# Is Julia ready to be adopted by HEP?

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**Tamas Gal – Erlangen Centre for Astroparticle Physics**

https://indico.cern.ch/event/1292759/contributions/5614633/

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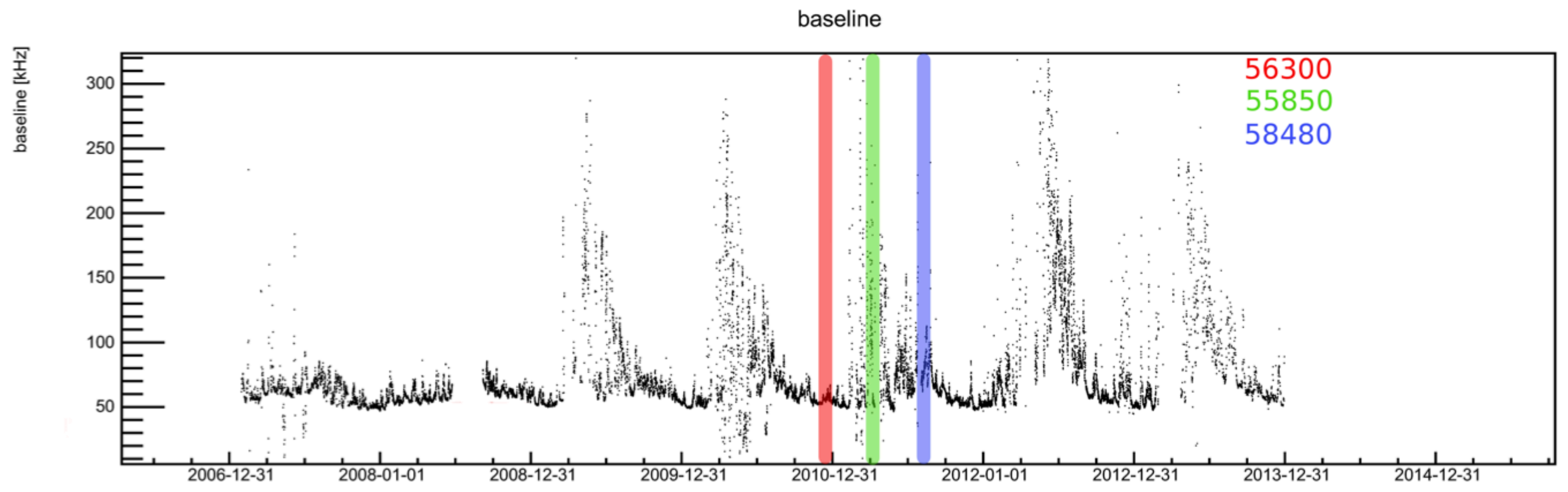
# My first encounter with the HEP software world

## as a graduate student and research assistant in 2012

- Analysing and visualising bioluminescence data recorded by the **ANTARES neutrino detector**



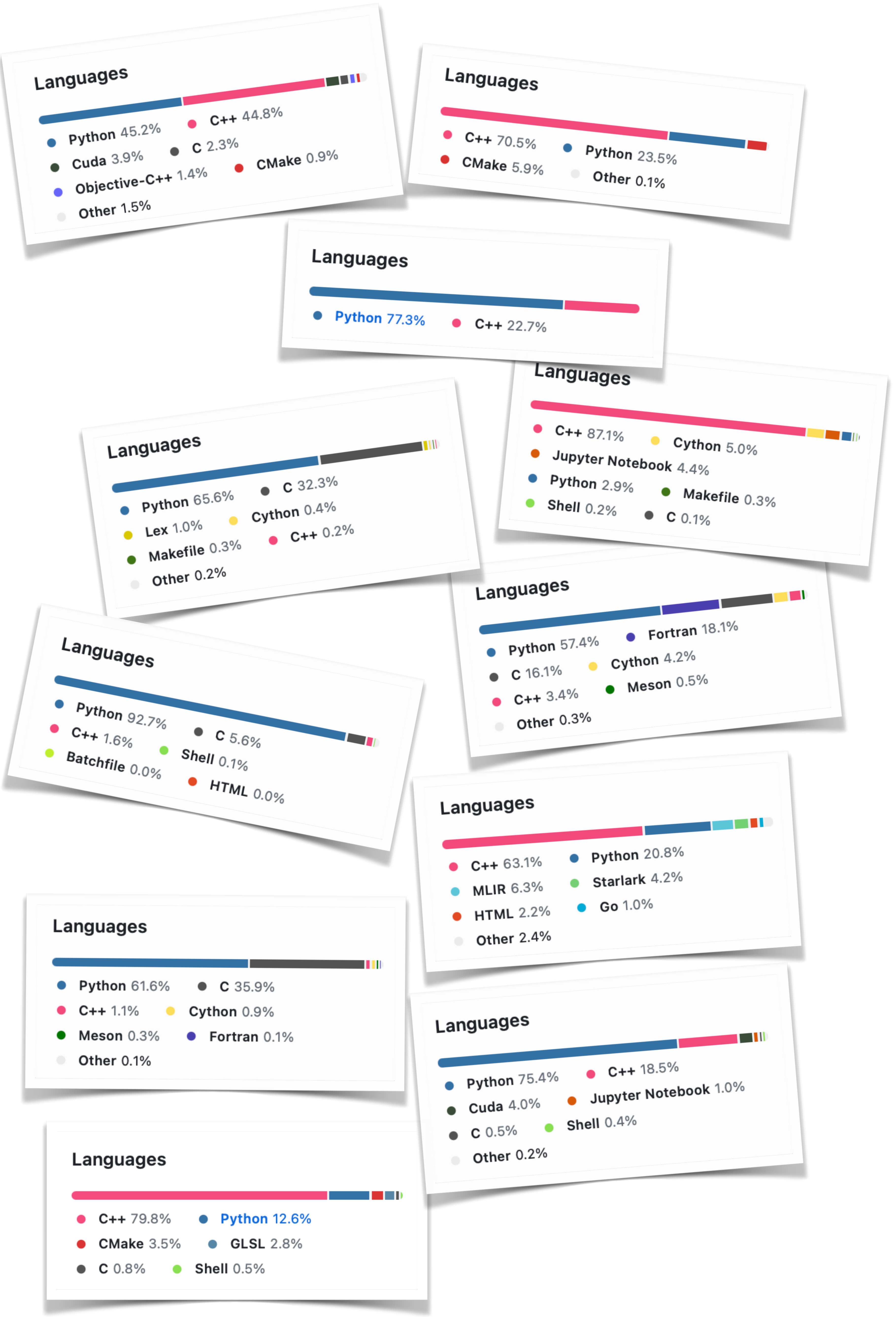

Source: "Untersuchung von Biolumineszenz im ANTARES Neutrinoteleskop", Maximilian Schandri

- Using a **ROOT**-based framework (which was btw. a nightmare to install on my MacBook running Mac OS X 10.6)
- **Why ROOT?** Because people who established ANTARES were familiar with ROOT and **humans crave convenience, stick to old habits**
- **Even with** more than 15 years of (self-taught) coding **experience** in different programming languages: **it was a real challenge**
- **Lot of work** spent until the first results were presentable (kind of embarrassing how long it took to create some simple scatter plots)
- **Most of** my fellow **students** had a much worse starting situation, having almost **no coding experience** at all
- **Python came to the rescue and started to gain some momentum in science**; I was already using it for a decade as a shell scripting replacement.
- Decided to work on (high-level) **Python tools** to **reduce boilerplates**, make things **more accessible** and exploit the benefits of **interactiveness** to lower the entry barrier especially for new-comers

# The years after...

## aka the "The Era of Python"

- I joined **KM3NeT** (the **ANTARES** neutrino detector's successor) and **push**ed hard **for Python**
- **Lot's of library code and packages** written to do both **low-level** calculations (e.g. real-time detector time calibrations using K40 coincidences) and **high-level** analysis ("big-data", machine-learning, HDF5, ...)
- **Convinced** many people that **Python is able to compete** with "compiled rivals" (mainly **C++/ROOT**) by using the **right tools to overcome its weak spots** regarding performance (GIL, duck typing, extremely slow loops...)
- **Virtual environments** and the **Python packaging system** allowed to increase the **reusability** of code and **reproducibility** of analyses
- Still, we ended up in a **technological Mikado**



