Is Julia ready to be adopted by HEP?

26th International Conference on Computing in High Energy & Nuclear Physics (CHEP2023)

Tamas Gal – Erlangen Centre for Astroparticle Physics

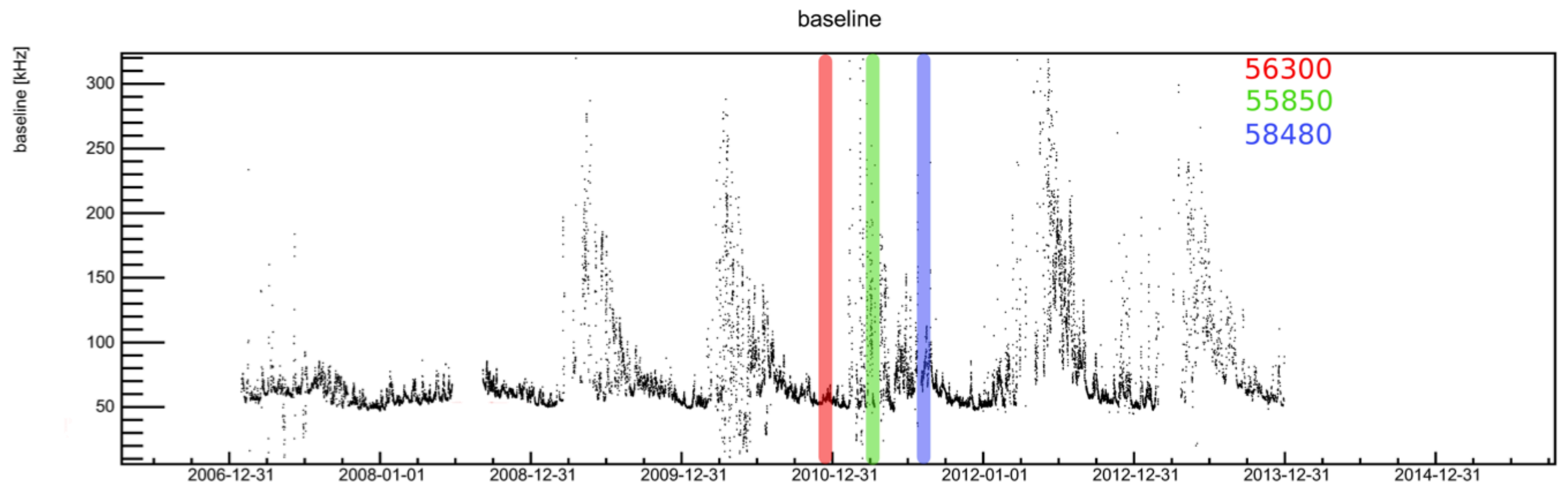
https://indico.jlab.org/event/459/contributions/11521/

Philippe Gras (IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France), **Pere Mato** (CERN, Switzerland), **Jerry Ling** (Harvard University), **Oliver Schulz** (TU Dormunt, Germany), **Uwe Hernandez Acosta** (CASUS, Görlitz, Germany), **Graeme A Stewart** (CERN, Switzerland)

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**
- 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**



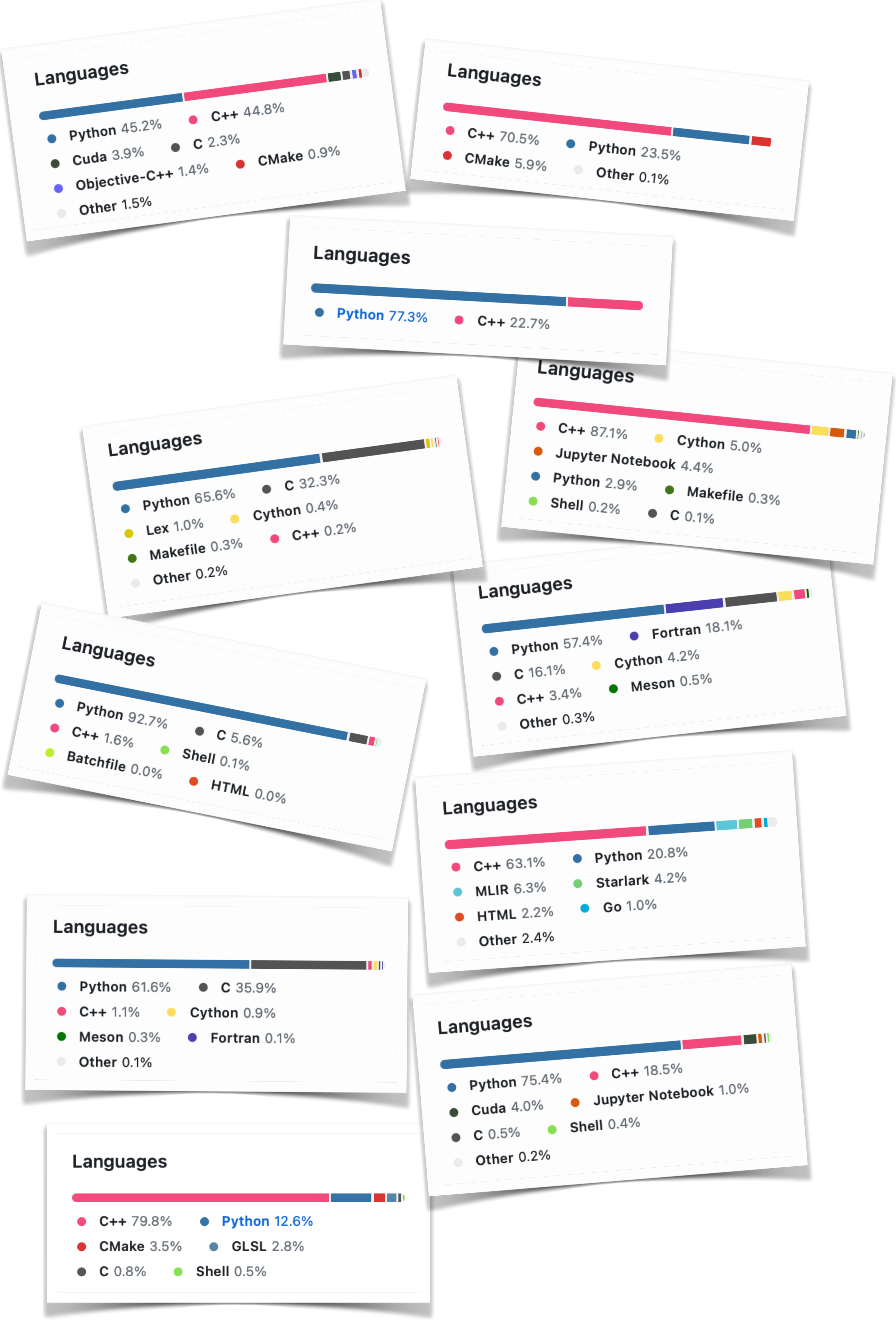
Source: "Untersuchung von Biolumineszenz im ANTARES Neutrinoteleskop", Maximilian Schandri

