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ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

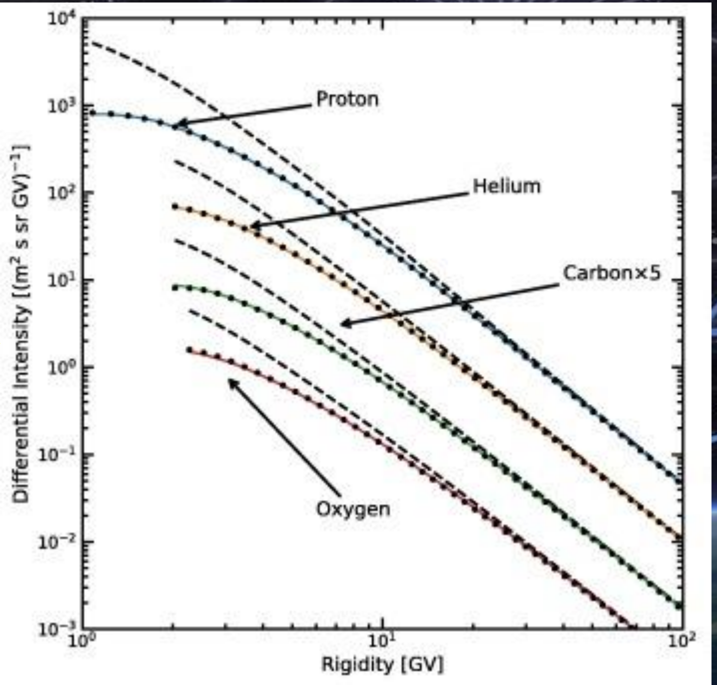
COSMICA: a novel parallel GPU code for Cosmic Rays propagation in heliosphere

Giovanni Cavallotto (INFN MiB), Stefano Della Torre (INFN MiB)

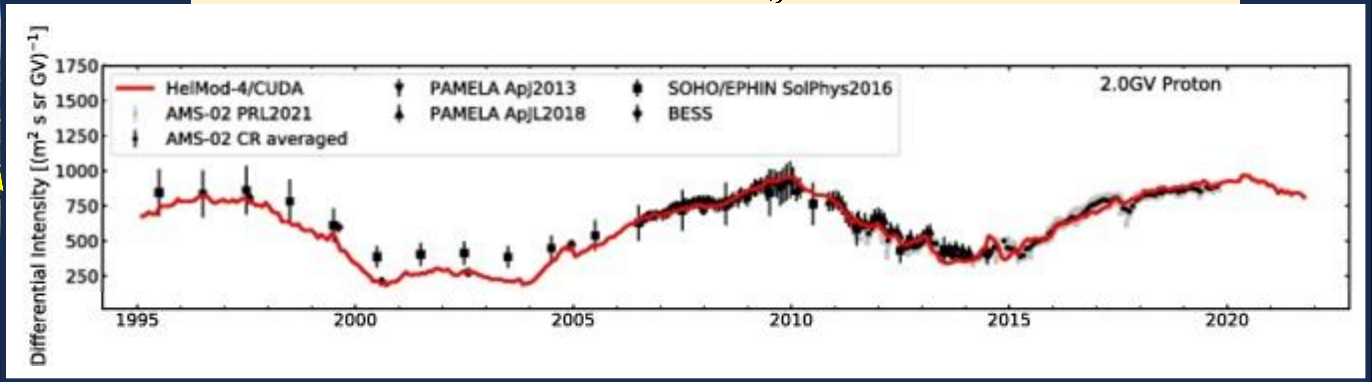
Spoke 3 II Technical Workshop, Bologna Dec 17 -19, 2024

Scientific Rationale

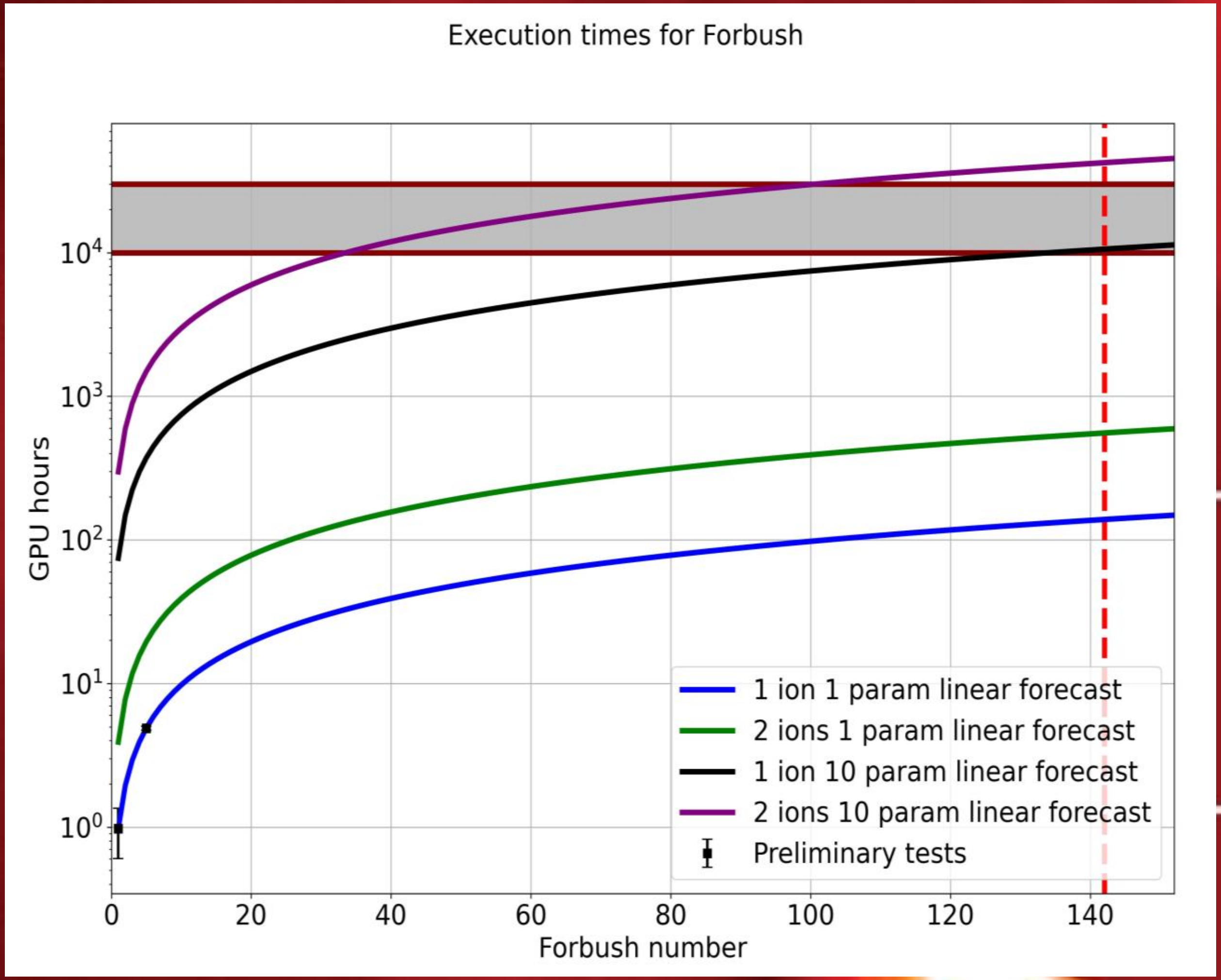
- GCR solar modulation
- SDE equivalent to PTE numerical integration
- Turbolent medium
  Time dependent environment
- Space weather
  CR astrophysics