# The Reality

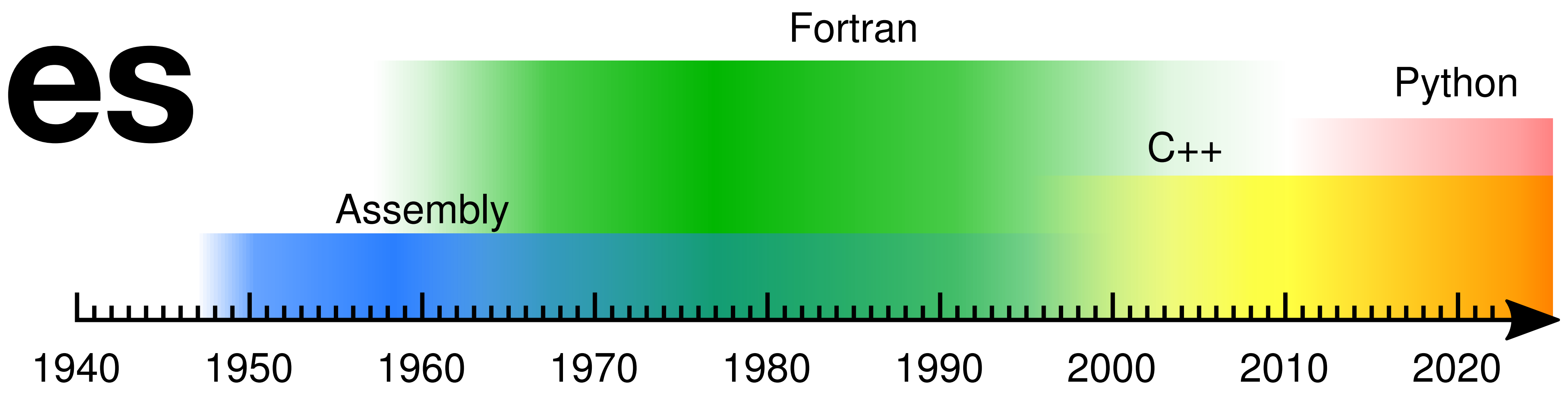
## The "two-language problem"

- Crafting **high-performant** code in the "**Python**" programming language is **demanding**
- It requires a **profound understanding** of
    - **computer architecture**
    - languages **interdependencies**
    - the art of **producing reusable code** libraries
- **Many** "solution **attempts**" exists to tackle the "**two-language problem**"
- The **maintenance overhead** rapidly escalates with each additional technology, which are mandatory
- **Python** is often merely **utilised as** the **high-level layer**, **restricting access to low-level** modifications
- **Loops in Python are a disaster** (as we all know), yet they remain a familiar paradigm for many programmers
- The solutions require to **make lots of compromises**

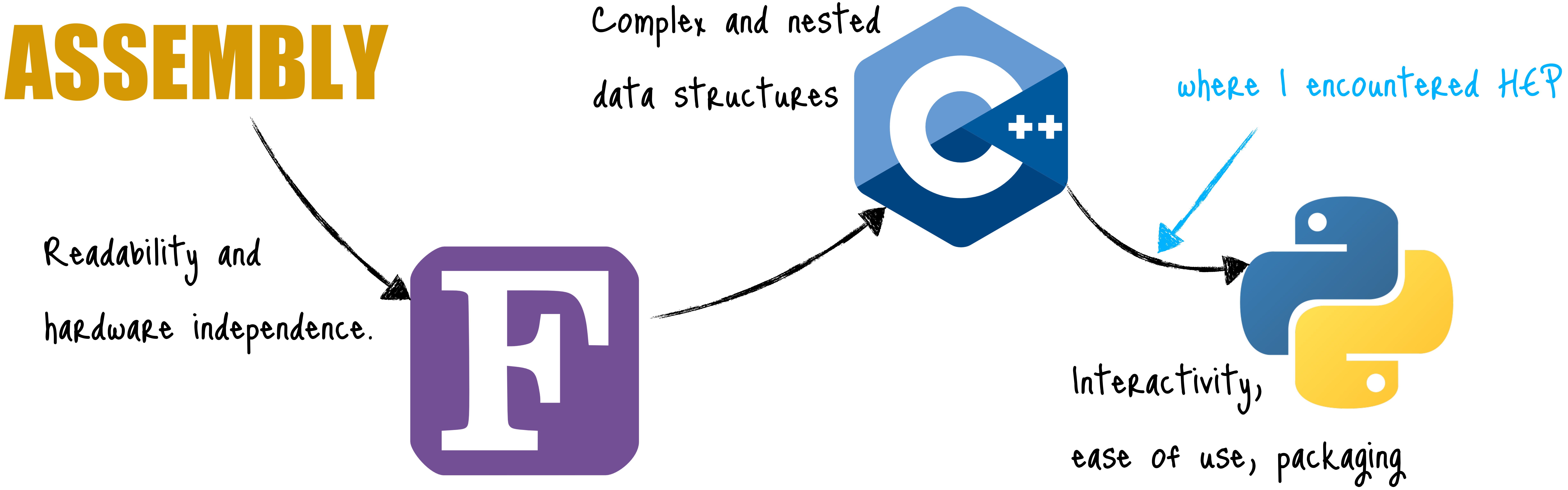
We need stuff like this to be able to enjoy Python's strengths...

# Reasons to switch languages

## A simplified storyline in HEP

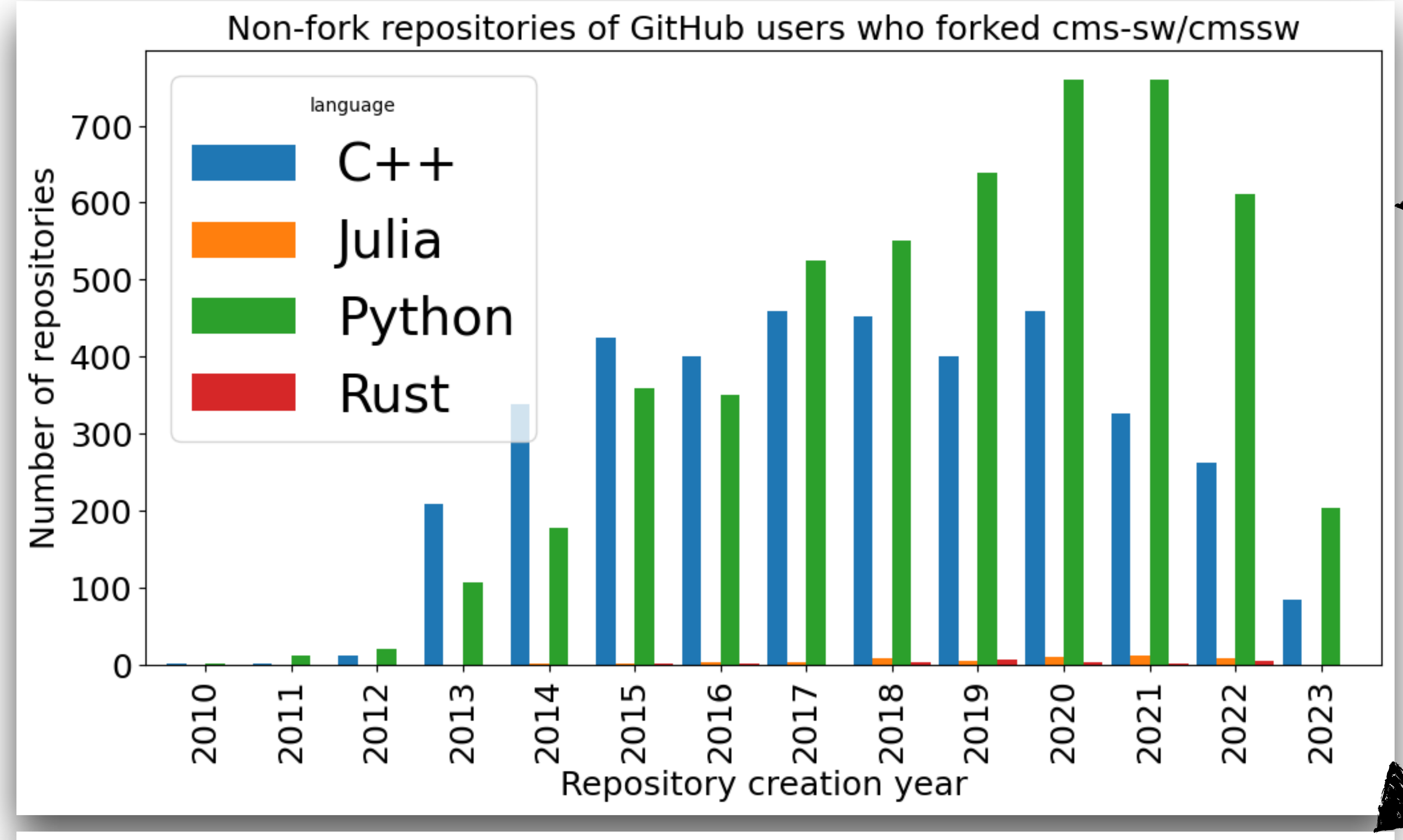



Taken from "Jagged, ragged, awkward arrays" by Jim Pivarski
(Strange Loop Conference 2019)

