Automatic trace analysis with the Scalasca Trace Tools

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trace tools
scalasca

Scalasca Trace Tools

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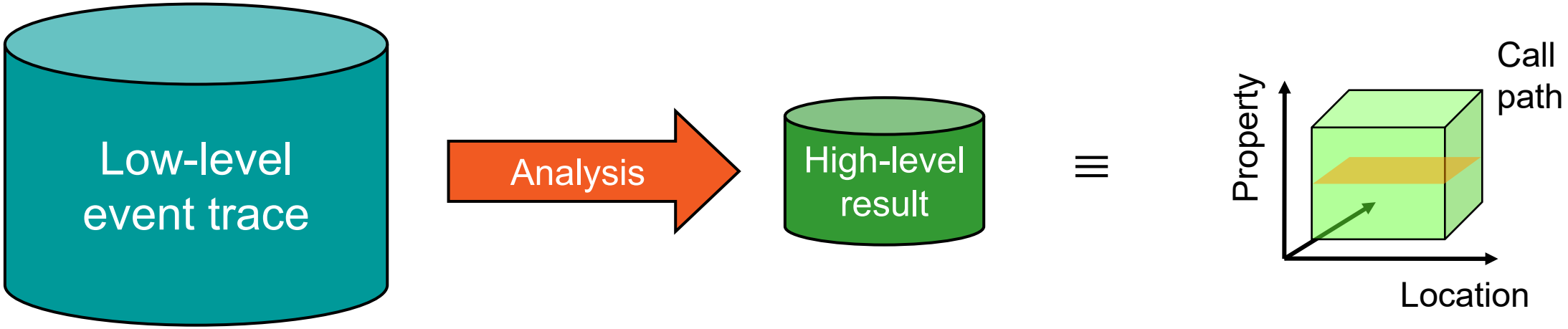
- **Scalable trace-based** performance analysis toolset for the most popular parallel programming paradigms
  - Current focus: MPI, OpenMP, and (to a limited extend) POSIX threads
  - Analysis of traces including *only host-side events* from applications using CUDA, OpenCL, or OpenACC (also in combination with MPI and/or OpenMP) is possible, but results need to be interpreted with some care

- Specifically targeting large-scale parallel applications
  - Demonstrated scalability up to 1.8 million parallel threads
  - Of course also works at small/medium scale

- Latest release:
  - Scalasca Trace Tools v2.6.2 (April 2025)

Automatic trace analysis

- Idea
  - Automatic search for patterns of inefficient behavior
  - Classification of behavior & quantification of significance
  - Identification of delays as root causes of inefficiencies



  - Guaranteed to cover the entire event trace
  - Quicker than manual/visual trace analysis
  - Parallel replay analysis exploits available memory & processors to deliver scalability