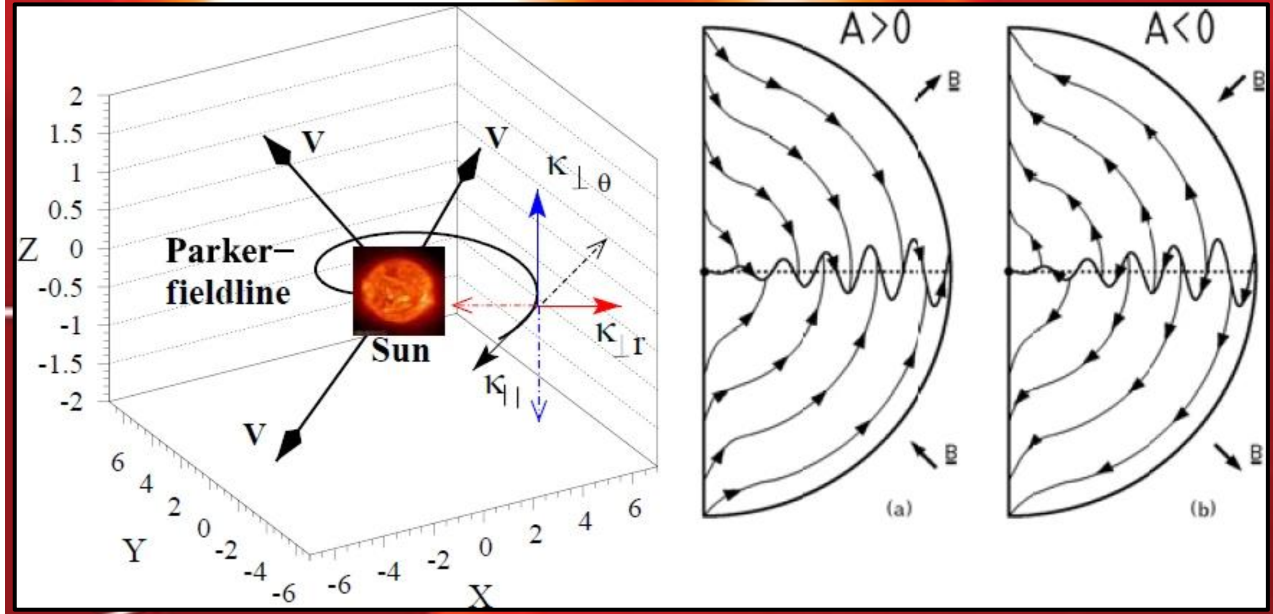


$$SDE: \quad \frac{\partial U}{\partial s} = \sum_i A_i(s,y)\frac{\partial U}{\partial y_i} + \frac{1}{2}\sum_{i,j} C_{ij}(s,y)\frac{\partial^2 U}{\partial y_i \partial y_j} - L\,U + S$$