- **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 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"

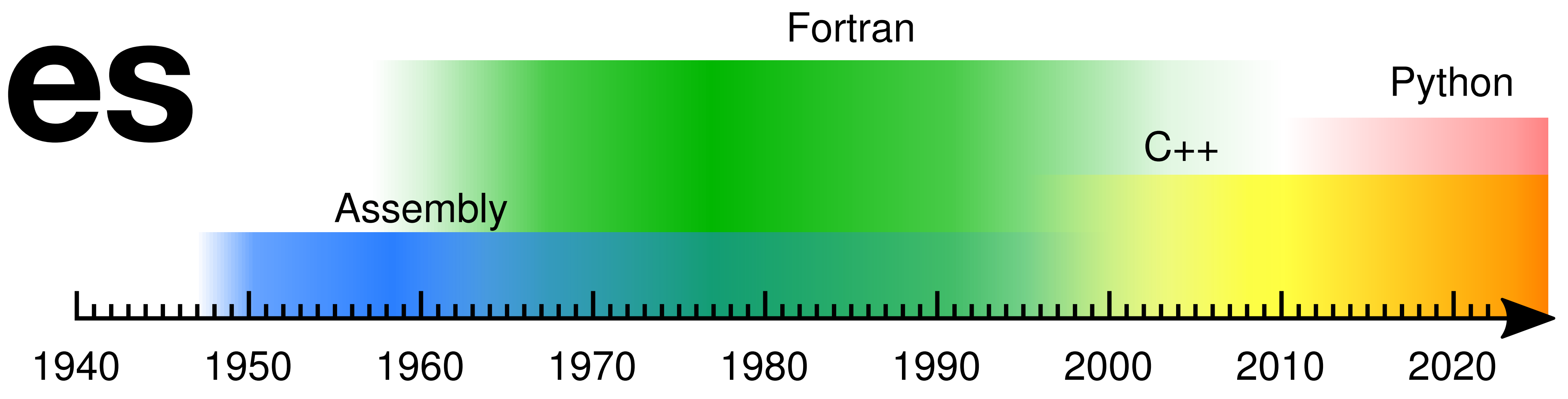
- Crafting **high-performant** code in the "**Python**" programming language is **demanding**
- It requires a **profound understanding** of
  - **computer architecture**
  - languages **interdependencies**
  - the art of **producing reusable code** libraries
- **Many** "solution **attempts**" exists 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...

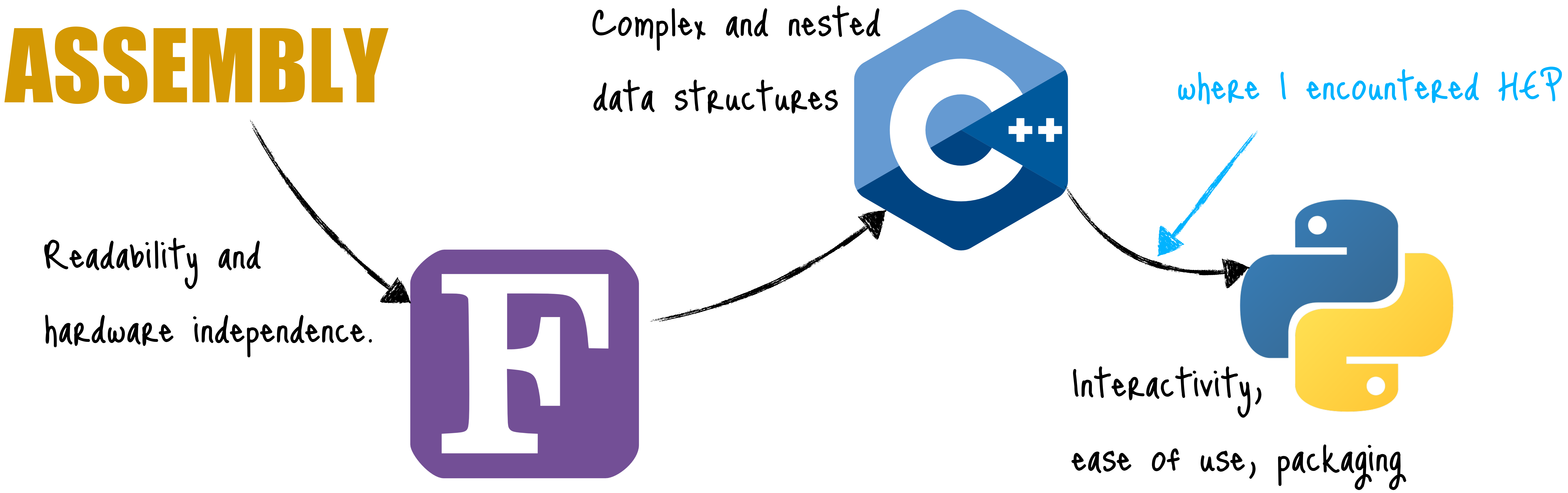
SWIG
theano
pybind11
Numba
Cython
NumPy
Boost.Python
pypy
cffi