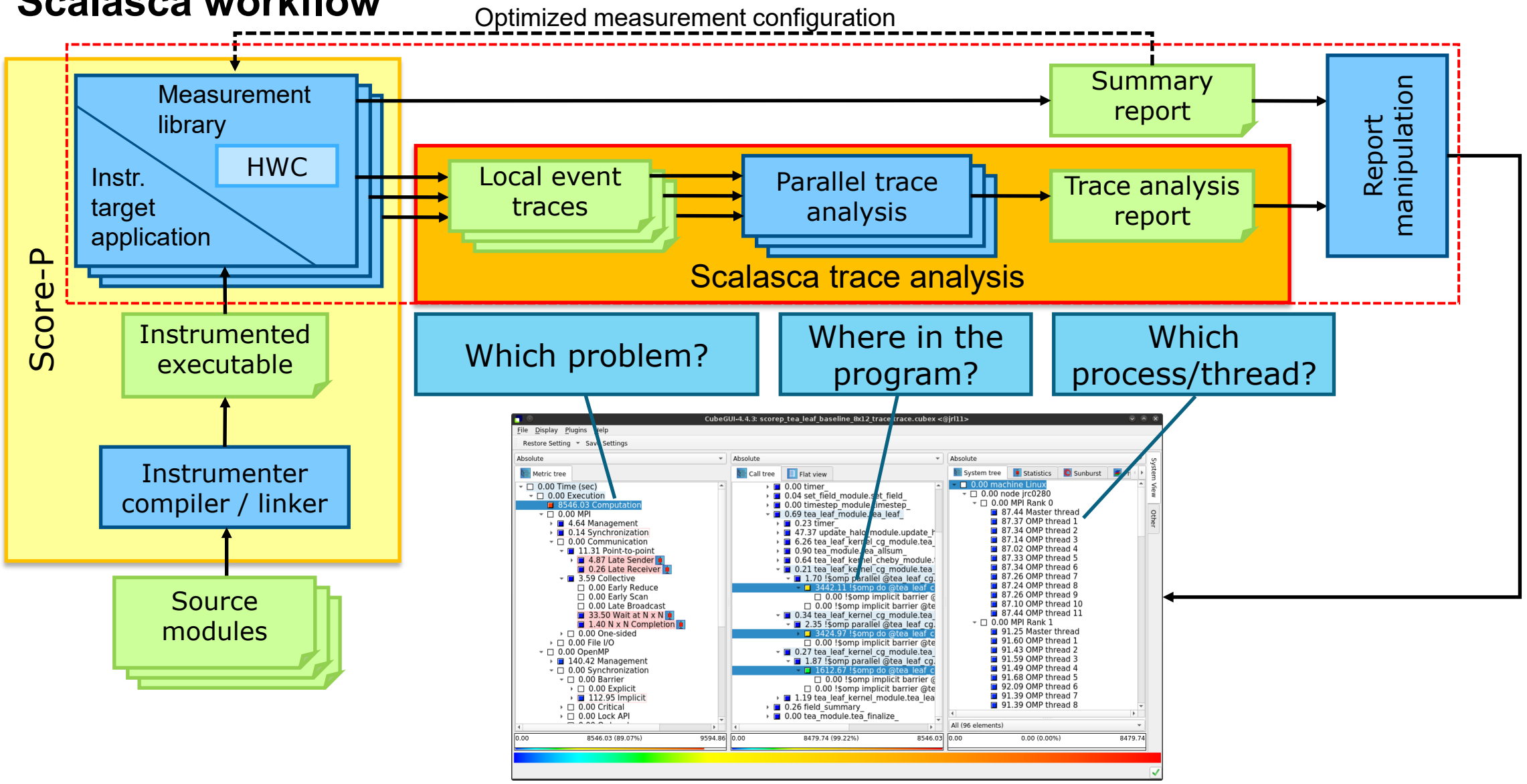
Scalasca Trace Tools: Features

- Open source, 3-clause BSD license
- Supports all major HPC platforms

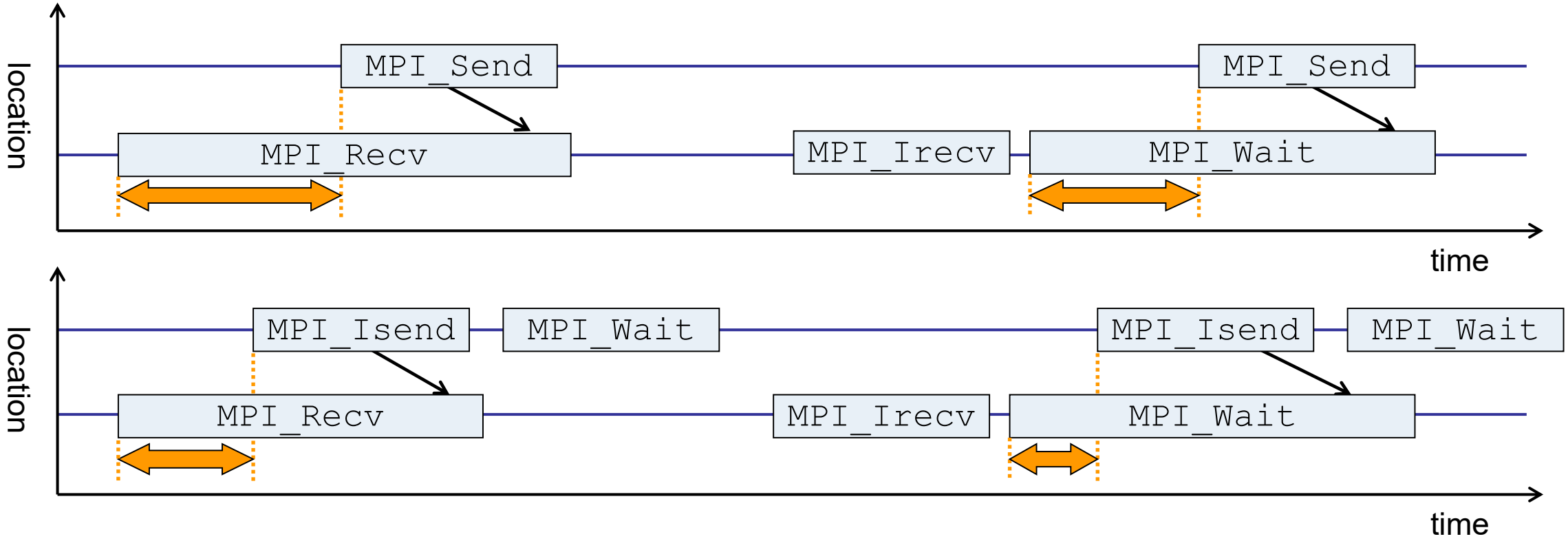
- Uses Score-P instrumenter & measurement libraries
  - Scalasca v2 core package focuses on trace-based analyses
  - Provides convenience commands for measurement, analysis, and post-processing
  - Supports common data formats
    - Reads event traces in OTF2 format
    - Writes analysis reports in CUBE4 format