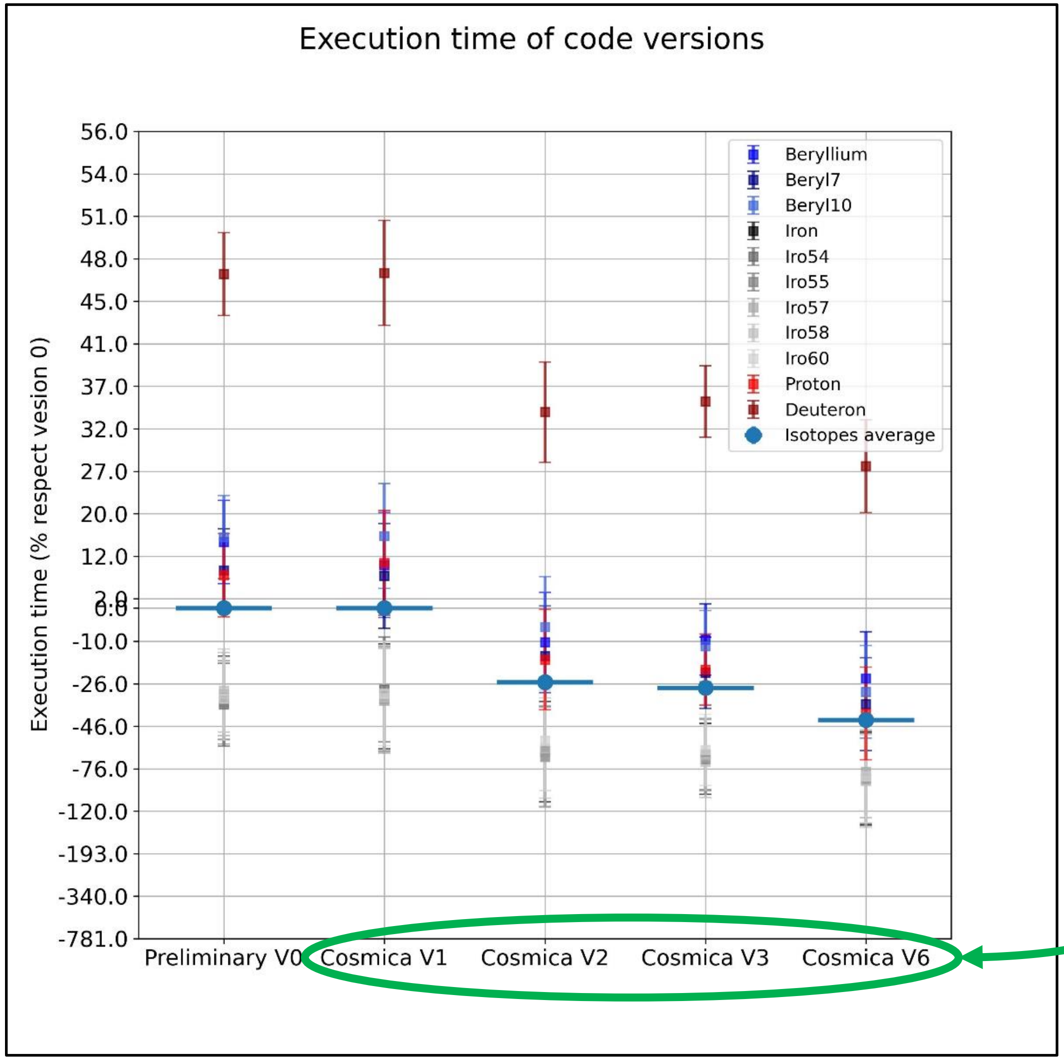


Technical Objectives





Methodologies and Solutions



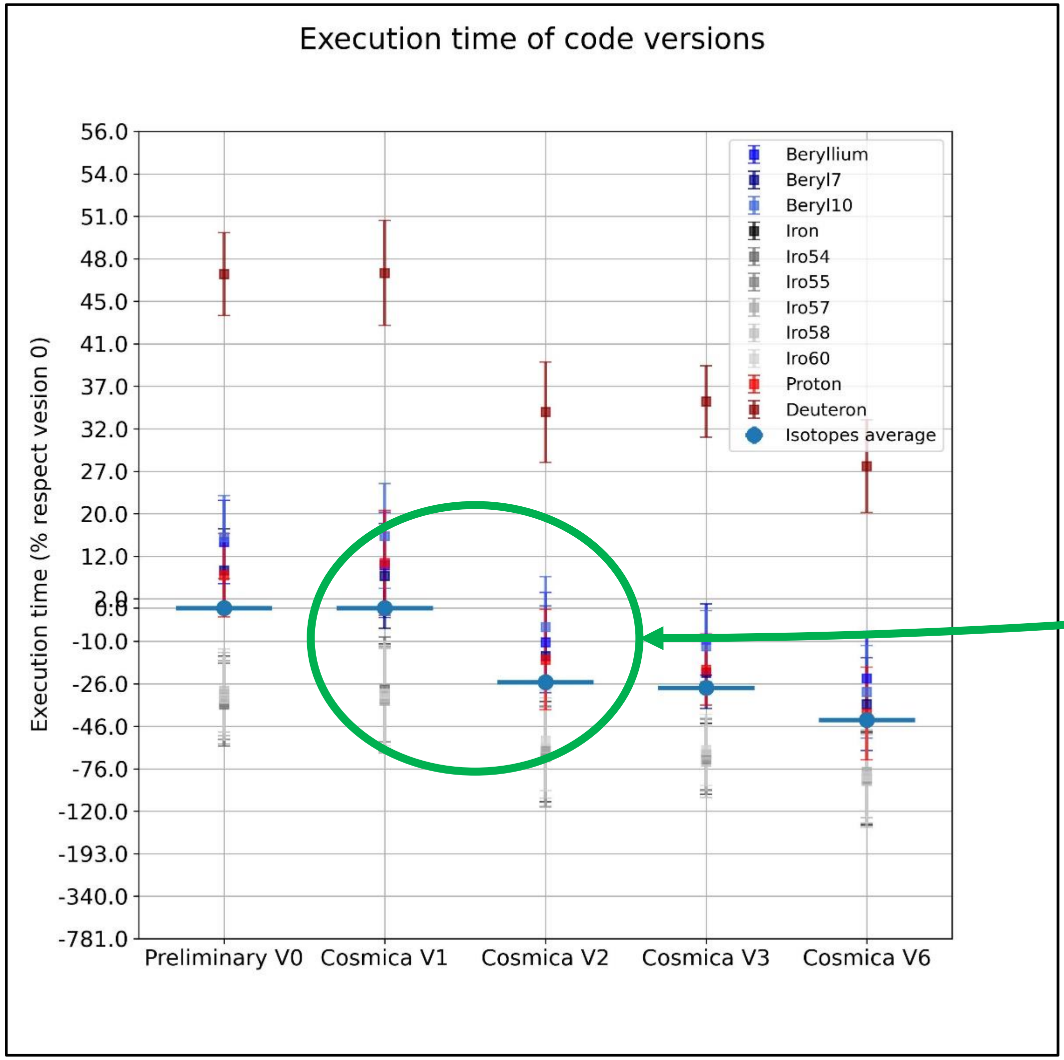
- **Particle propagation indipendence**
- **SIMD parallelization on GPU**

  CPU-GPU mixed CUDA code

- **Propagation kernel bottlenecks profiling (Nsight)**
- **Optimization of stochastic computations, WpB and passage to rigidity**

Available at the Spoke3 GitHub (open source)

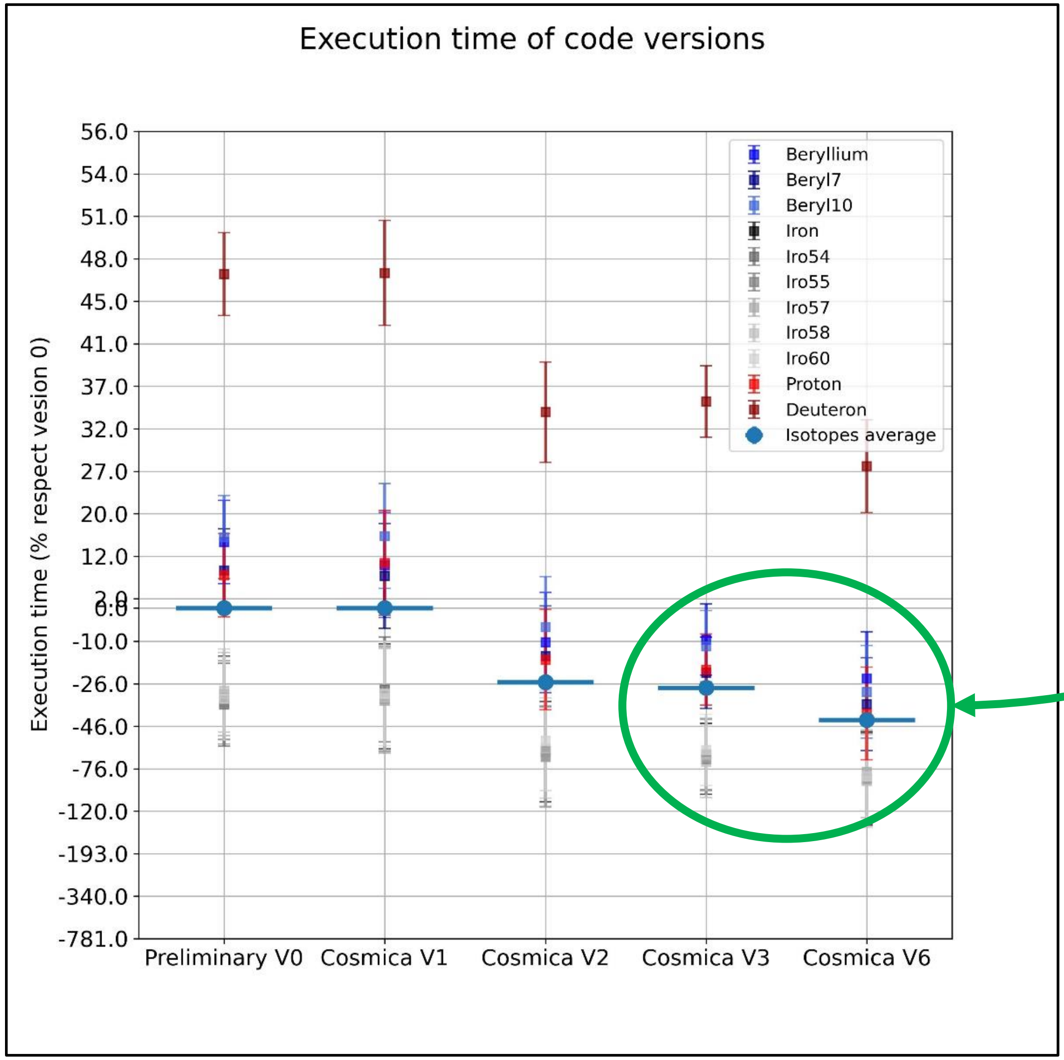
Main Results



V1 → V2 = 26% speedup:

- **Customized compilation flags → less registers**
- **Best WpB on A30 & A40 NVIDIA boards**

Main Results



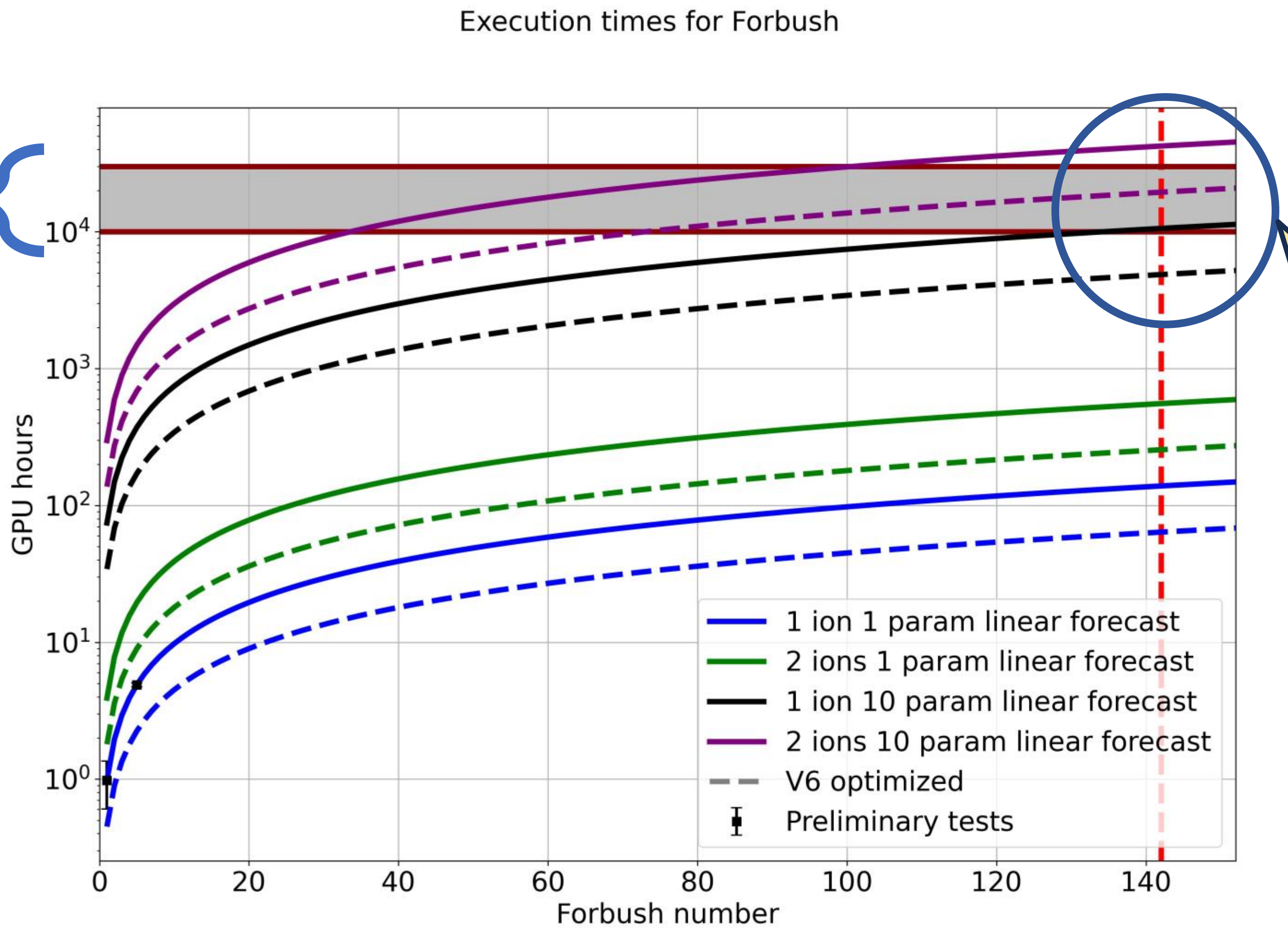
V3 → V6 = 19% speedup:

- Switch from energy to momentum-rigitity PTE

V0 → V6 = 46% complessive speedup

Large scale real case

Minimal & maximum resouces request at CINECA



- H not optimized **inside**
- H optimized **below**
- H and He not optimized **over**
- H and He optimized **just inside**

Cosmica 1D model

Updated on the Spoke3 GitHub (open source)

Cosmica 1D model

Here there are the codes and building scripts of the Cosmica 1D model of Cosmic Rays (CR) propagation in the heliosphere. These are the simplified version of the Cosmica code, which is 2D in modelling and 3D in propagation. The main algorithm is mantaine, but the propagation and implementation is reduced to its essential 1D components. This version of the model can be taken as toy model to understand the algorithm and perfor some test or start to develop a different physical propagation model.