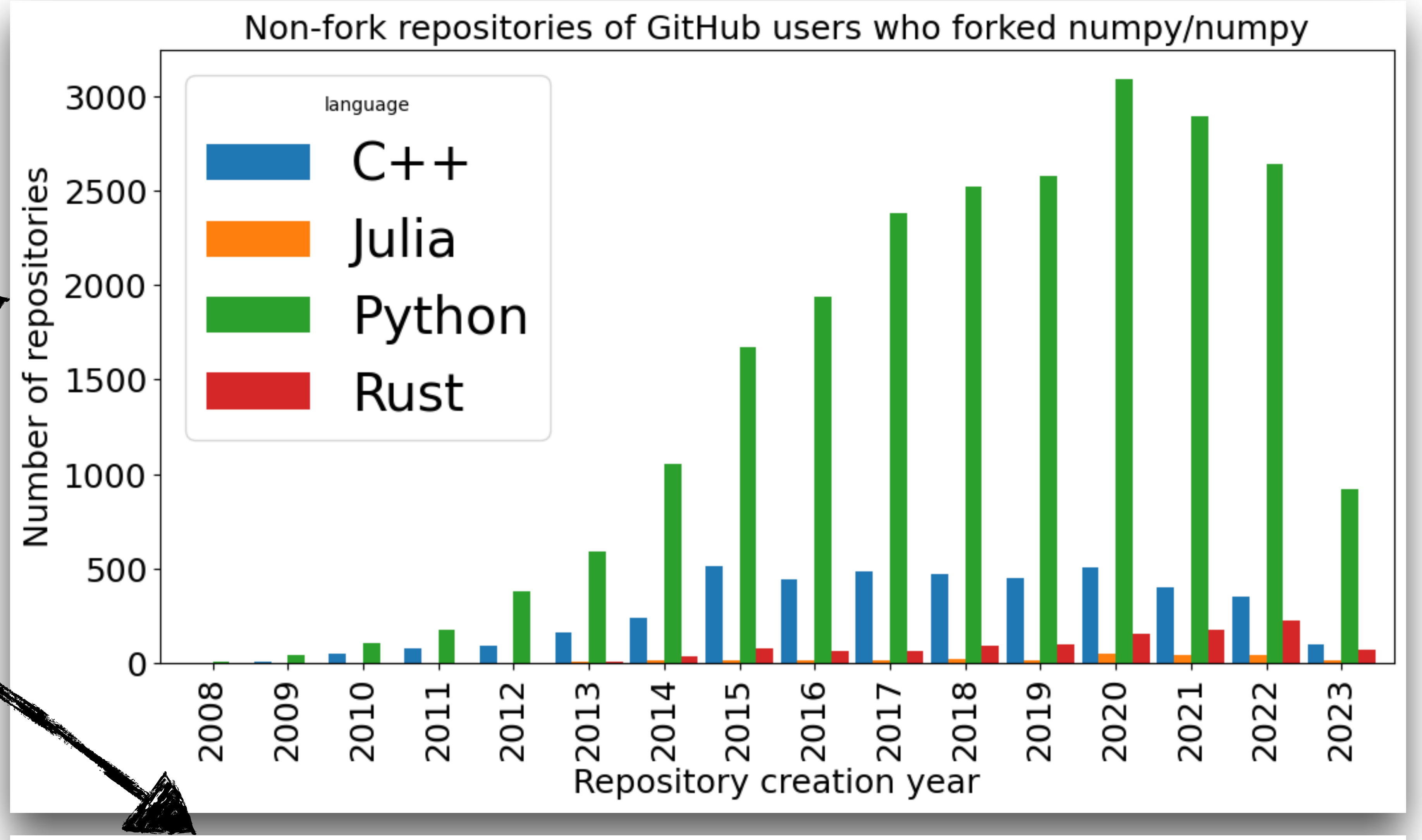


# Language usage development in the past 13 years

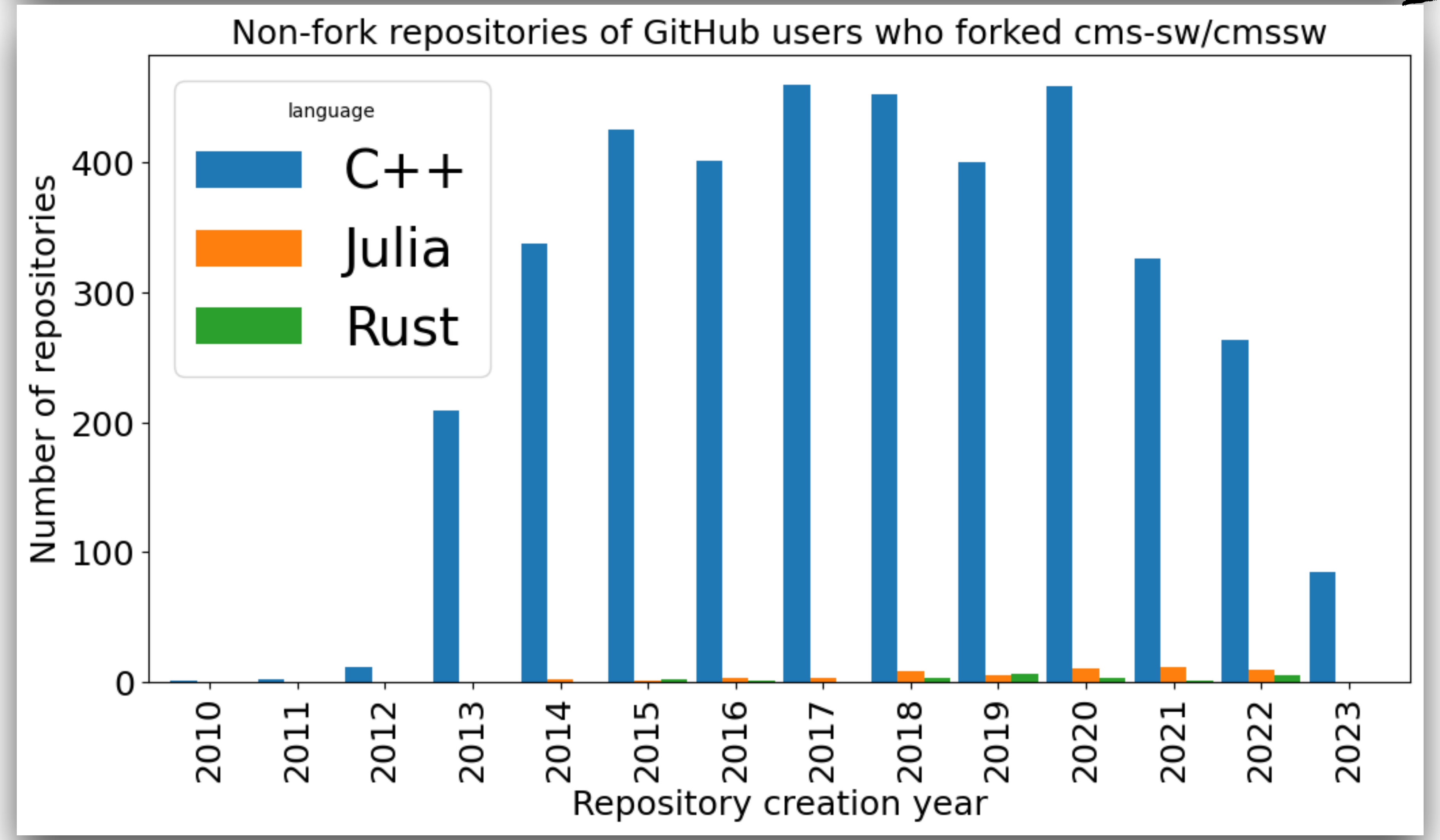
**Based on counting non-fork GitHub repositories created by people who forked a specific software.**