- Current limitations:
  - Unable to handle traces …
    - with MPI thread level exceeding MPI_THREAD_FUNNELED
    - containing memory events, CUDA/OpenCL device events (kernel, memcpy), SHMEM, or OpenMP nested parallelism
  - PAPI/rusage metrics for trace events are ignored

Scalasca workflow

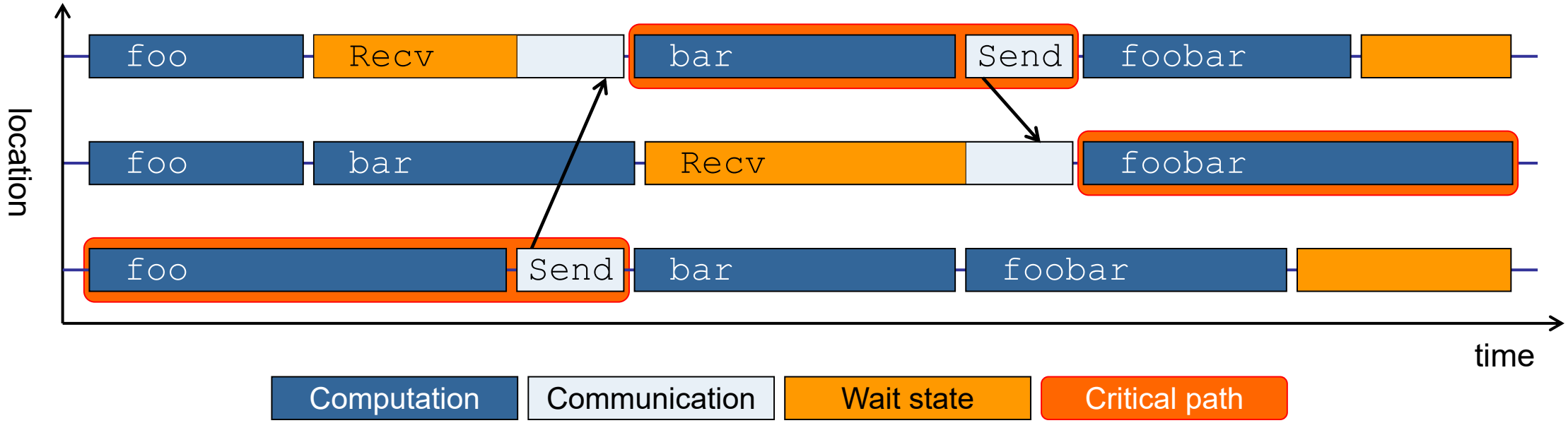


Example: "*Late Sender*" wait state



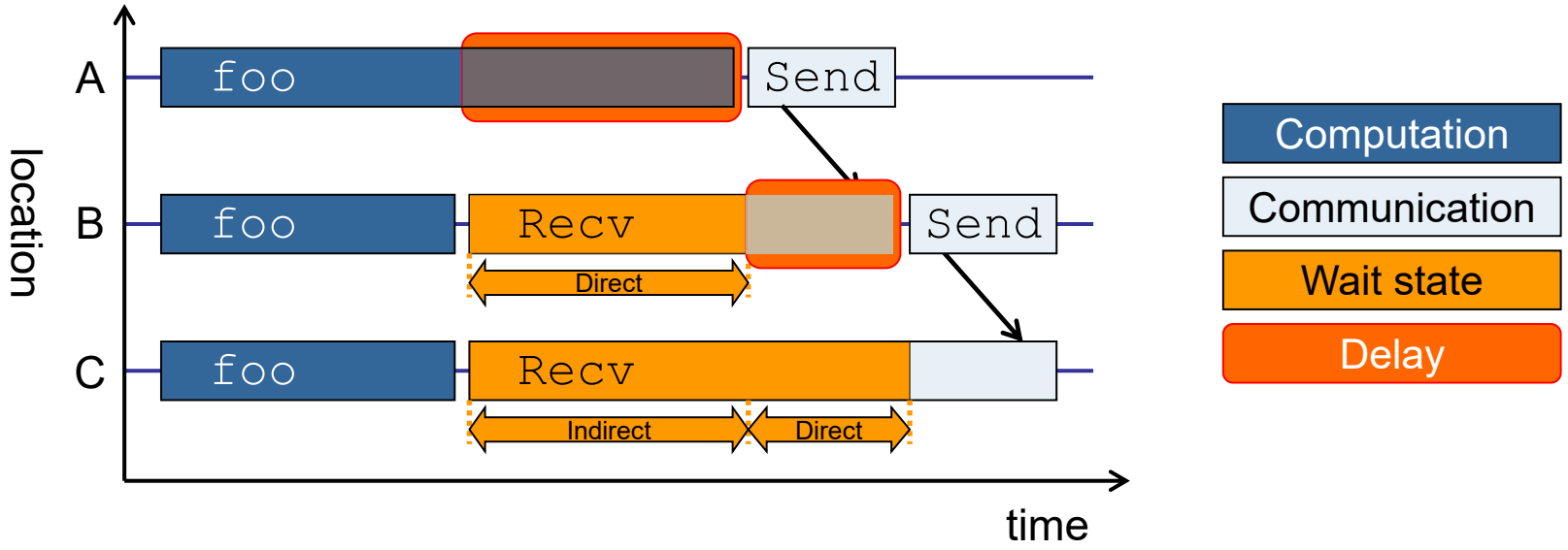
- Waiting time caused by a blocking receive operation posted earlier than the corresponding send
- Applies to blocking as well as non-blocking communication

Example: Critical path



- Shows call paths and processes/threads that are responsible for the program's wall-clock runtime
- Identifies good optimization candidates and parallelization bottlenecks

Example: Root-cause analysis



- Classifies wait states into direct and indirect (i.e., caused by other wait states)
- Identifies *delays* (excess computation/communication) as root causes of wait states
- Attributes wait states as *delay costs*

Hands-on:
NPB-MZ-MPI / BT

Recap: Setup for exercises

- Connect to your account on the local training system
  - Amplitude:

```
% ssh -Y <account>@login1.amplitude.uni-due.de
```

- Change to directory containing BT-MZ sources
  - Existing instrumented executable can be reused

```
% module use /cluster/vi-hps_tuning_workshop/examples/opt/modules
% module load scalasca/2.6.2-gcc-openmpi scorep/9.0-gcc-openmpi-cuda cube
