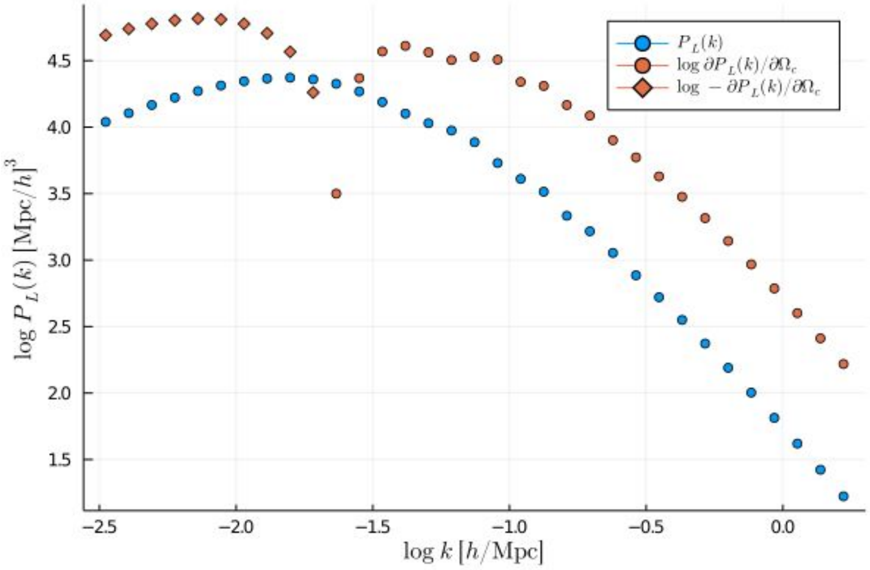
A better way?



Gradients for the CMB and LSS

Exact gradients of the CMB anisotropy, linear matter power spectra



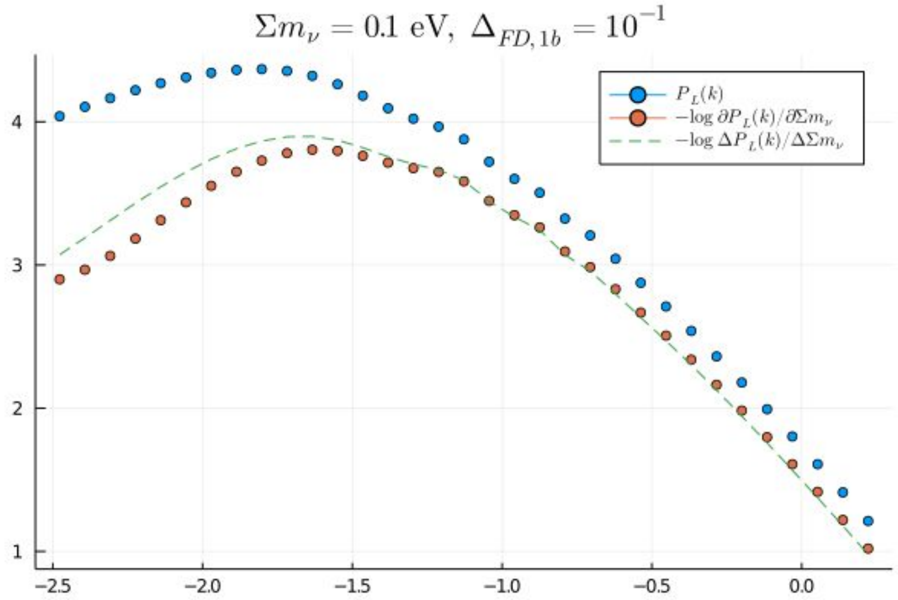


AD >> FD

Finite difference (FD) gives gradient approximations

Well-known that FD does not perform well for neutrino mass

Exact AD derivatives solve this problem!