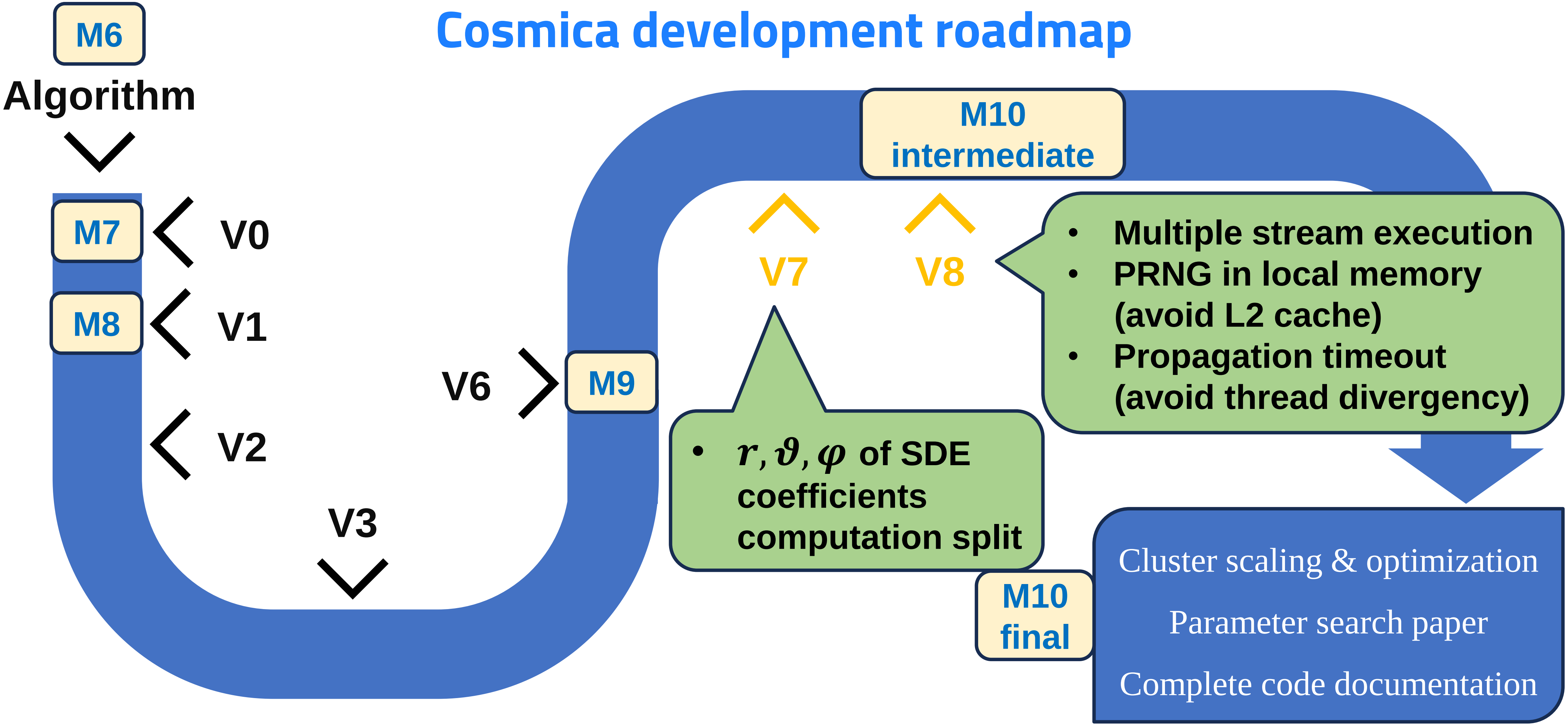
Tutorial COSMICA 1D

Preliminary new model agreement test

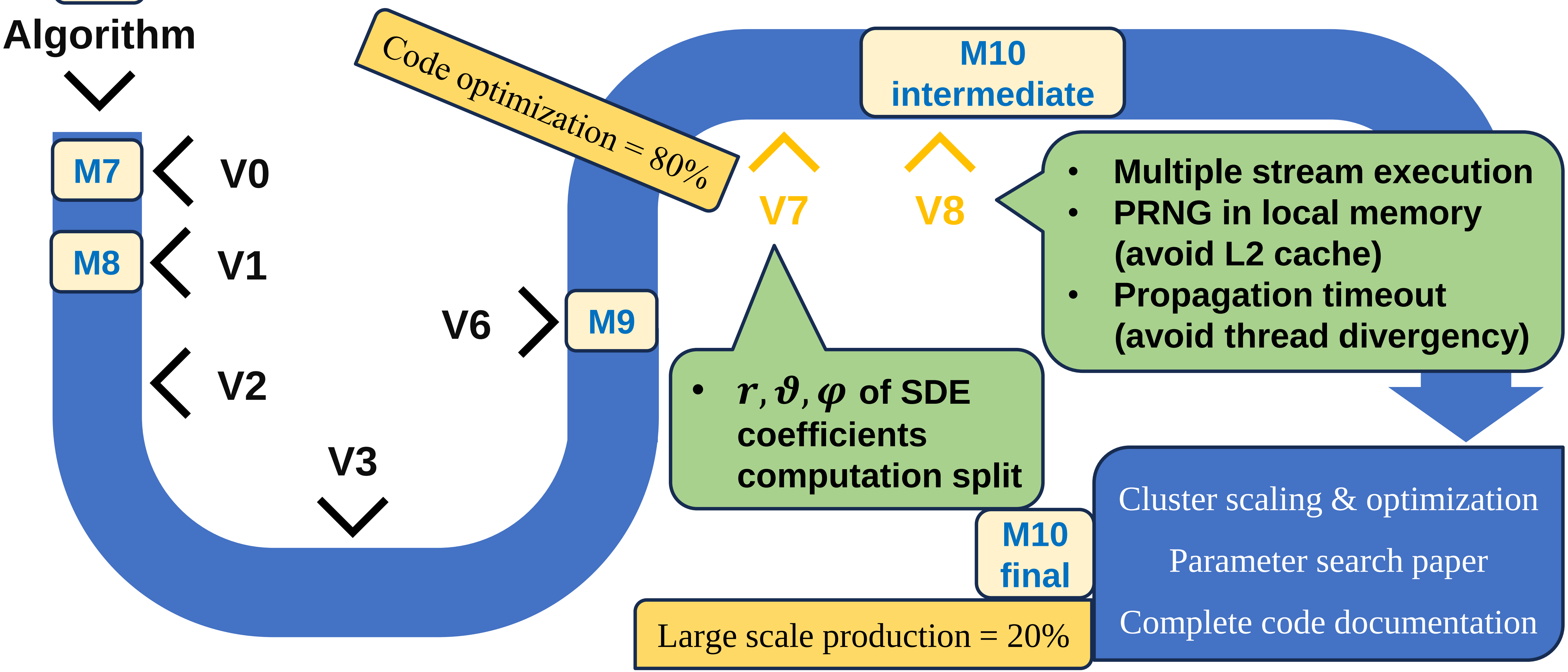
Code modularity

COSMICA 1D & COSMICA 3D

Cosmica development roadmap



Cosmica development roadmap



Final Steps

Last optimized version releases → Version 7
Version 8

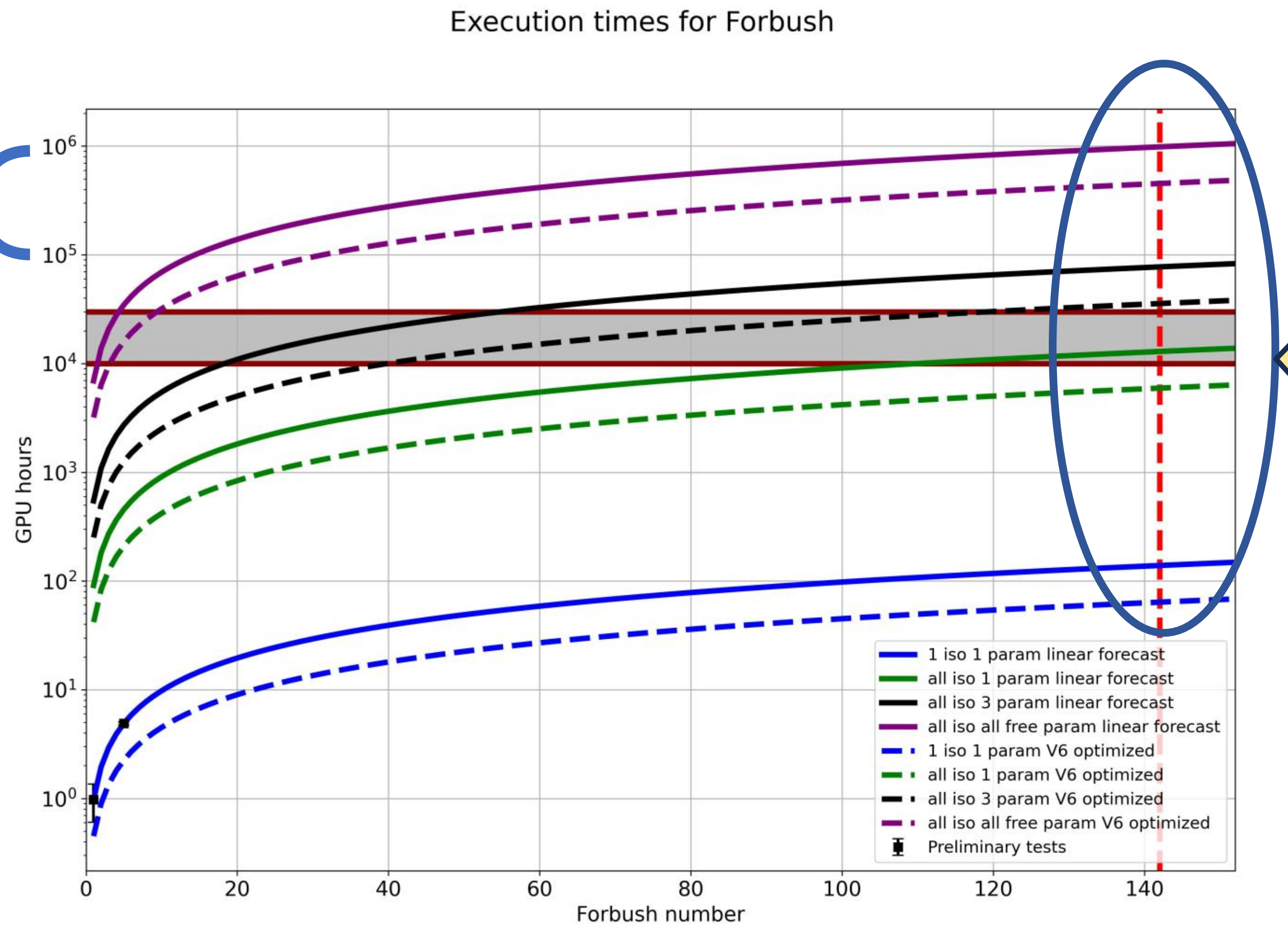
Test of different physical models and code modularity → Strauss-Moraal model
Latest tuning of the group