Reasons to switch languages

A simplified storyline in HEP

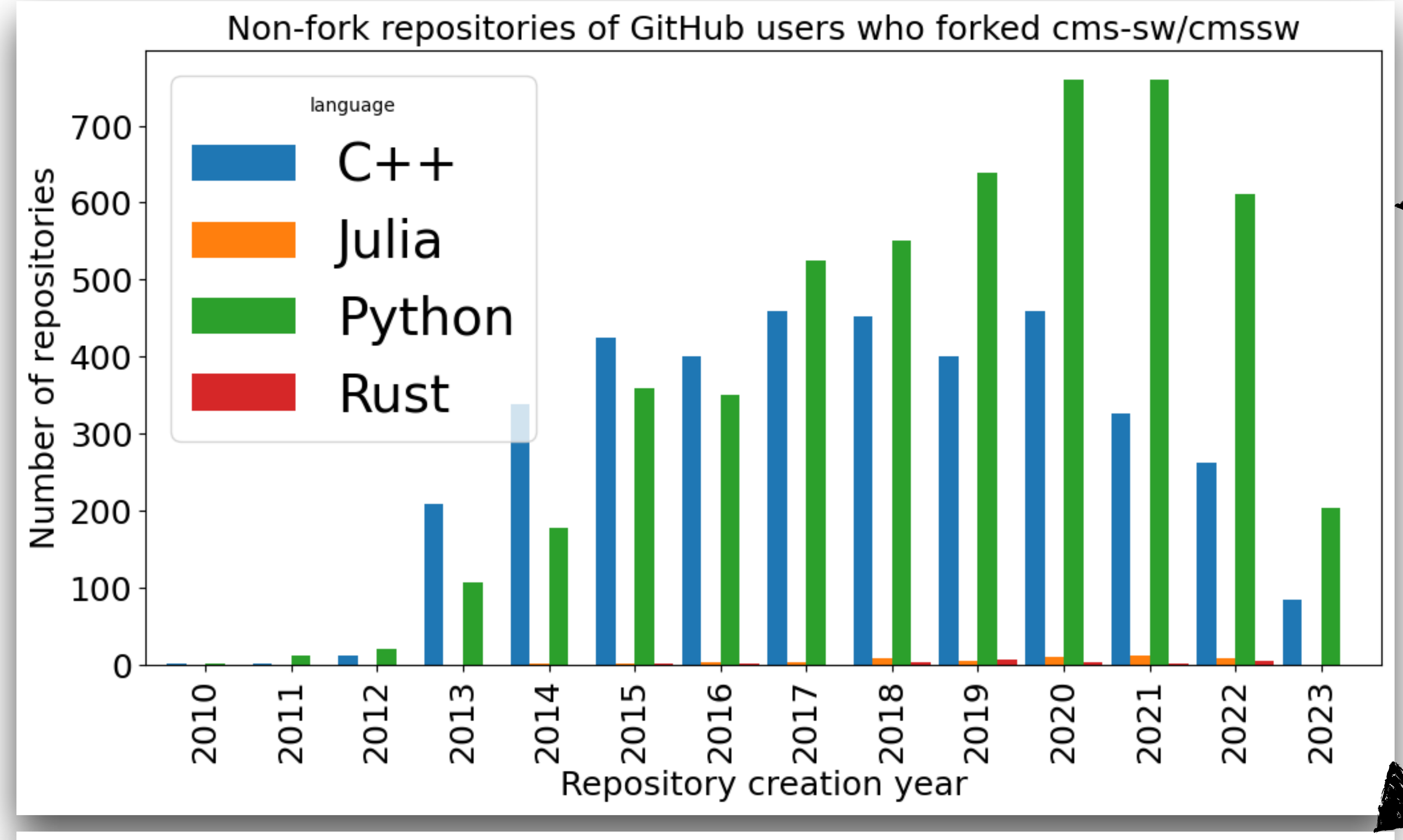


Taken from "Jagged, ragged, awkward arrays" by Jim Pivarski
(Strange Loop Conference 2019)