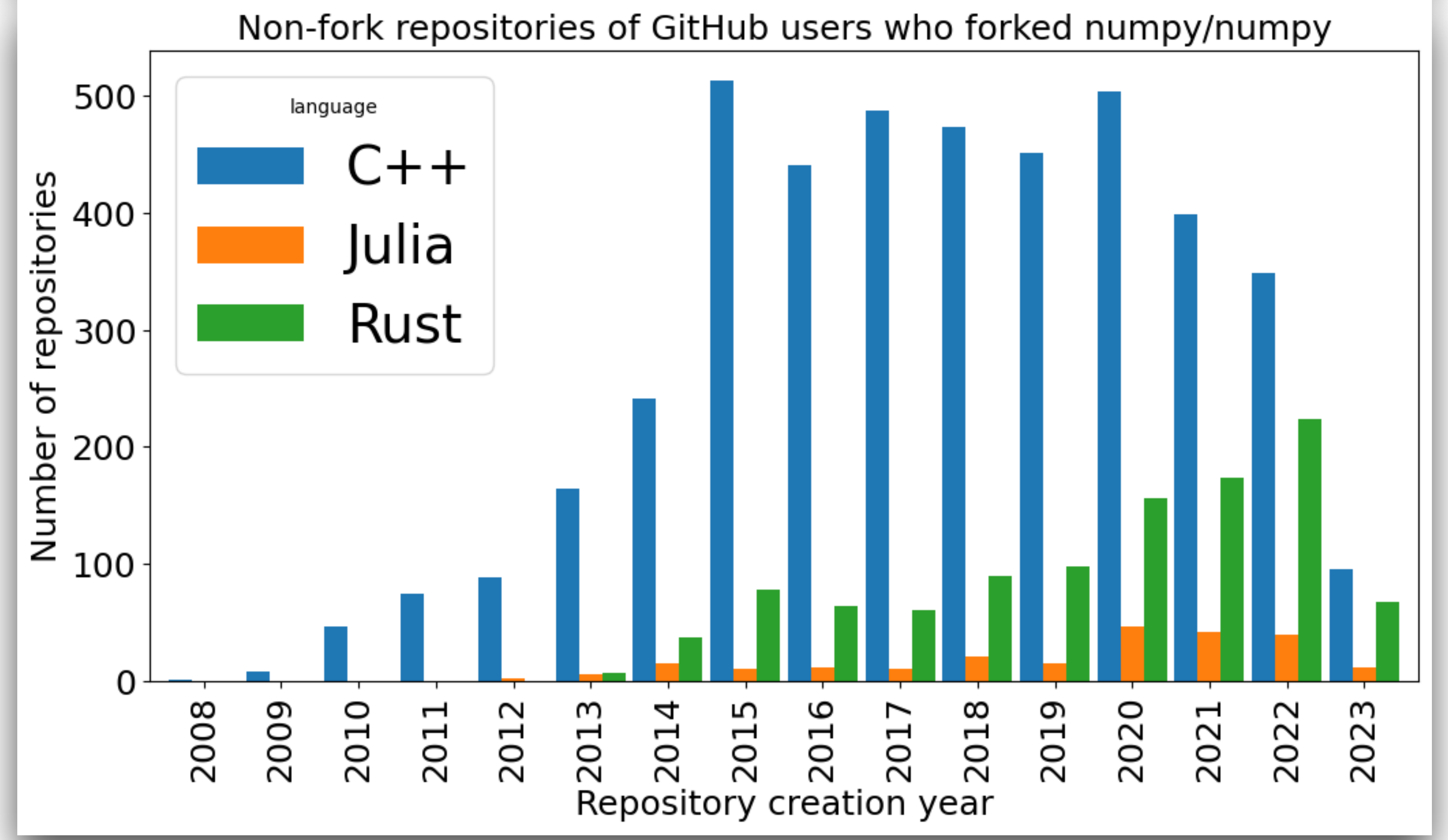

**cmssw** users ("**HEP**")




**numpy** users ("**data scientist**")




- **Python peaked** in **2020/2021**
- **Julia** is slowly emerging
- "**HEP**" seems to **follow the** "data scientist" **trend**
- **Turn-over** point of **Rust vs. C++** on the horizon for "data scientists"

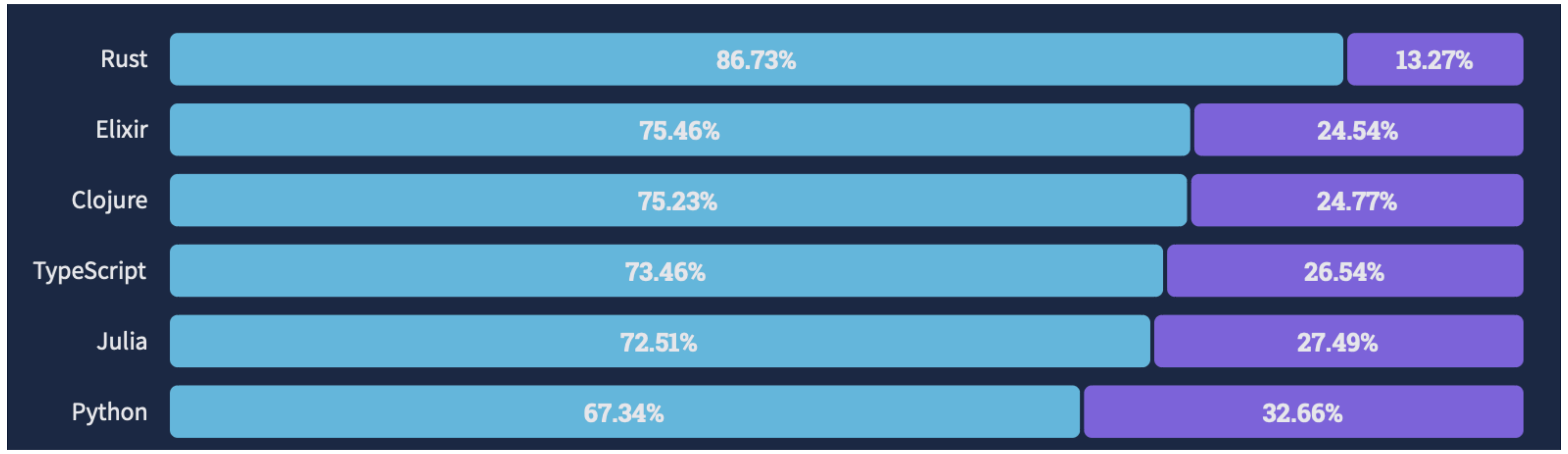


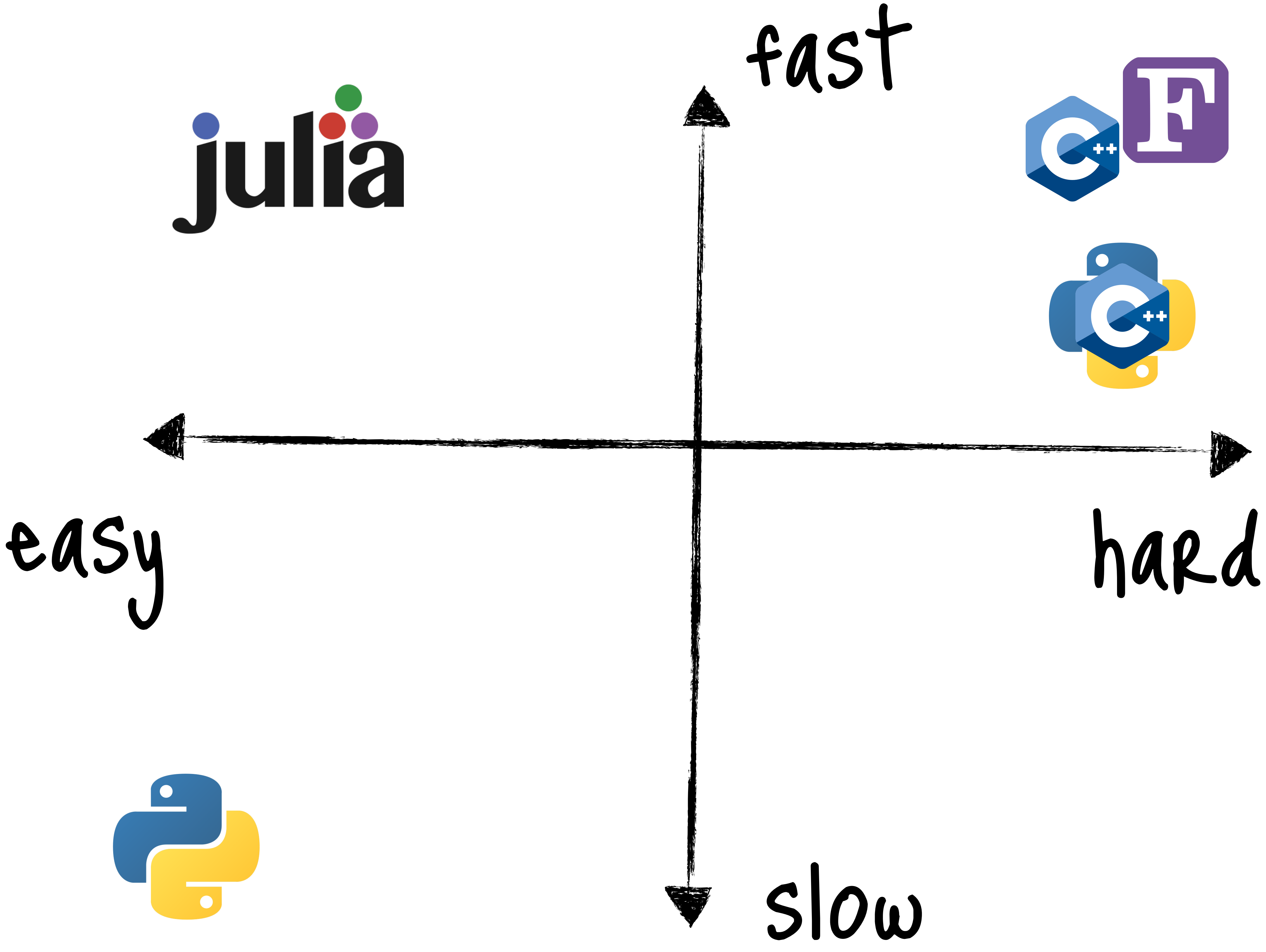
# Which language would we have picked in 2013 if we had to choose from today's programming languages?