% cd <your bt-mz path>/bin.scorep
```

Demo: BT-MZ summary measurement collection...

```
% vi ../jobscript/amplitude/scalasca.slurm

#SBATCH -J filter        <= change this to "scalasca"

# Measurement configuration
export SCOREP_FILTERING_FILE=../config/scorep.filt
#export SCOREP_METRIC_PAPI=PAPI_TOT_INS,PAPI_TOT_CYC
#export SCOREP_TOTAL_MEMORY=150M
#export SCAN_ANALYZE_OPTS="--time-correct"

# Run the application
scalasca -analyze   mpirun -n ${SLURM_NTASKS} \
--cpus-per-proc=${SLURM_CPUS_PER_TASK} ./bt-mz_$CLASS.$PROCS
```

- Change to the *bin.scorep* directory and edit the job script

Hint:
scan = scalasca -analyze
-s = profile/summary (default)

```
% sbatch ../jobscript/amplitude/scalasca.slurm
```

- Submit the job

scan: Automatic measurement configuration

- scan configures Score-P measurement by automatically setting some environment variables and exporting them
  - E.g., experiment title, profiling/tracing mode, filter file, …
  - Precedence order:
    - Command-line arguments
    - Environment variables already set
    - Automatically determined values
- Also, scan includes consistency checks and prevents corrupting existing experiment directories
- For tracing experiments, after trace collection completes then automatic parallel trace analysis is initiated
  - Uses identical launch configuration to that used for measurement (i.e., the same allocated compute resources)