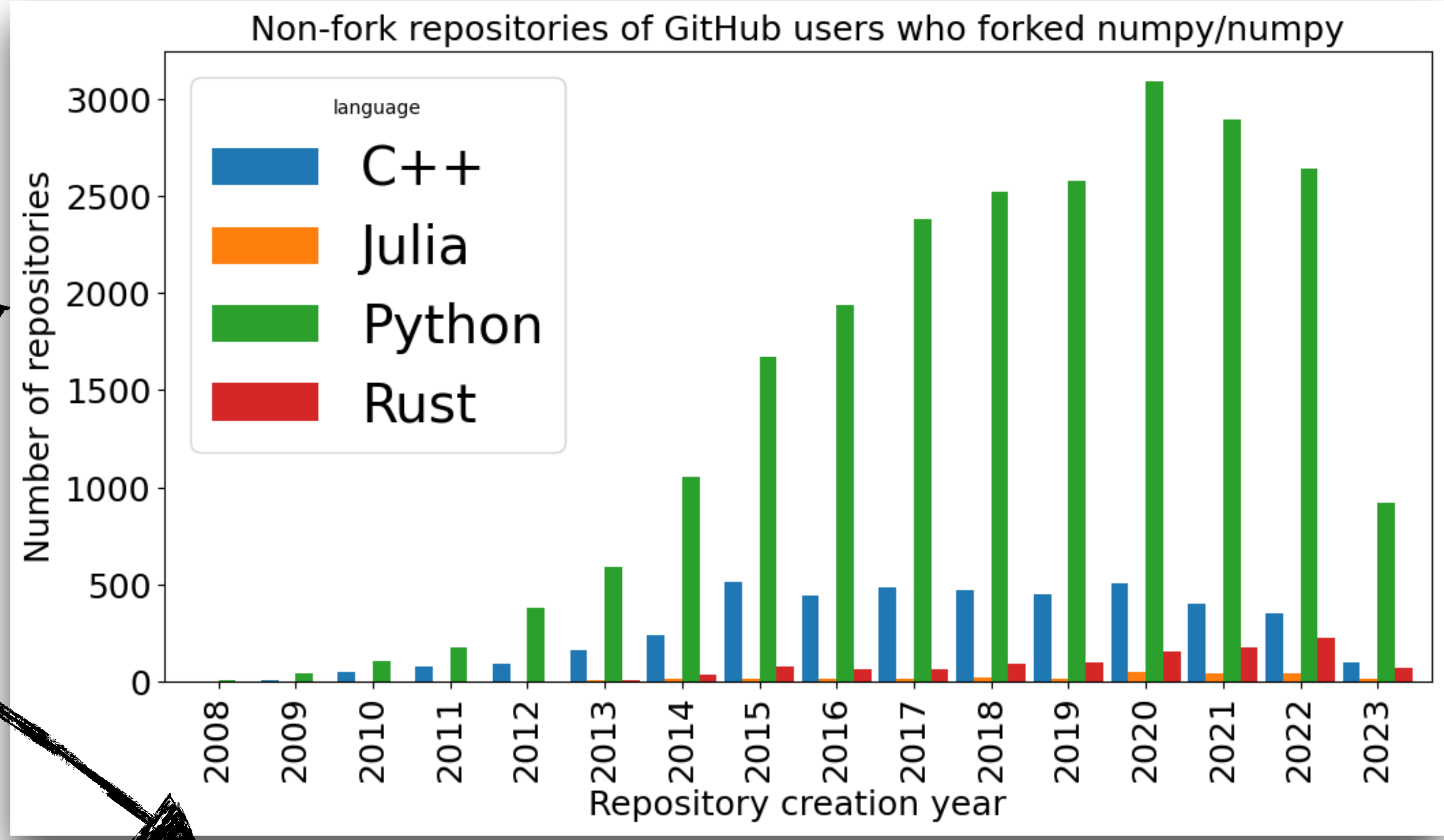


Language usage development in the past 13 years

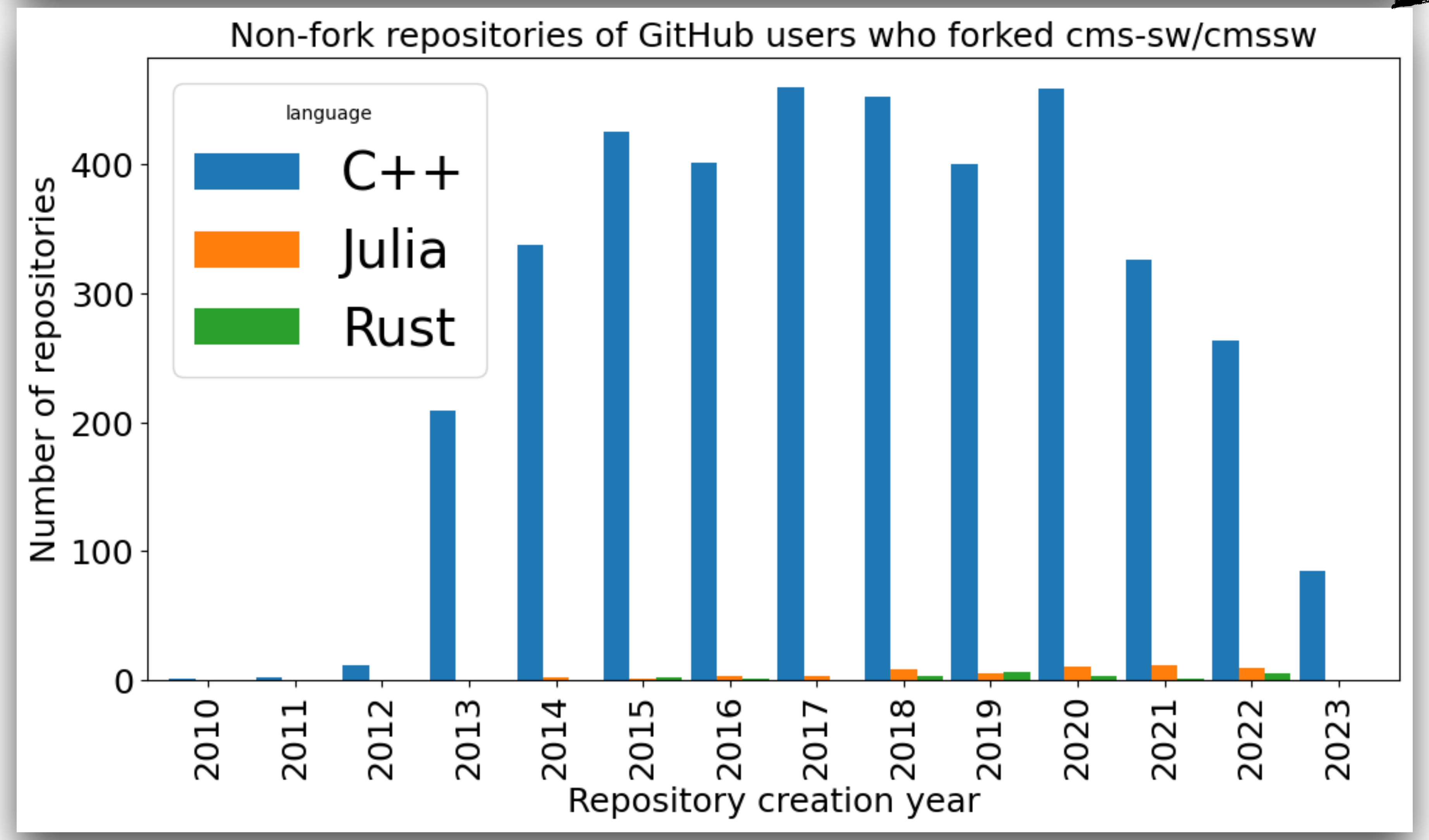
Based on counting non-fork GitHub repositories created by people who forked a specific software.



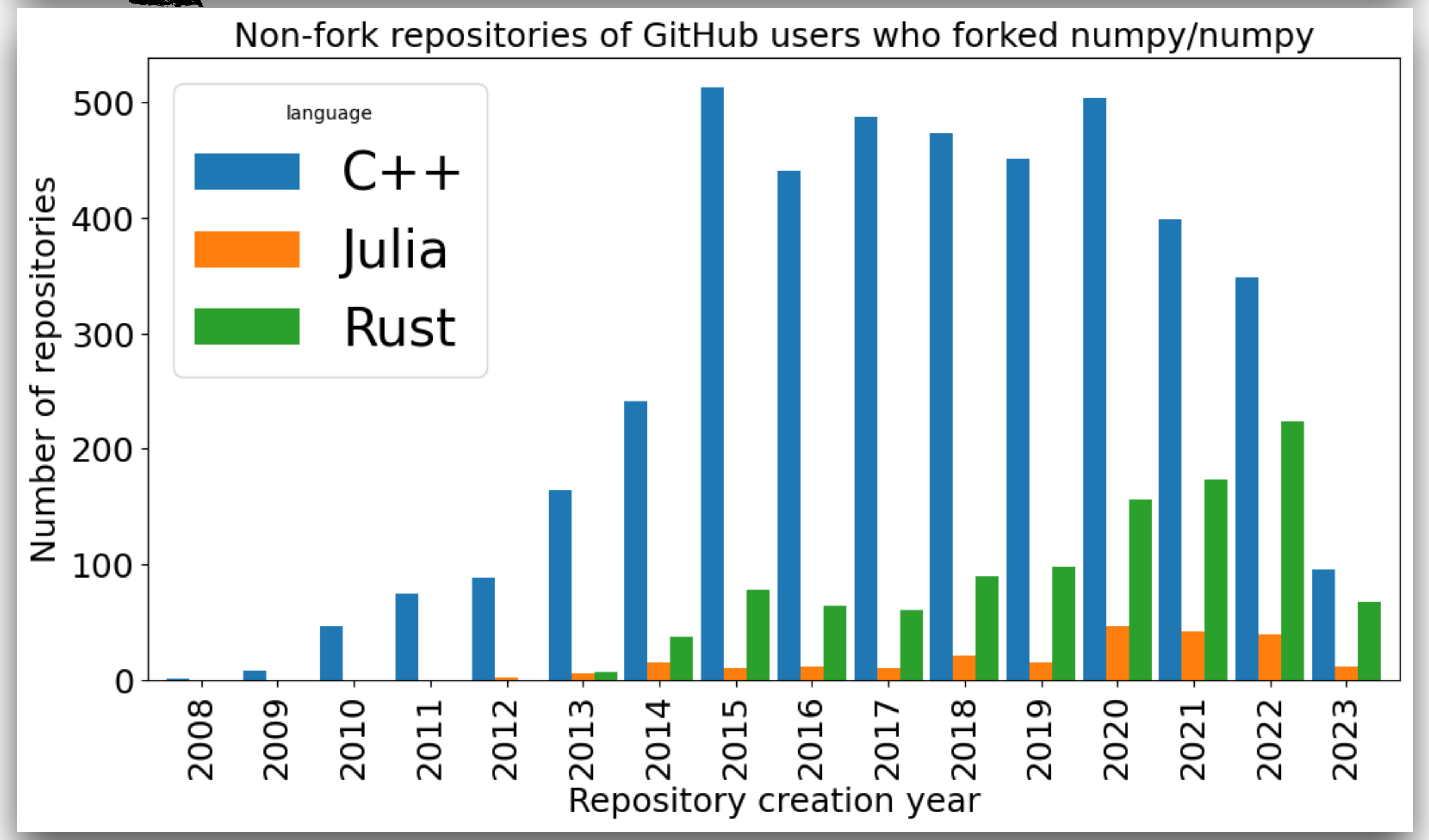
cmssw users
("**HEP**")