Large scaling and cluster optimization
Intermediet M10 terget → Parameter search paper publication
Complete code documentation
M10 final target


Thanks for
your attention

Technical Objectives, Methodologies and Solutions

Minimal & maximum resouces request at CINECA



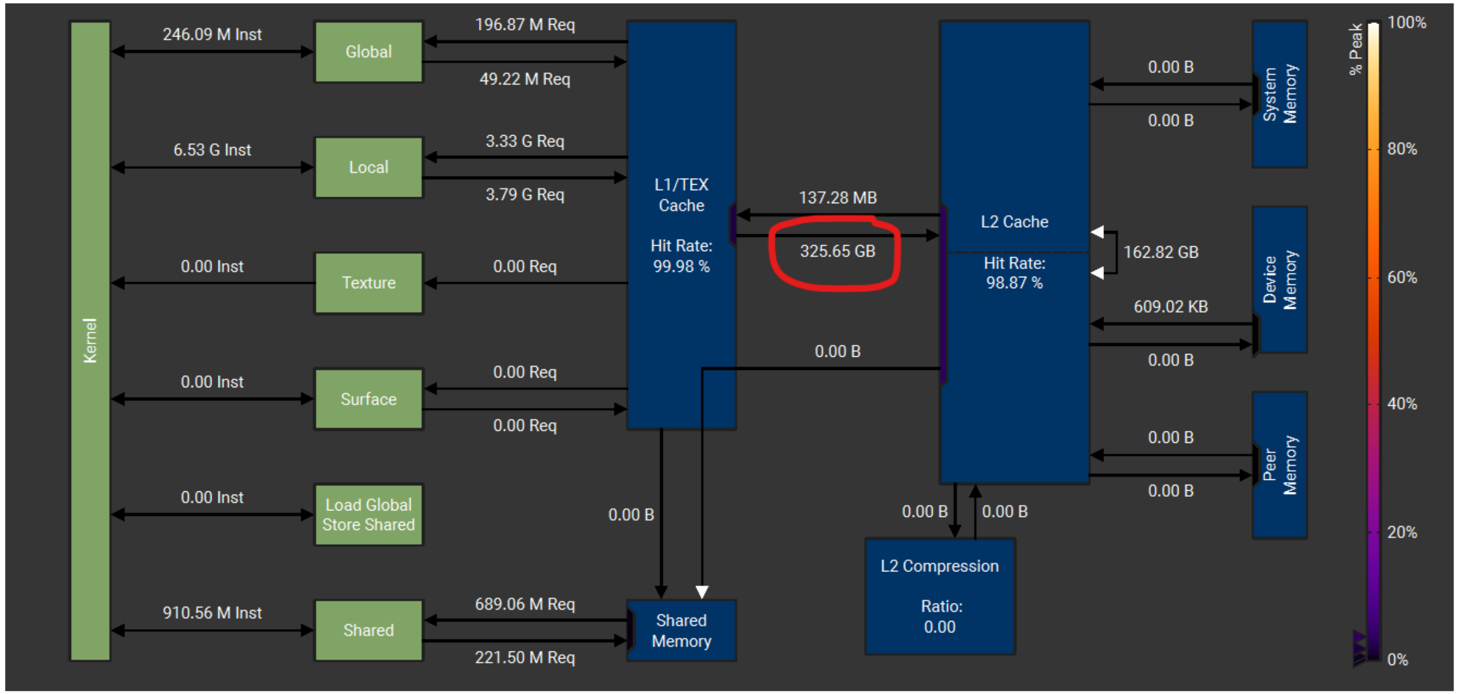
- 1 parameter not optimized **inside**
- 1 parameter optimized **below**
- 3 parameter not optimized **over**
- 3 parameter optimized **inside**

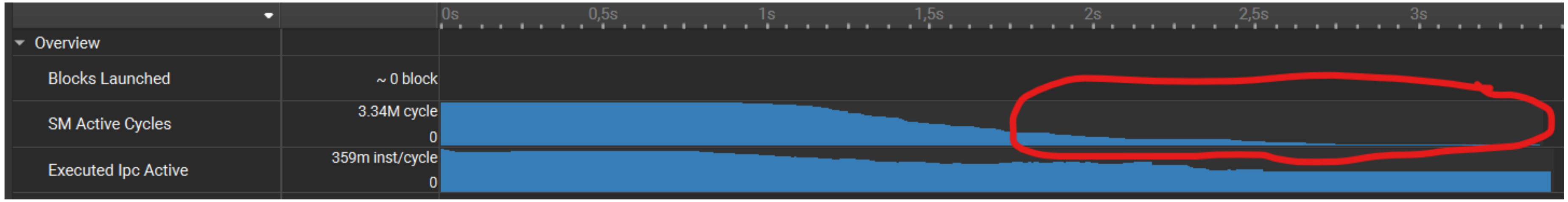
Cosmica development history

- **V1 Milestone 7 version of the code**
  - Illustrated in the Elba meeting
- **V2 Improving internal structure**
  - Usage of customized compilation flags to reduce register compilation allocation
  - Implementation of the best Warp number per block derived from performance tests executed on A30 and A40 NVIDIA boards
- **V3 Optimization of stochastic computations**
  - Optimization of partial computations of the stochastic differential equation coefficients
  - Reduction of the allocated variables lightening over-structures
- **V6 Use of the rigidity as main variable instead of kinetic energy**
  - Reformulation of SDE in momentum form (one of which becomes trivial)