We think **Julia** is a suitable candidate.

- **High-level** ("easy" and interactive) language without penalty on **performance**
- **Massive code reuse** and **sharing** due to the **multiple-dispatch** design
- **Interface with legacy code** written in different languages
- Well-designed **packaging/distribution system**
- **Parallel and distributed computing** are core features of Julia
- Ability to write **GPU kernels in native Julia**

Most loved languages (top 6 shown) https://survey.stackoverflow.co/2022

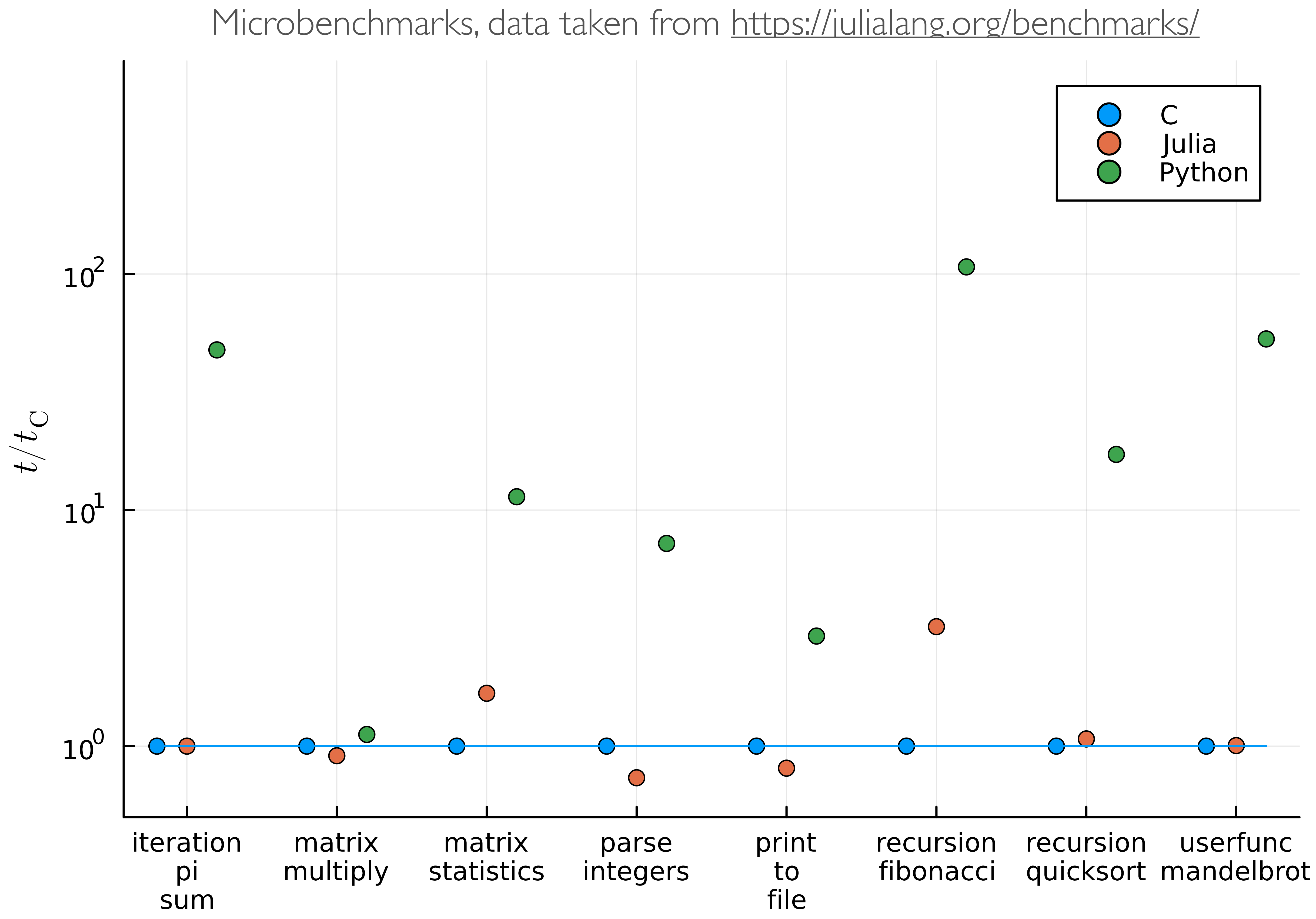


# Julia's native speed (compared to C and Python)

## Microbenchmarks

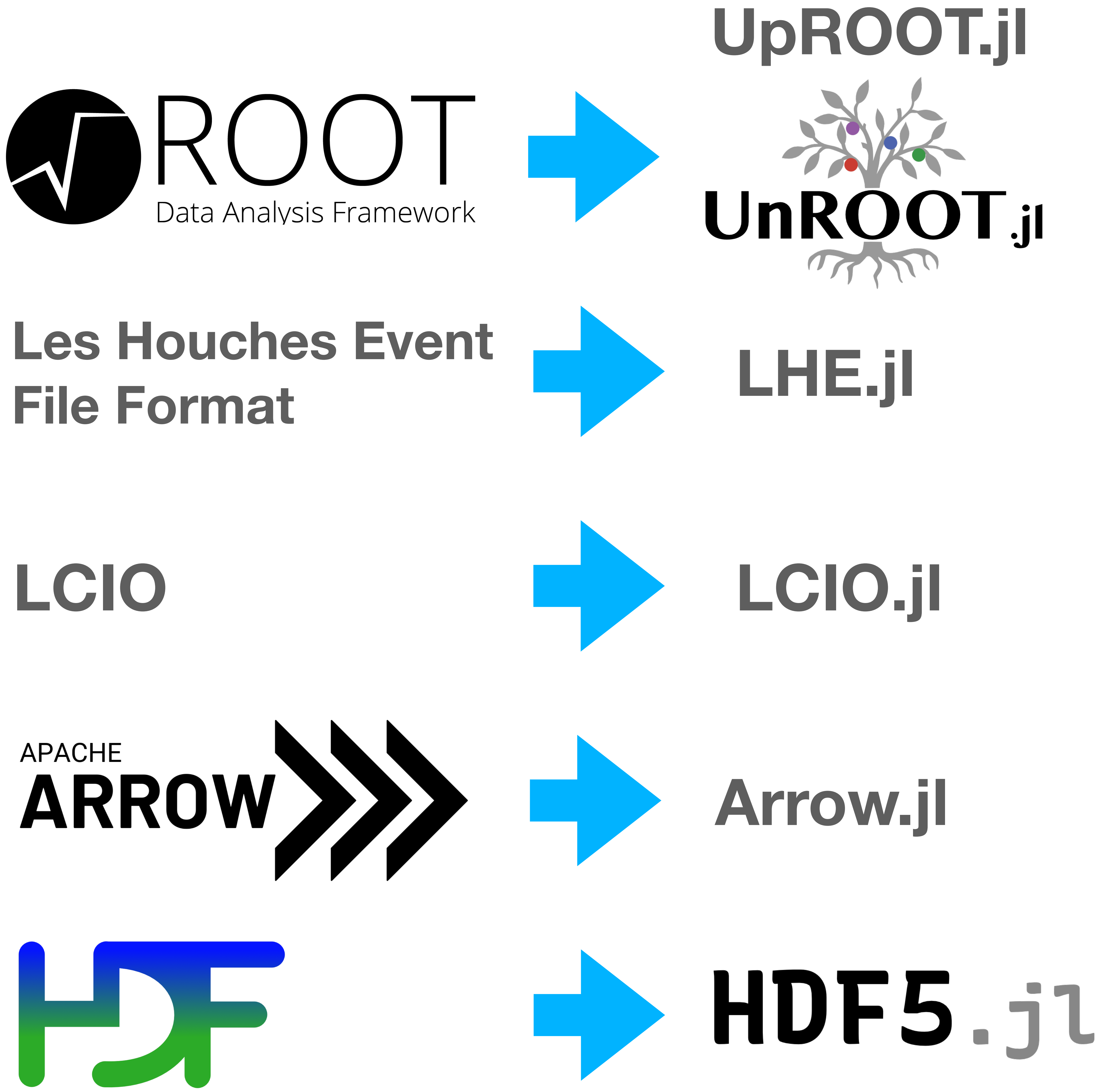
- Code "**naively**" **written in Julia** is often close to the peak performance
- It's a big deal since **physics students** do not have CS education and often **approach problems "naively"**
  - Such a code is (according to my experience) often **1-2 orders of magnitude slower** than it should be
  - **memory issues** all over the place (vectorised operations with unnecessary temporary allocations)
  - **bad scaling** due to "whole-meal" programming style
- "**Julia: A language that walks like Python, runs like C" --** K. S. Kuppusamy