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"

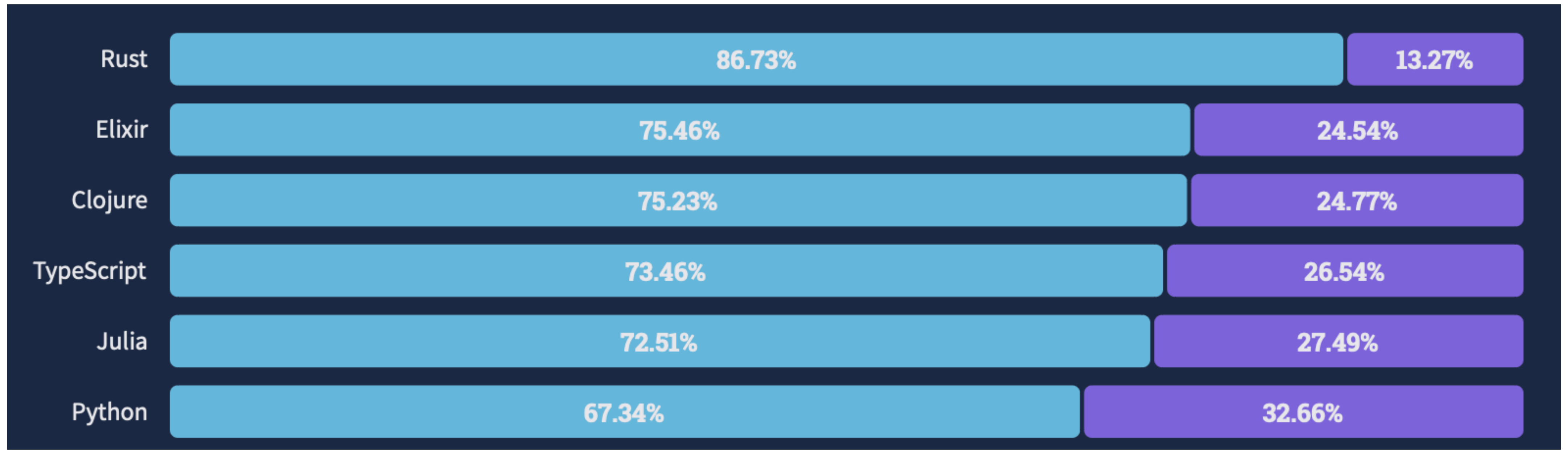


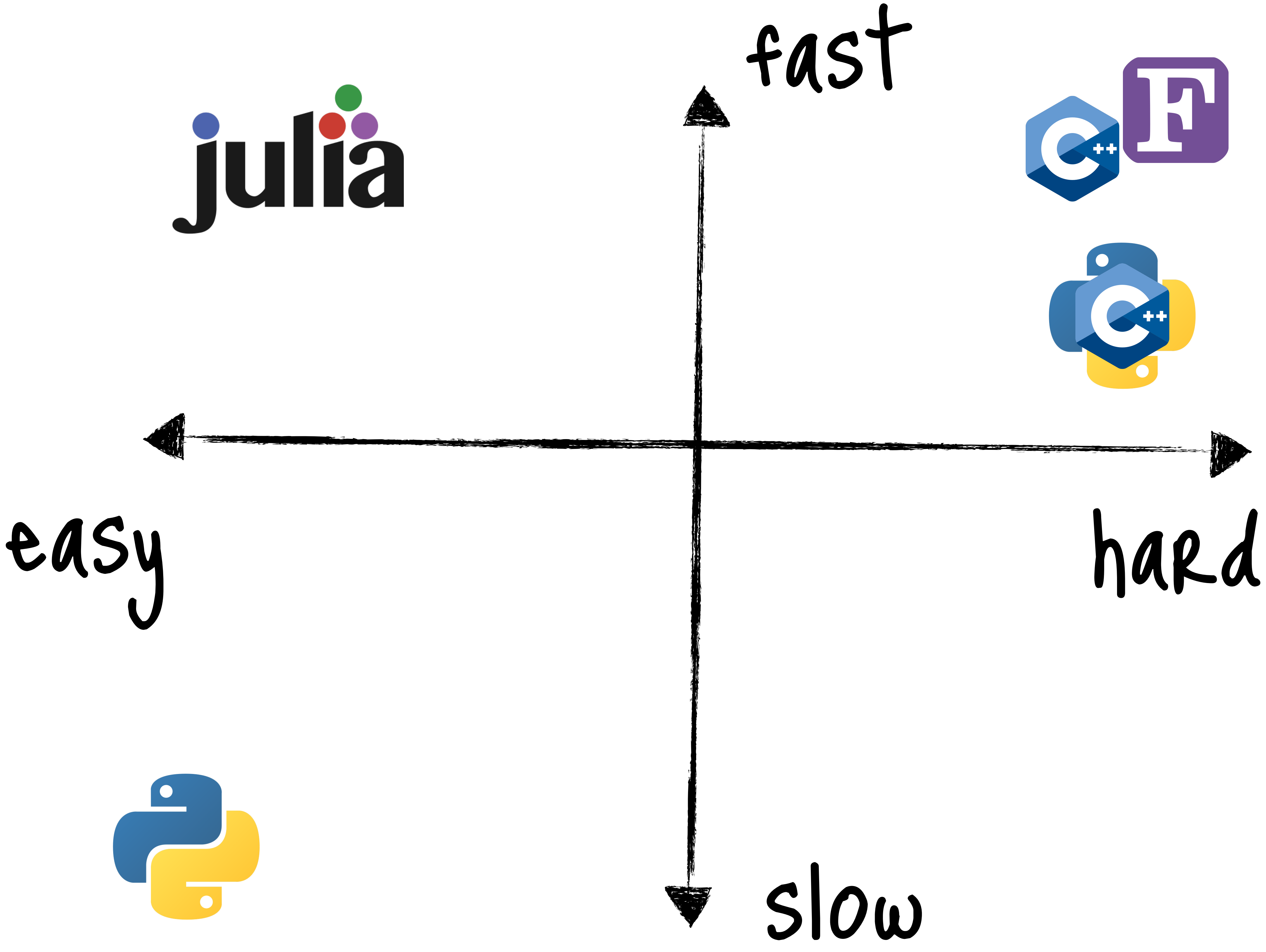
Which language would we have picked in 2013 if we had to choose from today's programming languages?