Demo: BT-MZ summary measurement

```
S=C=A=N: Scalasca 2.6.2 runtime summarization
S=C=A=N: scalasca/scorep_bt-mz_C_8x8_sum experiment archive
S=C=A=N: Fri Feb 23 11:54:48 2024: Collect start
srun … bin.scorep/bt-mz_C.8

 NAS Parallel Benchmarks (NPB3.3-MZ-MPI) -
    BT-MZ MPI+OpenMP Benchmark

 Number of zones:  8 x  8
 Iterations: 200    dt:   0.000100
 Number of active processes:     8

 [... More application output ...]

S=C=A=N: Fri Feb 23 11:55:09 2024: Collect done (status=0) 21s
S=C=A=N: scalasca/scorep-8-8-summary complete.
```

- Run the application using the Scalasca measurement collection & analysis nexus prefixed to launch command
- Creates experiment directory:
  scorep_bt-mz_C_8x8_sum

Demo: BT-MZ summary analysis report examination

- Score summary analysis report

```
% square -s scorep_bt-mz_C_8x8_sum
INFO: Post-processing runtime summarization report (profile.cubex)...
INFO: Score report written to scorep_bt-mz_C_8x8_sum/scorep.score
```

- Post-processing and interactive exploration with Cube

```
% square  scorep_bt-mz_C_8x8_sum
INFO: Displaying scorep_bt-mz_C_8x8_sum/summary.cubex

                    [GUI showing summary analysis report]
```

Hint:
Copy ‘summary.cubex’ to local system (laptop) using ‘scp’ to improve responsiveness of GUI

- The post-processing derives additional metrics and generates a structured metric hierarchy

BT-MZ trace measurement collection...

```
% vi ../jobscript/amplitude/scalasca.slurm

#SBATCH -J scalasca          <= change this to "trace"

# Measurement configuration
export SCOREP_FILTERING_FILE=../config/scorep.filt
#export SCOREP_METRIC_PAPI=PAPI_TOT_INS,PAPI_TOT_CYC
export SCOREP_TOTAL_MEMORY=150M
#export SCAN_ANALYZE_OPTS="--time-correct"

# Run the application
scalasca -analyze -t  mpirun -n ${SLURM_NTASKS} \
--cpus-per-proc=${SLURM_CPUS_PER_TASK} ./bt-mz_$CLASS.$PROCS
```

```
% sbatch ../jobscript/amplitude/scalasca.slurm ch
```

- Change to the top-level directory and edit the job script
- Add "-t" to the `scan` command
- Submit the job

BT-MZ trace measurement … collection

```
S=C=A=N: Scalasca 2.6.2 trace collection and analysis
S=C=A=N: Fri Feb  23 12:49:25 2024: Collect start
srun … bin.scorep/bt-mz_C.8

 NAS Parallel Benchmarks (NPB3.3-MZ-MPI) - BT-MZ MPI+OpenMP \
>Benchmark

 Number of zones:  8 x  8
 Iterations: 200    dt:   0.000100
 Number of active processes:     8

 [... More application output ...]

S=C=A=N: Fri Feb  23 12:49:45 2024: Collect done (status=0) 20s
```

- Starts measurement with collection of trace files …

BT-MZ trace measurement … analysis

```
…
S=C=A=N: Fri Feb  23 12:49:45 2024: Analyze start
 srun […] scout.hyb --time-correct \
>    scorep_bt-mz_C_8x8_trace/traces.otf2

SCOUT   (Scalasca 2.6.1)

Analyzing experiment archive scorep_bt-mz_C_8x8_trace/traces.otf2

Opening experiment archive ... done (0.002s).
Reading definition data    ... done (0.002s).
Reading event trace data   ... done (1.117s).
Preprocessing              ... done (0.729s).
Timestamp correction       ... done (4.370s).
Analyzing trace data       ... done (23.496s).
Writing analysis report    ... done (0.284s).

Max. memory usage         : 3048.270MB

        # passes         : 1
        # violated       : 0

Total processing time     : 30.087s
S=C=A=N: Fri Feb  23 12:50:21 2024: Analyze done (status=0) 36s
```

- Continues with automatic (parallel) analysis of trace files

BT-MZ trace analysis report exploration

- Produces trace analysis report in the experiment directory containing trace-based wait-state metrics

```
% square  scorep_bt-mz_C_8x8_trace
INFO: Post-processing runtime summarization report (profile.cubex)...
INFO: Post-processing trace analysis report (scout.cubex)...
INFO: Displaying scorep_bt-mz_C_8x8_trace/trace.cubex...

                [GUI showing trace analysis report]
```