# Accessing data formats used in HEP

## The entry point...

- Being able to **read** (write) data is **essential**
- The most **popular data formats** used in **HEP** are supported with **native Julia** packages*
- Additional formats can be introduced to HEP through Julia

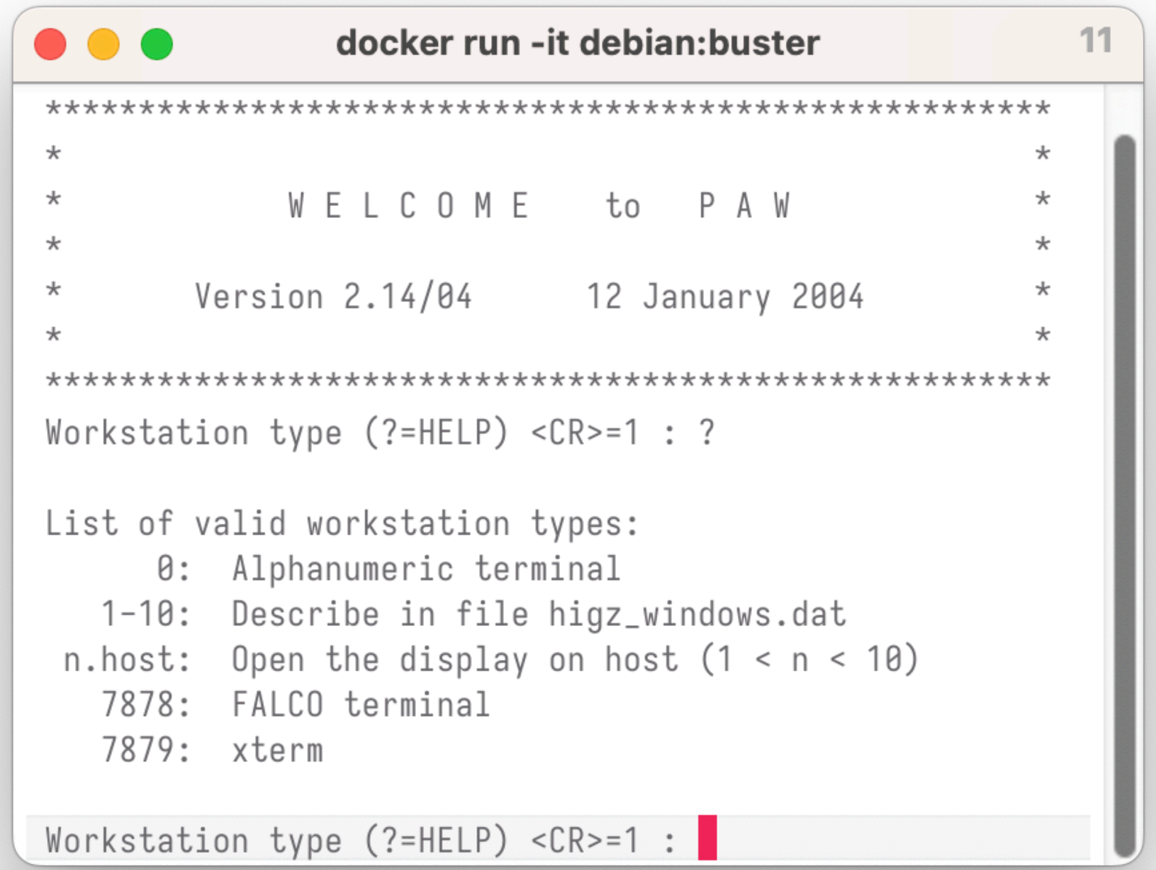


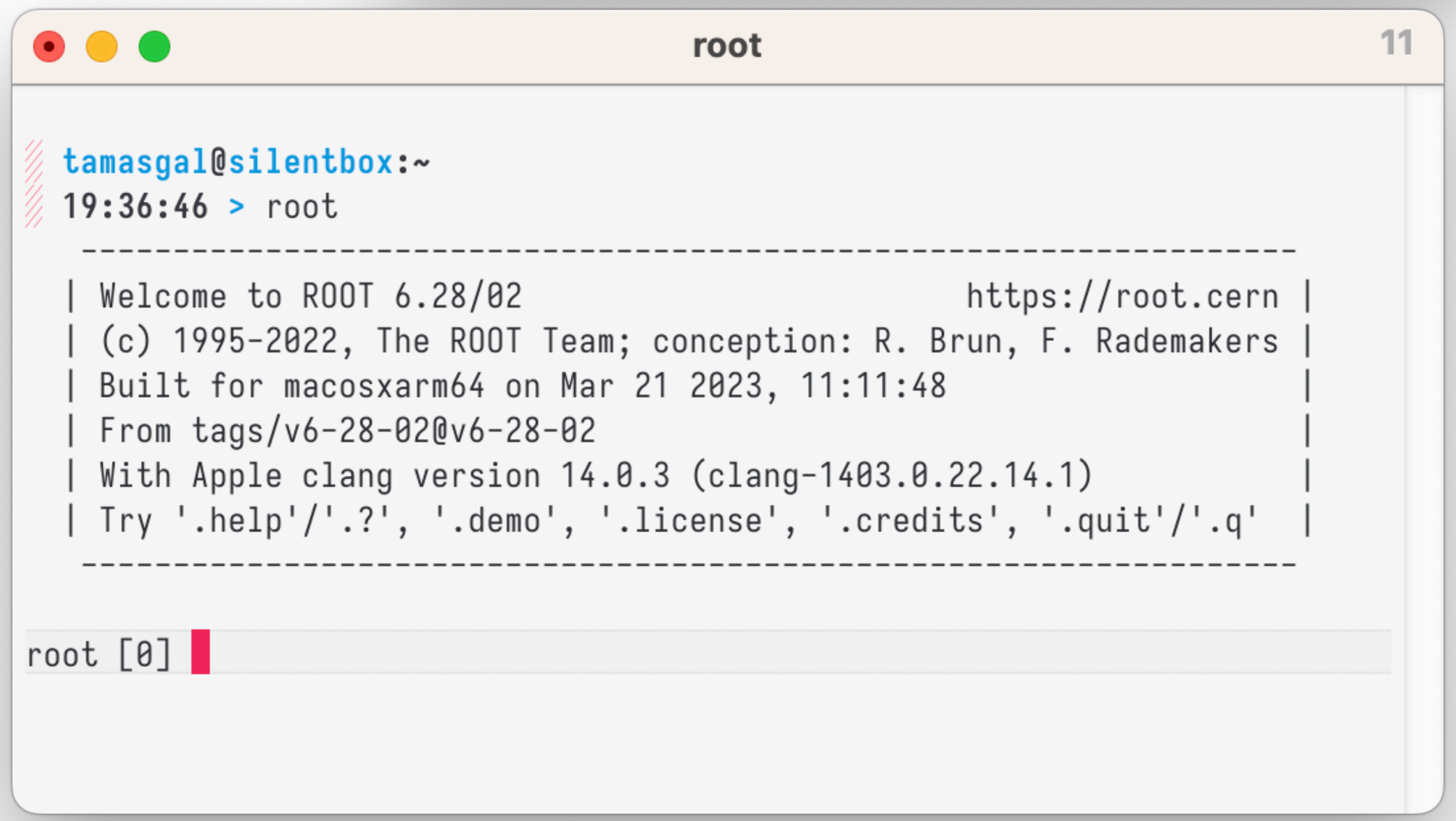

* reading of ROOT files has some limitations
writing ROOT relies on the Python package uproot