Bolt.jl Design Recap

Goals:

1. Differentiability
2. Promote rapid physics prototyping

Design aspects:

1. Julia & automatic differentiation (AD)
2. Minimal approximations

Bolt - Model Extension “Live” Demo

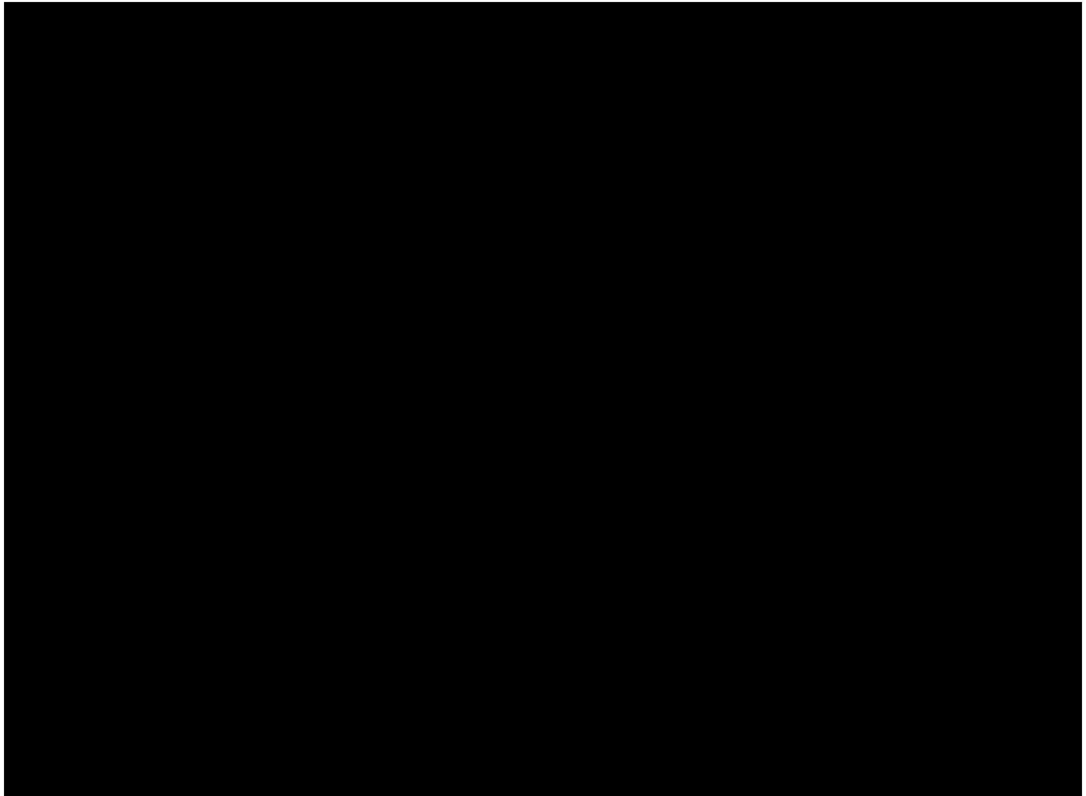
Add dark radiation with an interaction a la Lesgourgues++2015*:

$$
\begin{aligned}
\dot{\delta}_{\mathrm{dm}} &= -\theta_{\mathrm{dm}} + 3\dot{\phi} \\
\dot{\theta}_{\mathrm{dm}} &= -\frac{\dot{a}}{a}\theta_{\mathrm{dm}} + a\Gamma(\theta_{\mathrm{dr}} - \theta_{\mathrm{dm}}) + k^2\psi \\
\dot{\delta}_{\mathrm{dr}} &= -\frac{4}{3}\theta_{\mathrm{dr}} + 4\dot{\phi} \\
\dot{\theta}_{\mathrm{dr}} &= k^2\frac{\delta_{\mathrm{dr}}}{4} + k^2\psi + \frac{3}{4}\frac{\rho_{\mathrm{dm}}}{\rho_{\mathrm{dr}}}a\Gamma(\theta_{\mathrm{dm}} - \theta_{\mathrm{dr}})
\end{aligned}
$$

*Thanks to Ben Wallisch for pointing me to this paper

Bolt - Model Extension "Live" Demo

A few minutes and 17 lines to add DR and run HMC!