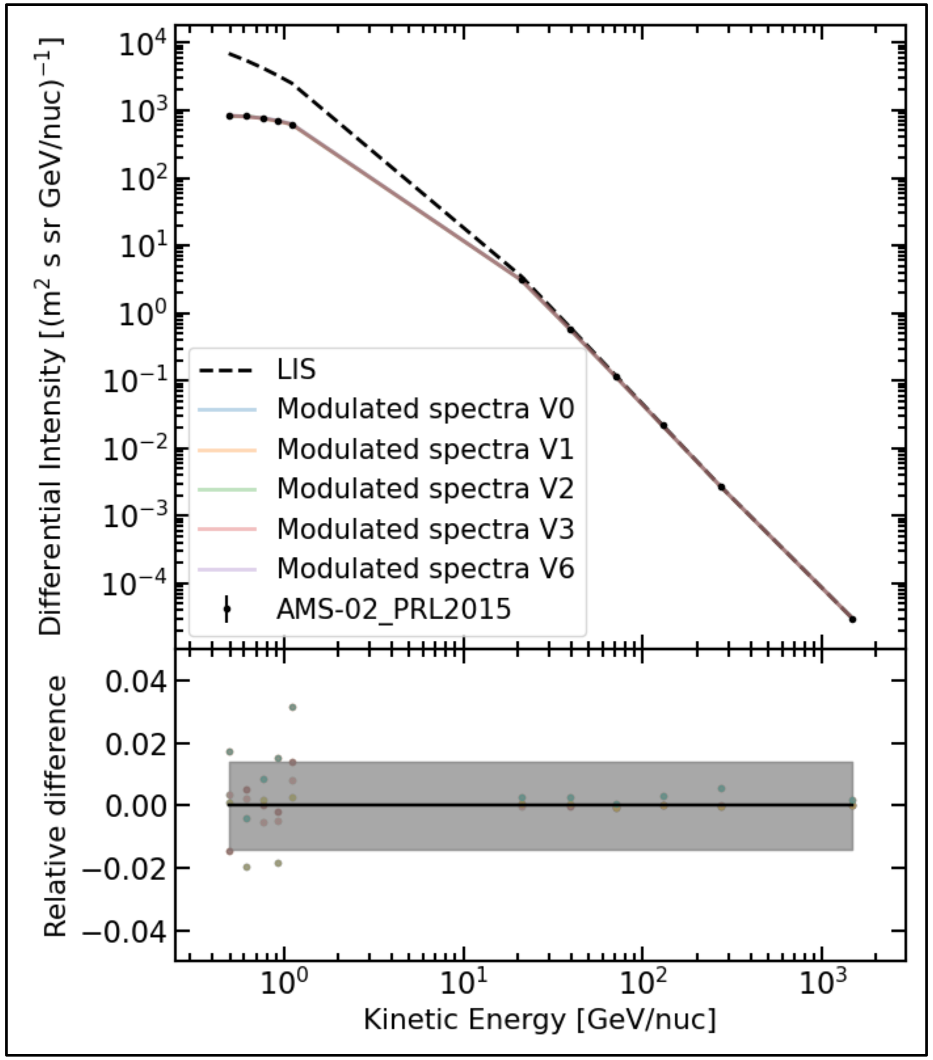
Available on the Spoke3 GitHub (open source)

Cosmica Epicure profile





Main Results



New propagation computation

Energy formulation

- $A_r = \frac{2k_{rr}}{r} + \frac{dk_{rr}}{dr} + \frac{dk_{r\theta}}{r\,d\theta} + \frac{\cot(\theta)k_{r\theta}}{r} + \frac{dk_{r\varphi}}{r\,\sin(\theta)\,d\varphi} - v_{drift,r} - v_{sw}$
- $A_\theta = \frac{\cot(\theta)k_{\theta\theta}}{r^2} + \frac{dk_{\theta\theta}}{r^2 d\theta} + \frac{dk_{r\theta}}{r dr_K} + \frac{dk_{\theta\varphi}}{r^2 \sin(\theta)\,d\varphi} + \frac{k_{r\theta}}{r^2} - \frac{v_{drift,\theta}}{r}$
- $A_\phi = \frac{dk_{\varphi\varphi}}{r^2\,\sin^2(\theta)\,d\varphi} + \frac{k_{r\varphi}}{r^2\,\sin(\theta)} + \frac{dk_{r\varphi}}{r\,\sin(\theta)dr} + \frac{dk_{\theta\varphi}}{r^2\,\sin(\theta)d\theta} - \frac{v_{drift,\phi}}{r\,\sin(\theta)}$
- $A_T = \frac{2Tv_{sw}(T+2T_0)}{3r(T+T_0)}$
- $C = \begin{pmatrix} 2k_{rr} & \frac{2k_{rt}}{r} & \frac{2\csc(\theta)k_{rp}}{r} \\ \frac{2k_{rt}}{r} & \frac{2k_{tt}}{r^2} & \frac{2\csc(\theta)k_{tp}}{r^2} \\ \frac{2\csc(\theta)k_{rp}}{r} & \frac{2\csc(\theta)k_{tp}}{r^2} & \frac{2\csc^2(\theta)k_{pp}}{r^2} \end{pmatrix}$
- $L_B = -\frac{2v_{sw}(2T^2+4TT0+T0^2)}{3r(T+T0)^2}$

Rigidity formulation

- “
- “
- “
- $A_P = \frac{2}{3}\frac{V_{SW}}{r}P$
- “
- $L = 0$

1 trivial propagation equation

Energy – Rigidity conversion

Energy unit

$$J = \frac{\beta U}{4\pi}$$

$$J_{mod}(T_{inj}) = \frac{\beta(T_{inj})}{N_{ev}} \sum_{j=1}^{N_{ev}} \frac{J_{LIS}(T_j)}{\beta(T_j)} \cdot \exp(L_j)$$

$$J_{LIS}(T_j) = J_{LIS}(P_j) \cdot \frac{dP}{dT}$$

Rigidity unit

$$J = fP^2 \qquad \left(p = \frac{Ze}{c}P\right)$$

$$J_{mod}(R_{inj}) = \frac{P_{inj}^2}{N_{ev}} \sum_{j=1}^{N_{ev}} \frac{J_{LIS}(P_j)}{P_j^2} \cdot \exp(L_j)$$