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

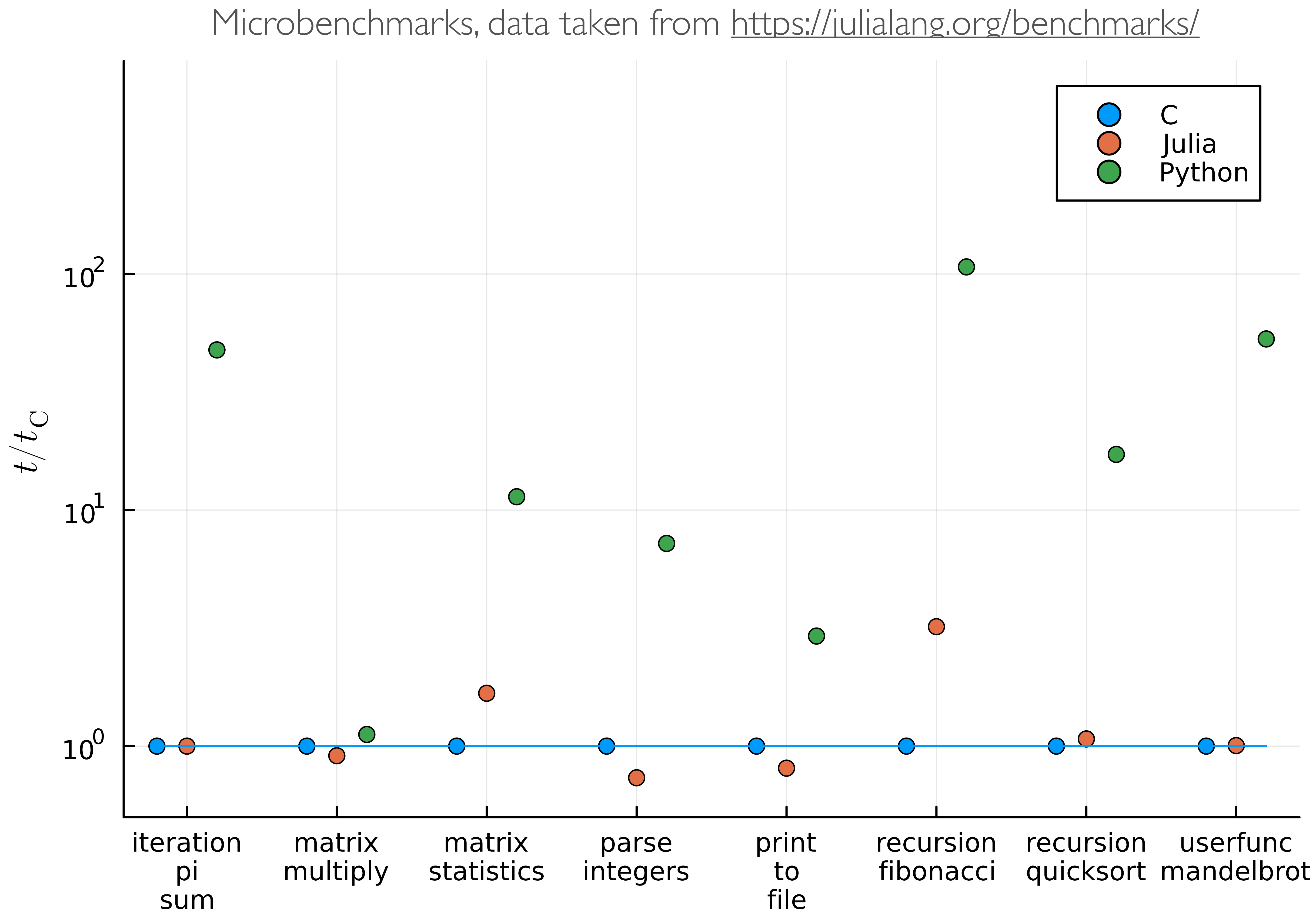




Julia's native speed (compared to C and Python)

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*
- Addition formats can be introduced to HEP through Julia

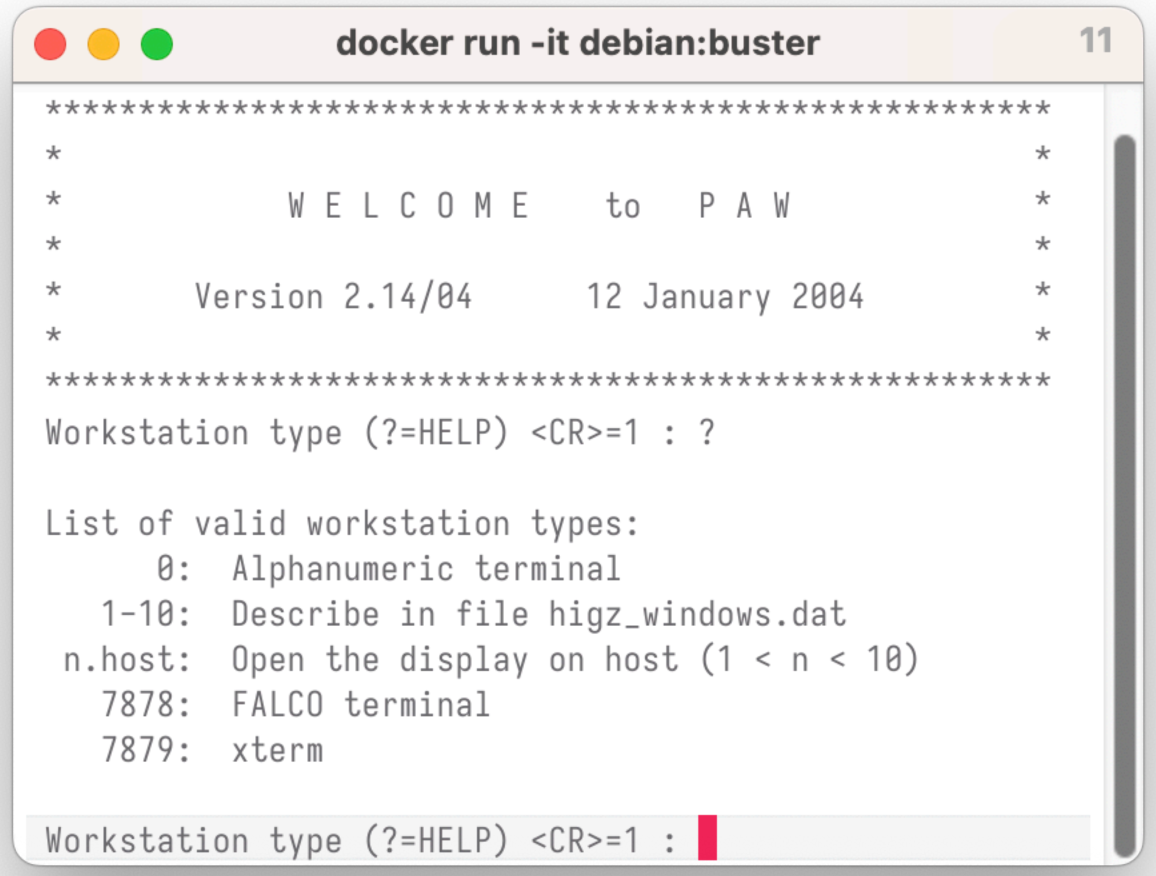
ROOT Data Analysis Framework	UpROOT.jl UnROOT.jl
Les Houches Event File Format	LHE.jl
LCIO	LCIO.jl
APACHE ARROW	Arrow.jl
HDF	HDF5.jl