Hint:
Run ‘square -s’ first and then copy ‘trace.cubex’ to local system (laptop) using ‘scp’ to improve responsiveness of GUI

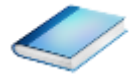
Case study:
TeaLeaf MPI+OpenMP

Case study: TeaLeaf MPI+OpenMP

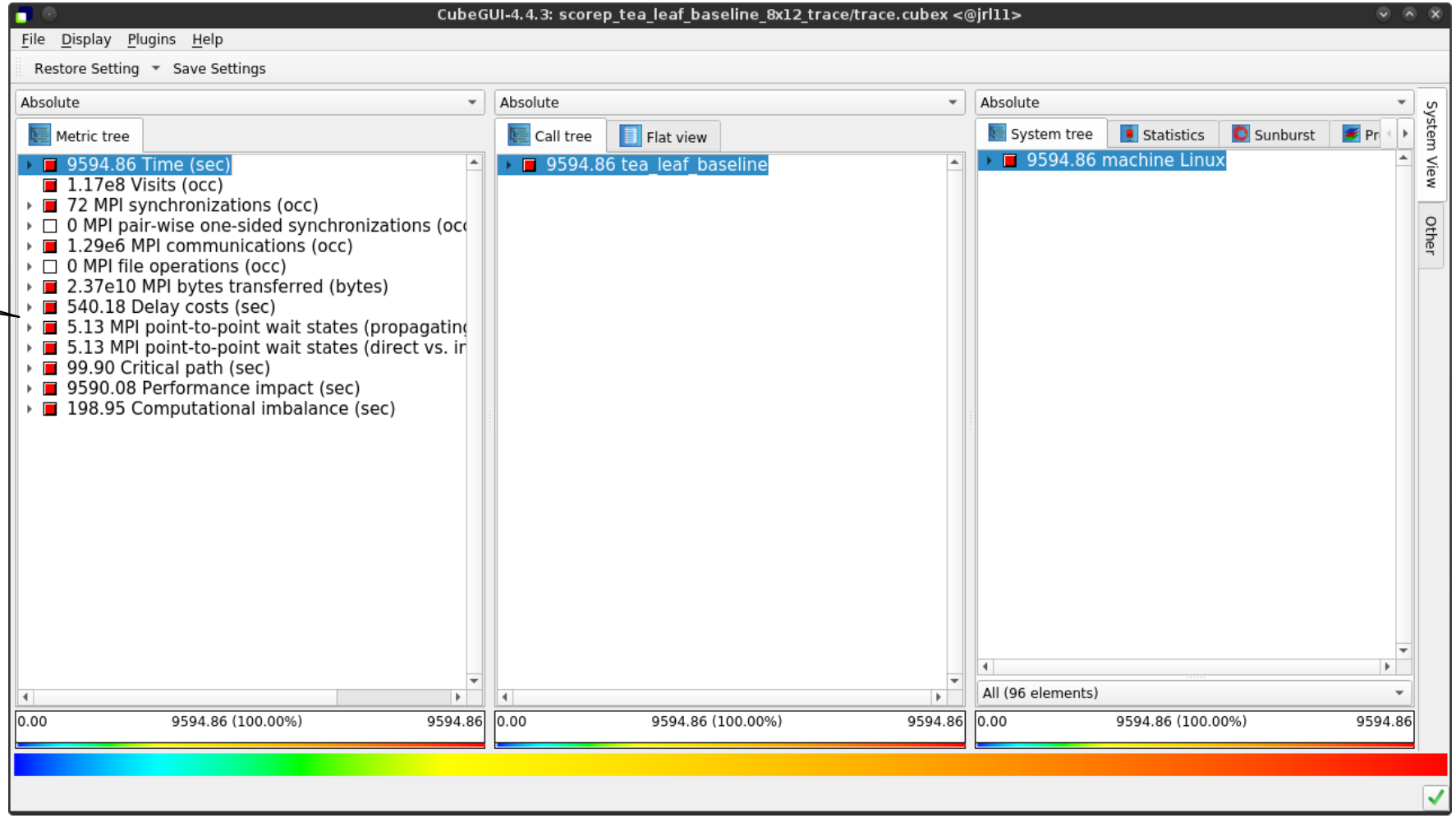
- HPC mini-app developed by the UK Mini-App Consortium
  - Solves the linear 2D heat conduction equation on a spatially decomposed regular grid using a 5 point stencil with implicit solvers
  - Part of the Mantevo 3.0 suite
  - Available on GitHub: https://uk-mac.github.io/TeaLeaf/
- Measurements of TeaLeaf reference v1.0 taken on Jureca cluster @ JSC
  - Using Intel 19.0.3 compilers, Intel MPI 2019.3, Score-P 5.0, and Scalasca 2.5
  - Run configuration
    - 8 MPI ranks with 12 OpenMP threads each
    - Distributed across 4 compute nodes (2 ranks per node)
    - Test problem "5": 4000 × 4000 cells, CG solver

```
% cube scorep_tea_leaf_baseline_8x12_trace/trace.cubex
                          [GUI showing post-processed trace analysis report]
```