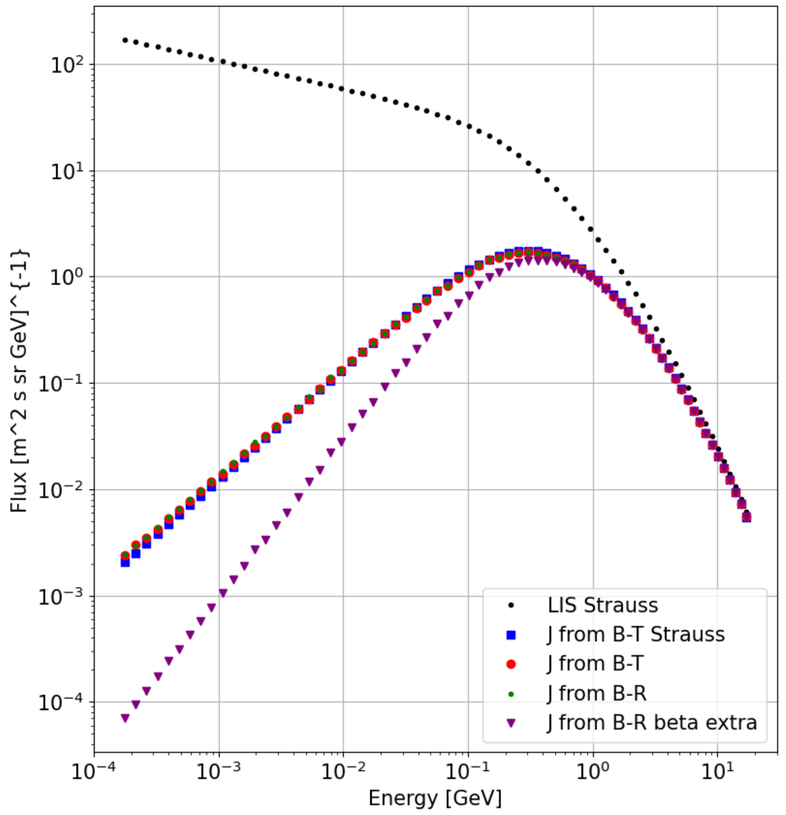
Extra conversion not needed

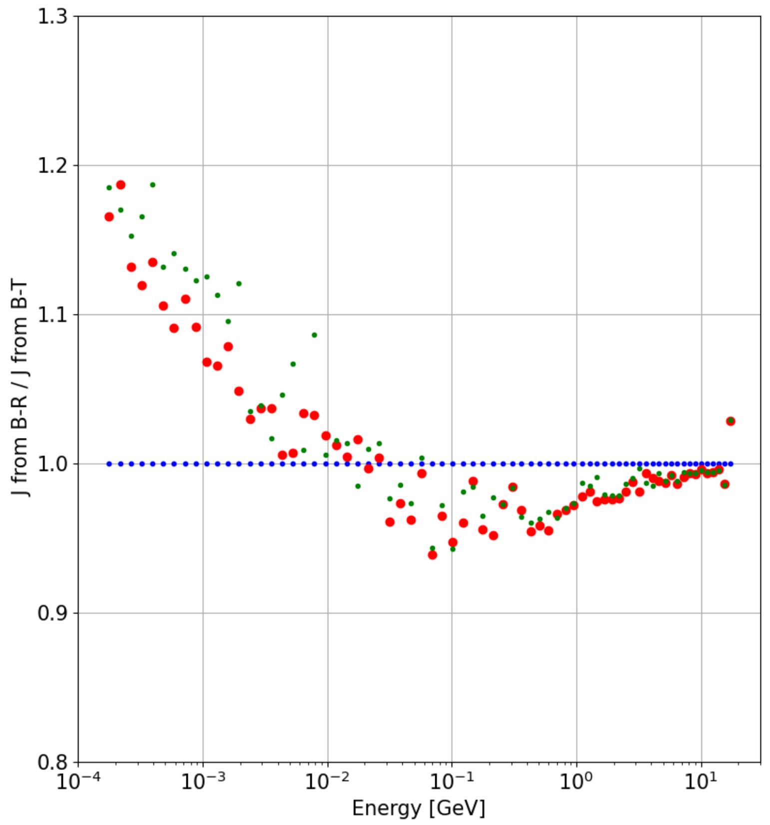
$$\frac{dP}{dT} = \frac{1}{\beta}$$

β term cancels with $\frac{dR}{dT}$

Energy – Rigidity conversion

Comparison between Strauss-Moraal and Cosmica models





Main Results

PDP 2025

33rd Euromicro International Conference on Parallel, Distributed, and Network-Based Processing (PDP 2025)

12-14 March 2025, Turin (Italy)

Submission of a paper to a HPC and parallel computing conference

Cosmica: a novel parallel GPU code for Cosmic Rays propagation in heliosphere

Giovanni Cavallotto
National Institute for Nuclear Physics (INFN), Division of Milano-Bicocca
giovanni.cavallotto@mib.infn.it
Stefano Della Torre
National Institute for Nuclear Physics (INFN), Division of Milano-Bicocca
Piazza della Scienza, 3 - 20126 Milano (Italy)
stefano.dellatorre@mib.infn.it
Giuseppe La Vacca
National Institute for Nuclear Physics (INFN), Division of Milano-Bicocca
Piazza della Scienza, 3 - 20126 Milano (Italy)
giuseppe.lavacca@mib.infn.it
Massimo Gervasi
National Institute for Nuclear Physics (INFN), Division of Milano-Bicocca
Piazza della Scienza, 3 - 20126 Milano (Italy)
University of Milano-Bicocca, Department of Physics "Giuseppe Occhialini"
Piazza della Scienza, 3 - 20126 Milano (Italy)
massimo.gervasi@mib.infn.it

***Abstract*—The complex structure of interplanetary magnetic fields and their variability, due to solar activity, make it necessary to compute the CR modulation with numerical simulations. COde for a Speedy Monte Carlo Involving Cuda Architecture (COSMICA) is a speedy and high precision Monte Carlo simulator of CR modulation, which solve the system of Stochastic Differential**

I. INTRODUCTION

Galactic Cosmic Rays (GCR) are charged particles mainly originating from astrophysical sources outside the solar system. These particles enter isotropically the heliosphere, which

Activated new project paths

- **Sdegno Cascade founding project: parameter search (Cafoscari)**
- **Forbush scale study: CINECA GPU hours allocation (PICA)**

Project: CN HPC
AccountID: 1667457
CRPSF - Spoke3
Science Domain: Astrophysics and Plasma Physics
Validity: Monday, 16 September, 2024 to Thursday, 28 August, 2025
Status:
Active
ExpirationDelay:
6
Note:
16/09/2024: creazione progetto per 2024Q2 (tts#49882 - FDP) 27/09/2024: sostituzione fake user con PI Cavallotto - giovanni.cavallotto@mib.infn.it (tts#49882 - FDP)

Details

Hosts: LEONARDO_B
Budget (standard hours): 30 000
WORK Quote (in GB): 1 024

People

External Supervisor (PI): Giovanni Cavallotto - INFN - Istituto Nazionale di Fisica Nucleare - 2 43 Dipartimento di Fisica

Collaborators

Collaborators: Stefano Della Torre - Non Italian Universities - INFN Sezione di Milano Bicocca

Cosmica development plan

- **V7 (under development) Separation of SDE coefficients computation for each coordinate**
  - Instead of using matrices of coefficients they are computed separately to relieve the register pressure

- **V8 (planned) Multi stream execution**
  - Execute multiple streams on the same GPU instead of using a 1 tot 1 coupling CPU-GPU with multiple GPUs
  - Relieve register pressure with architecture compiler flag
  - Change the PRNG (now it is Philox4_32_10 of cuRAND) to have more local RNG (not in L2 cache)
  - Avoid thread divergency and execution time differences