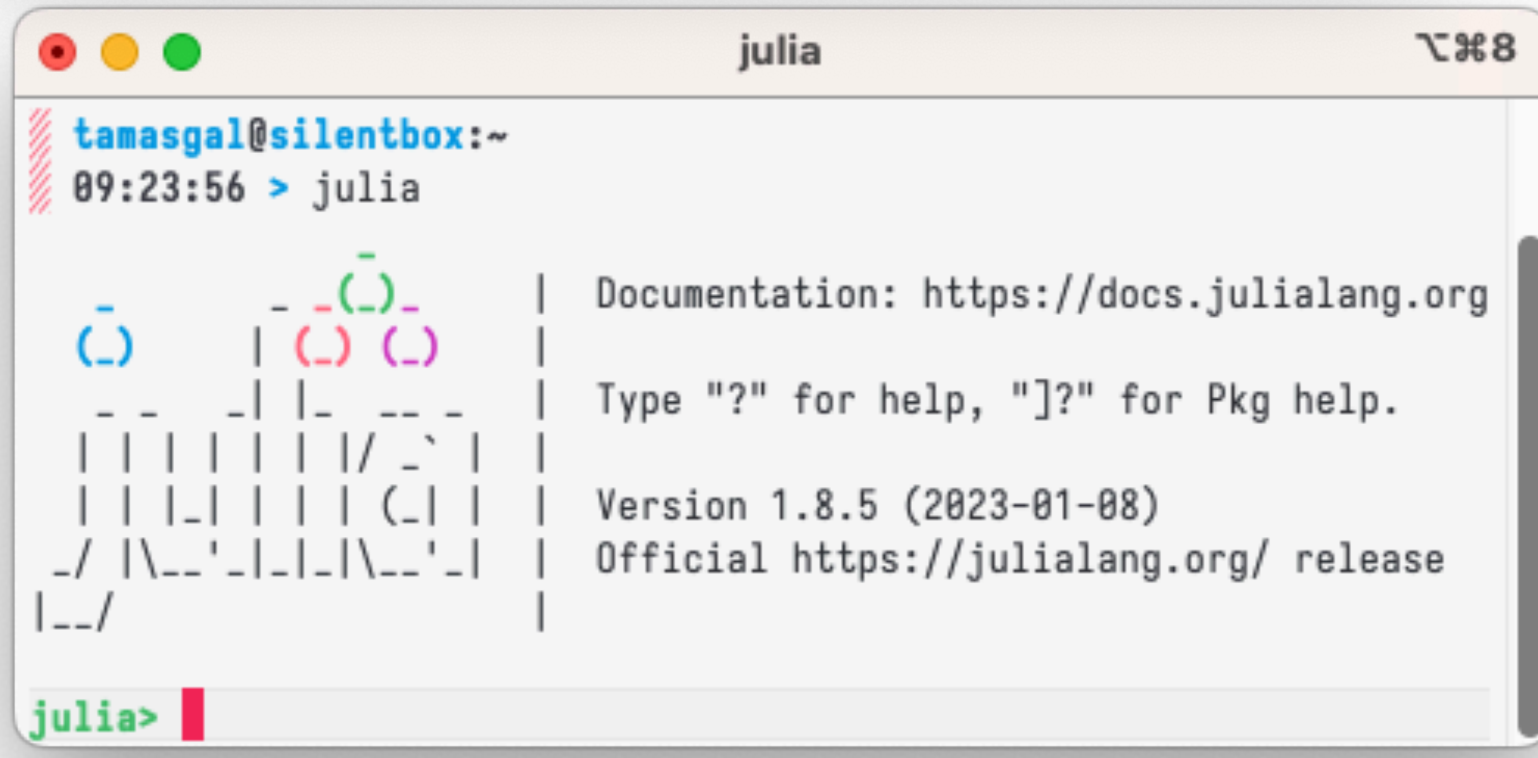
# High-level and interactive coding

## Without penalty on performance

- **Interactive scientific computing** for rapid prototyping has a **long history** in **HEP**, introduced by **PAW** (1986) at CERN and later in **ROOT** (**CINT** 1995, **Cling** 2013)
- **Python** among other languages **popularised the REPL** in other **scientific fields**
- **Julia offers** the **same interactivity** without penalty on **performance**
- **Type inference** allows **generic programming** and yet type safety and optimised machine code
- **Jupyter** notebook support (btw. **Ju** stands for **Julia**...)



# Code reusability and extensibility

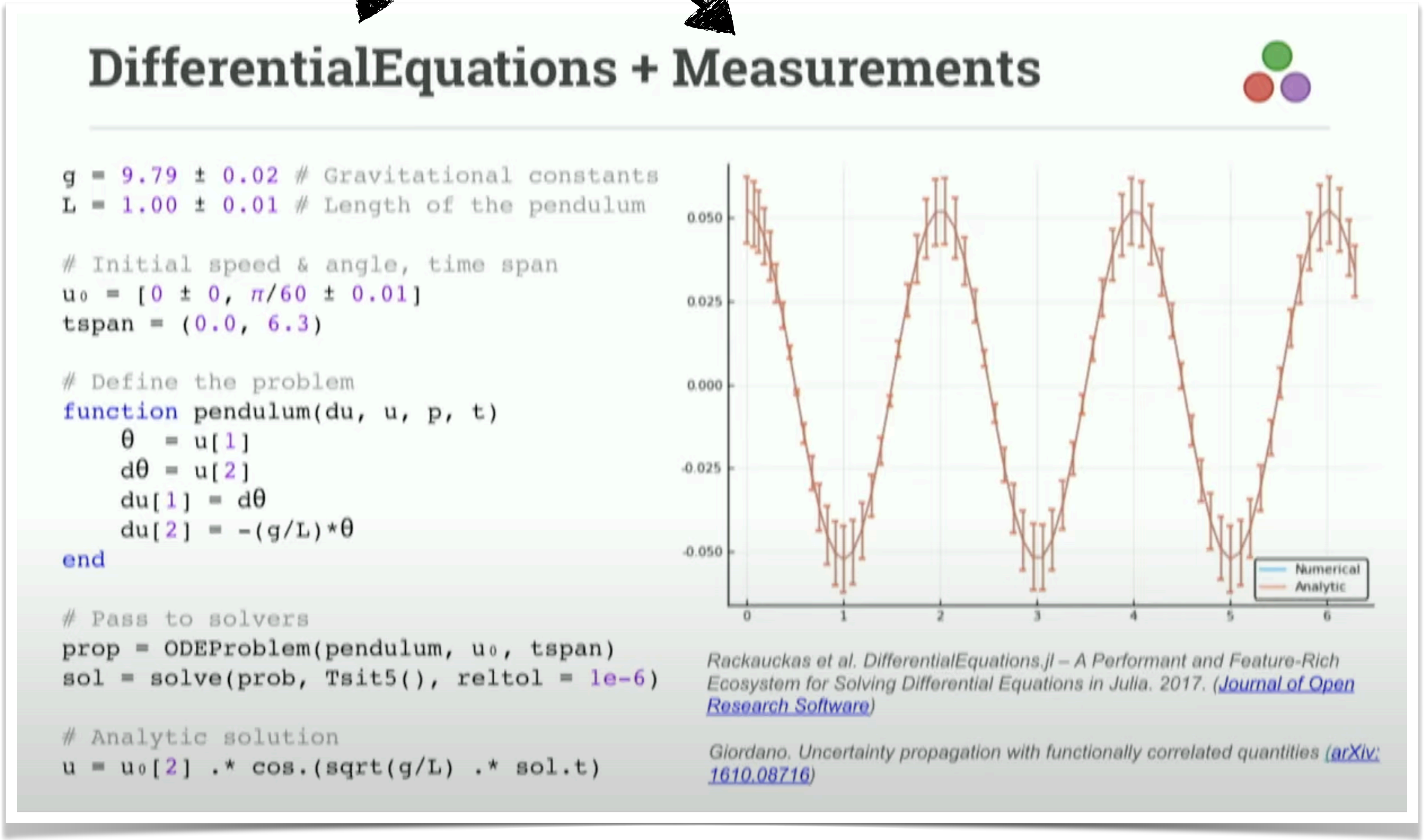
## "The Expression Problem"

- The ability to easily **define new types to which existing operations apply**
    - Easy in object-oriented languages / Hard in functional languages
- The ability to easily **define new operations which apply to existing types**
    - Easy in functional languages / Hard in object-oriented languages
- **Being able to do both easily is "The Expression Problem"**

An **elegant solution** is **multiple-dispatch** – the **main paradigm** of the **Julia language**

- **"Generic programming"** and **JIT type inference** allows **mixing code** from different Julia packages
- Add new methods to **existing generic functions** for **new types**
- Add new methods to **new generic functions** for **existing types**

These two packages don't know about each other!




JuliaCon 2019 I **The Unreasonable Effectiveness of Multiple Dispatch** I Stefan Karpinski
https://www.youtube.com/live/kc9HwsxE1OY

# Interfacing legacy code

- Many high-quality, **mature libraries** for numerical computing written in C and Fortran were developed and optimised over **the past decades**
- Julia supports **native call** (without any glue code) **into C and Fortran** libraries (via the built-in `ccall()` function)
- **C++** wrapping available via external packages like **CxxWrap.jl**
- **Zero-overhead Python** wrapping (**PyCall.jl**)
- An honorable mention for a **fully wrapped HEP** software
  - **Geant4.jl** (fully wrapped using CxxWrap.jl) Join the talk from Pere Mato on Thursday at 11:20: https://indico.cern.ch/event/1292759/contributions/5613048/
  - https://github.com/JuliaHEP/Geant4.jl

julia — 31×19

```
julia> using PyCall

julia> np = pyimport("numpy");

julia> np.random.rand(3) * 100
3-element Vector{Float64}:
 38.961726053176136
 71.3368957480925
  8.307181033489208

julia> np.sin(rand(5, 2))
5×2 Matrix{Float64}:
 0.784982   0.282252
 0.202079   0.220945
 0.637406   0.0921307
 0.0869371  0.395478
 0.383479   0.150941

julia>
```

GEANT4
A SIMULATION TOOLKIT

# Julia's packaging and distribution system

Reproducible environments, (private) package registries

- **Reproducible environments** with **exact versions** of all **dependencies** is a **built-in** feature in **Julia**
- **(Private) package registries** can be utilised to distribute unpublished packages, **seamless integration** into the package dependency solver
- **Distribution** of **pre-built binaries** of external dependencies (e.g. HDF5lib, libdeflate, ...) for a **large combinatorics of OS**, **architectures**, **compiler features**, etc.