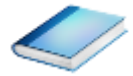
Scalasca analysis report exploration (opening view)



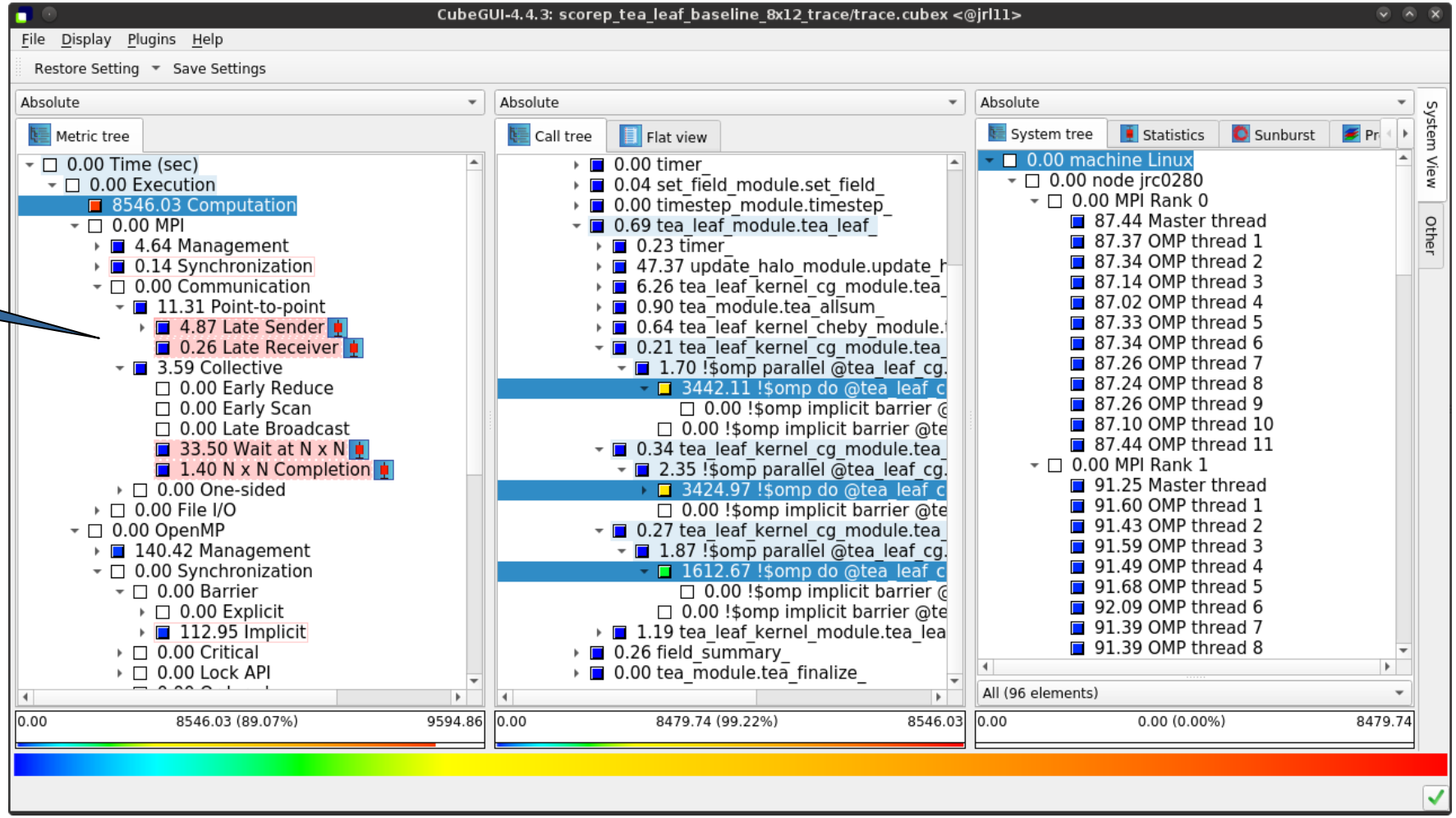
Additional top-level metrics produced by the trace analysis…