A new workflow for linear cosmology?

How do we learn unknown physics?

Background has been explored, but now preturbations!

Embed neural network *inside* ODE function:

$$\delta_i'(k, u, x) = NN_1^{(\theta)}(u, x)$$
$$v_i'(k, u, x) = NN_2^{(\theta)}(u, x)$$

As flexible as you desire! (or dare)

Farhang++12,Liu++19,Hart+Chluba20,Lee++23

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Pretend we “forgot” CDM linear theory - can it be learned?

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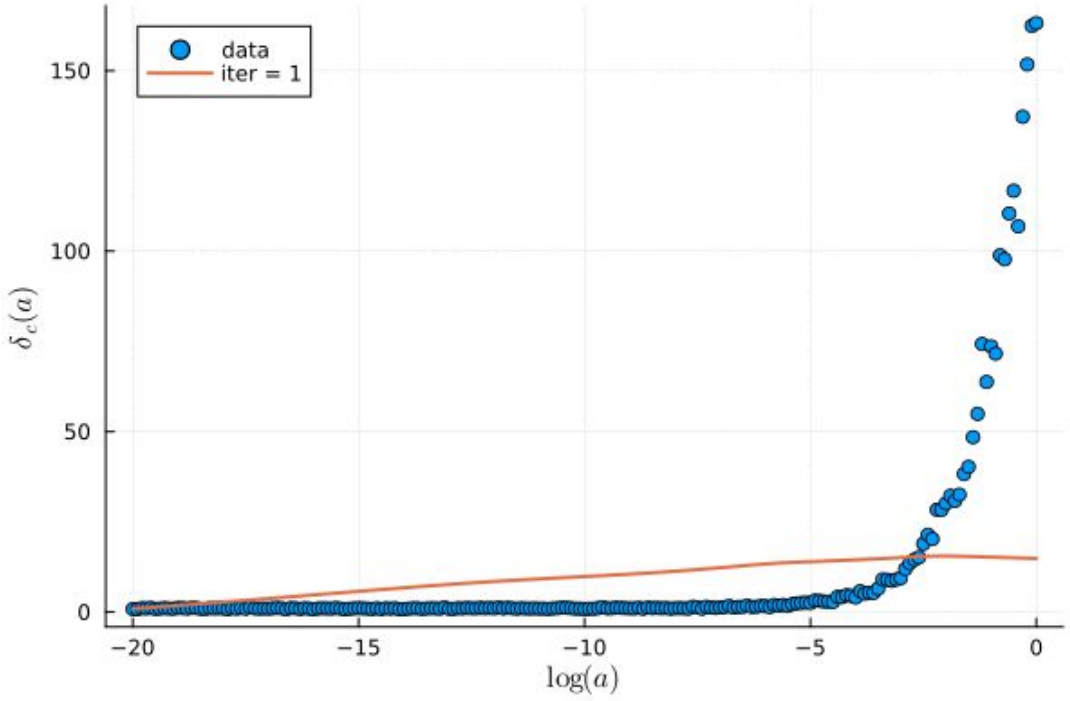

Yes!*

What's next? - NN Uncertainty!

NNs in ODEs a step forward in flexibility

But does **not** tell you **where** to focus model-building efforts

Workflow goal is to guide **human** model building

Luckily, we can obtain uncertainty estimates for neural network predictions - current work!

Summary

Bolt **differentiably solves** the stiff E-B system for the **first time**

Leverage this to **relax standard assumptions**

Lack of approximations and readability helps **quickly try new physical models**

Flexible neural network models will **guide model builders** toward **missing physics**

Differentiability indispensable for high-dimensional inference