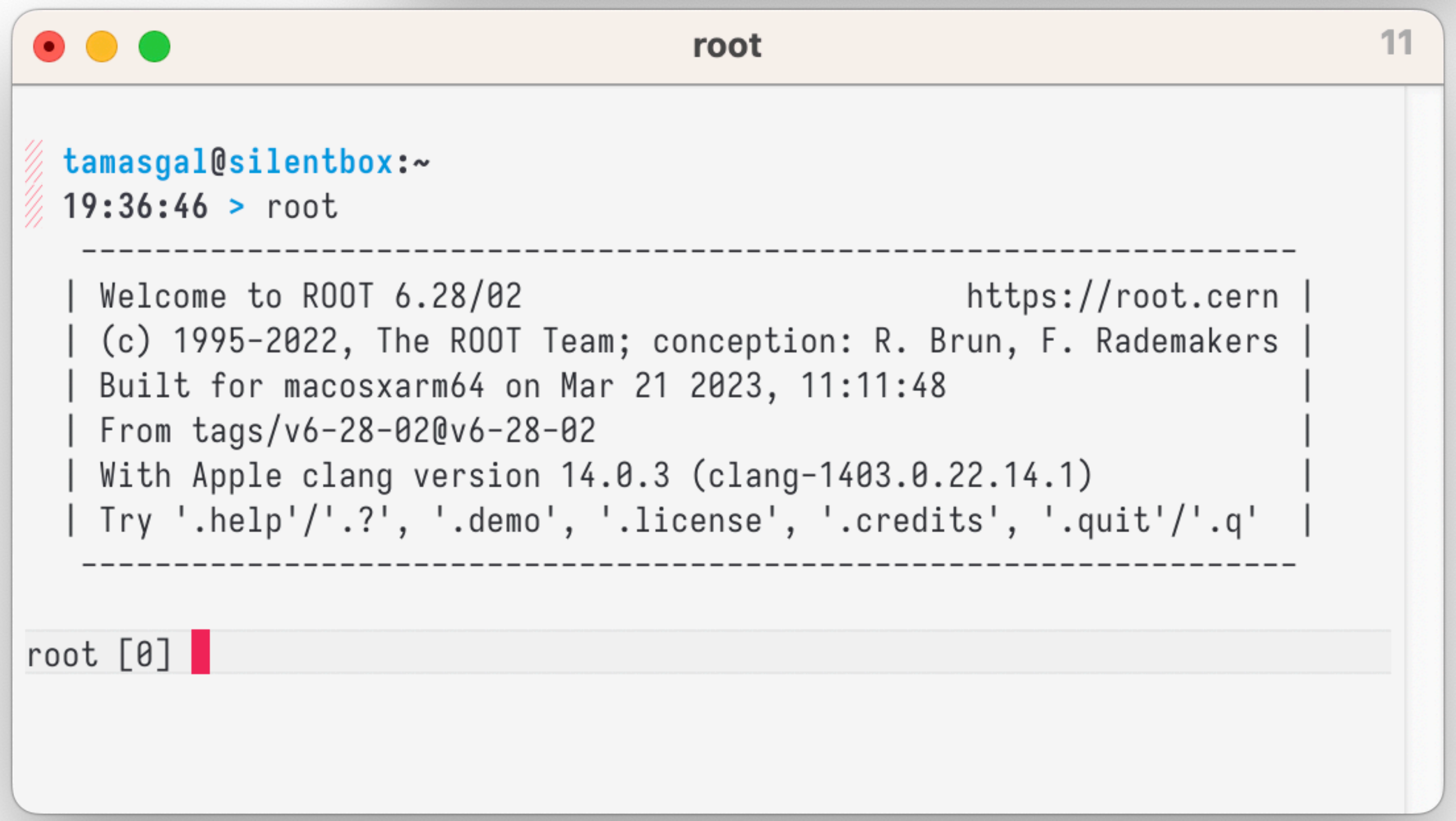
* reading of ROOT files has some limitations
writing ROOT relies on the Python package uproot