# Julia's packaging and distribution system

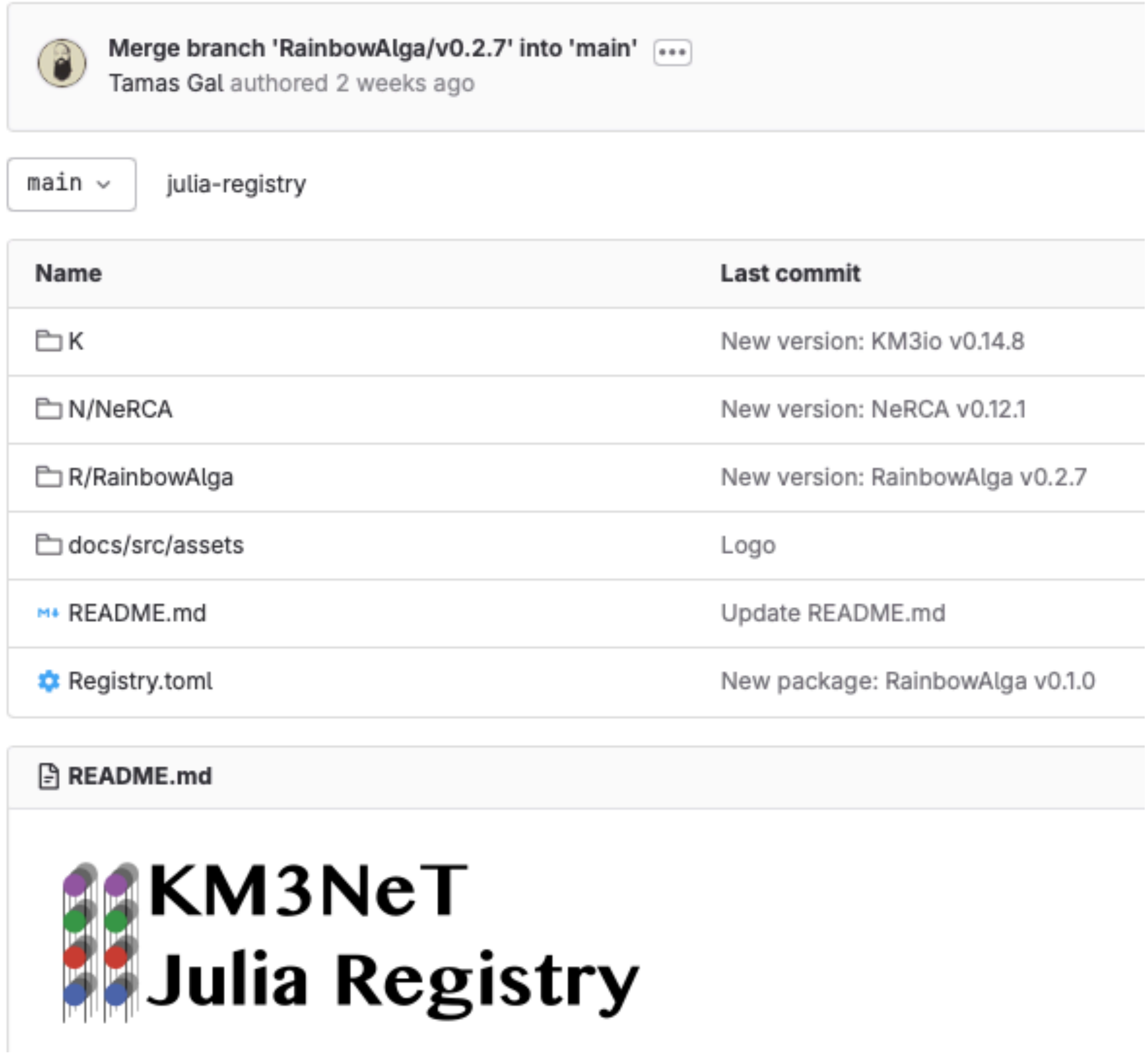
## **Reproducible environments**, (private) package registries

- There are two configuration files related to dependency managemen
- **Project.toml** defines the dependencies of a project/package including constraints on their versions
  - Sufficient for e.g. a software package or library which is meant to be combined with other software
  - The package manager (**Pkg.jl**) will use the information to determine the most suitable versions of all required dependencies
- **Manifest.toml** contains all the dependencies and their sub-dependencies  (including compiled non-julian binaries) with exact versions to be able to fully reproduce the environment
  - Mandatory for e.g. scientific analyses, to be able to reproduce their results

# Julia's packaging and distribution system

## Reproducible environments, **(private) package registries**

- An example of the public **KM3NeT Julia registry**
- **Multiple registries** can be active **at the same** time (similar to Python's pip, but based on meta-data and not the actual source distribution)
- **Dependencies** can spread over **multiple registries**
- **Private registries** work seamlessly with **SSH key authentication** in the background (**Git**-based, in contrast to pip's simplified webserver approach)



# Parallel, Distributed and GPU Computing

## "Built-in" or "built for" ; )

- Loops can **easily** be **parallelised** by adding a **keyword** (macro-/meta- programming)

- **Loop optimization** with processor-level parallelisation **(SIMD).** Can be **fine-tuned** with **third-party packages** like **LoopVectorization.jl.**
  **Related talk** at CHEP 2023 from **Graeme Stuart**
  https://indico.jlab.org/event/459/contributions/11540

- An impressive example from **KernelAbstractions.jl** which allows **Julia code** to be passed as a **kernel** function **to GPUs**:

- **Distributed** (built-in): execute code **asynchronously** in **multiple processes** and/or **multiple machines** (like MPI)

```
julia> for event ∈ mytree
           # process event
       end
```

```
julia> Threads.@threads for event ∈ mytree
           # process event
       end
```

```
julia> function dotbaseline(a::AbstractArray{T}, b::AbstractArray{T}) where {T}
           s = zero(T)
           @fastmath @inbounds @simd for i ∈ eachindex(a,b)
               s += a[i]' * b[i]
           end
           s
       end
```

```
@kernel function mul2_kernel(A)
  I = @index(Global)
  A[I] = 2 * A[I]
end
```

# Paper Published

- A paper on this topic has been published this year in the "**Computing and Software for Big Science**" Journal of Springer
- Eschle, J., Gál, T., Giordano, M. et al. **Potential of the Julia Programming Language for High Energy Physics Computing**. Comput Softw Big Sci 7, 10 (2023). https://doi.org/10.1007/s41781-023-00104-x

Computing and Software for Big Science (2023) 7:10
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RESEARCH

## Potential of the Julia Programming Language for High Energy Physics Computing

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**Abstract**
Research in high energy physics (HEP) requires huge amounts of computing and storage, putting strong constraints on the code speed and resource usage. To meet these requirements, a compiled high-performance language is typically used; while for physicists, who focus on the application when developing the code, better research productivity pleads for a high-level programming language. A popular approach consists of combining Python, used for the high-level interface, and C++, used for the computing intensive part of the code. A more convenient and efficient approach would be to use a language that provides both high-level programming and high-performance. The Julia programming language, developed at MIT especially to allow the use of a single language in research activities, has followed this path. In this paper the applicability of using the Julia language for HEP research is explored, covering the different aspects that are important for HEP code development: runtime performance, handling of large projects, interface with legacy code, distributed computing, training, and ease of programming. The study shows that the HEP community would benefit from a large scale adoption of this programming language. The HEP-specific foundation libraries that would need to be consolidated are identified.

**Keywords** Julia · HEP · Python · High energy and nuclear physics · Programming language · HPC

### Introduction

High throughput computing plays a major role in high energy physics (HEP) research. The field requires the development of sophisticated computing codes, which are continuously evolving in the course of the research work. Computing grids, connecting computer centers all around the world, are required to process the experiments' data [1]. Computer algebra systems and high performance computers are used to build new models and to calculate particle production cross sections.

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15 University of Oregon, Eugene, OR, USA

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# Summary

- We think that the **two-language problem needs** more attention and a **fundamentally different approach than** creating more and more **Python extensions and libraries**
- **Julia** is an **excellent language for scientific computing** with **high potential for HEP**
- **HEP specific needs** are very **well covered** by Julia
- **Code sharing** and **extending** foreign packages **are a no-brainer**, thanks to the package distribution system and the **multiple dispatch** design
- **Distributed and parallel computing** are first-class citizens in Julia
- Join the **JuliaHEP GitHub** organisation**:** https://github.com/JuliaHEP