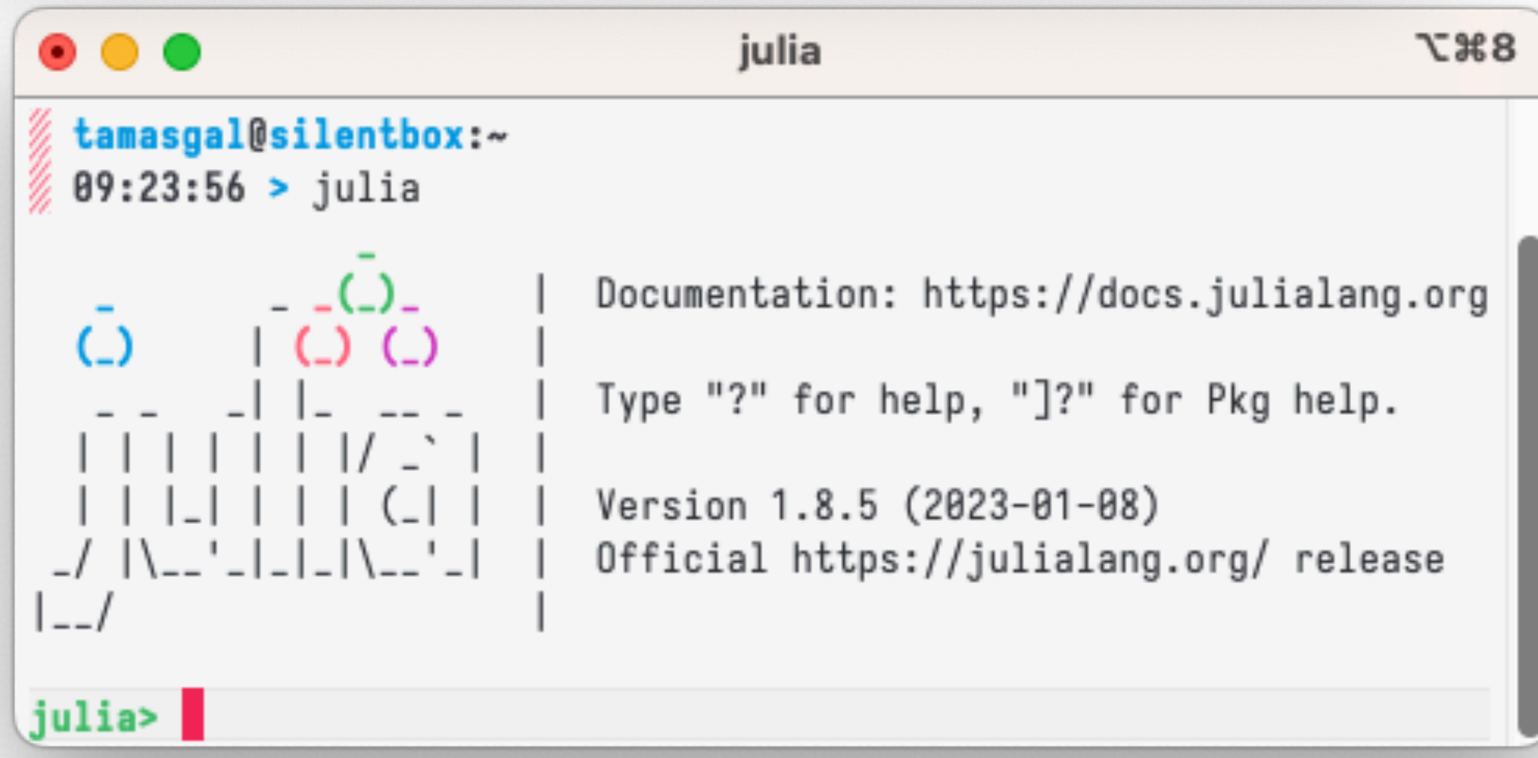
High-level and interactive coding

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

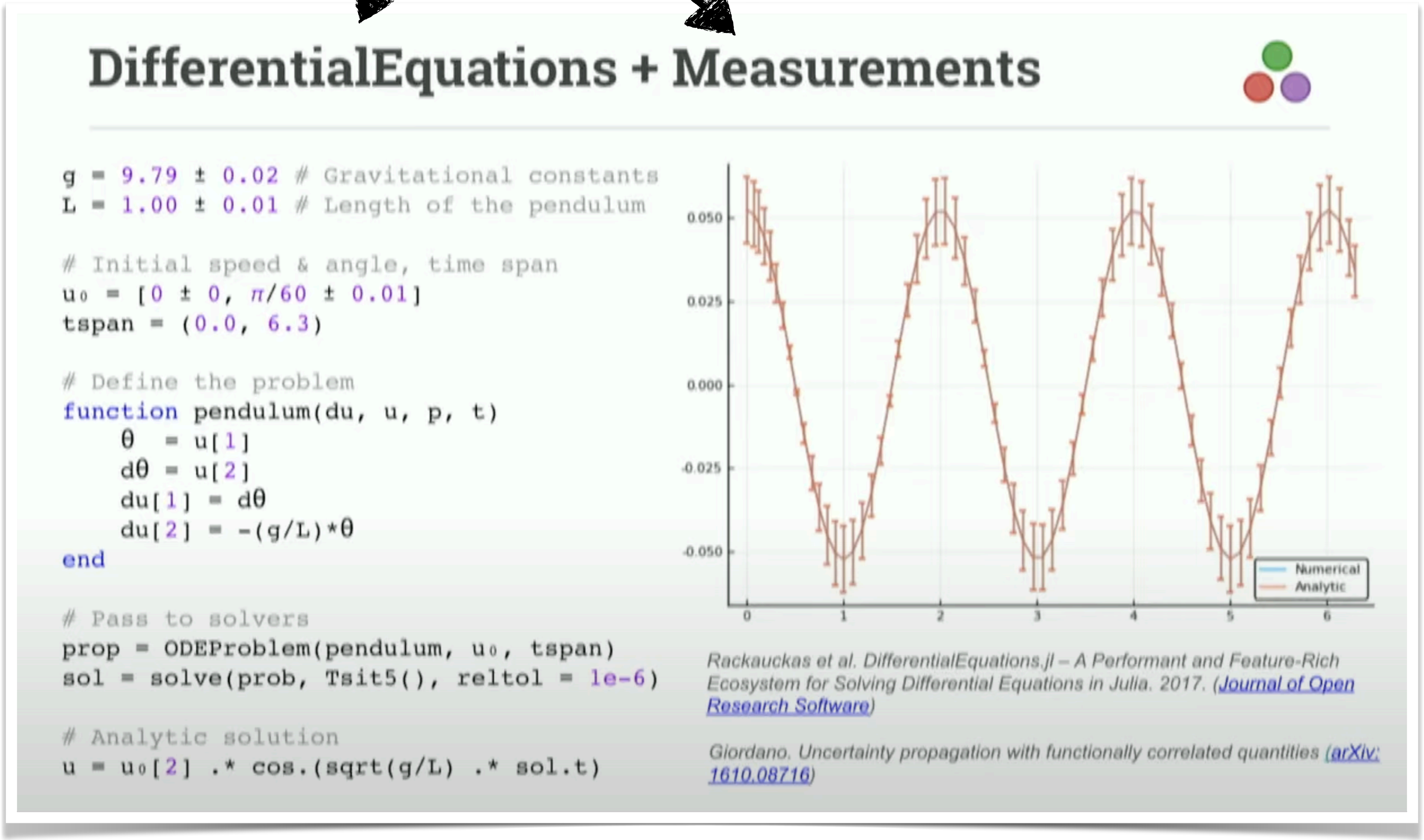
"The Expression Problem"

- 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 | **The Unreasonable Effectiveness of Multiple Dispatch** | 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)

```
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.

Parallel, Distributed and GPU Computing

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

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

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

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

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

```
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
```

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

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

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

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** as first-class citizens in Julia
- Upcoming paper:
  Potential of the Julia language for High Energy Physics computing
- Join the **JuliaHEP GitHub** organisation**:** https://github.com/JuliaHEP