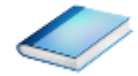
Scalasca wait-state metrics



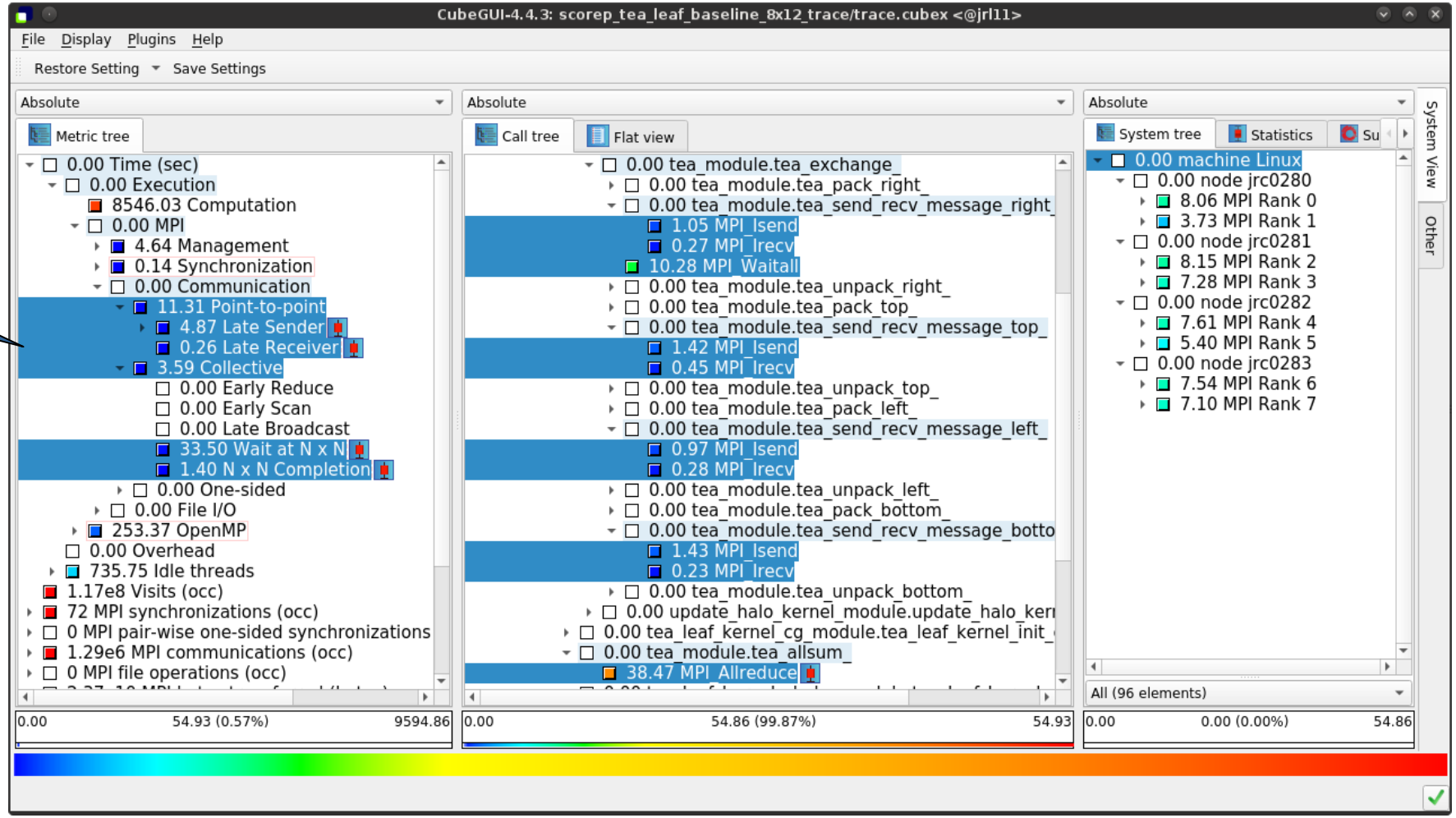
…plus additional wait-state metrics as part of the “Time” hierarchy



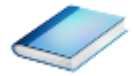
TeaLeaf Scalasca report analysis (I)



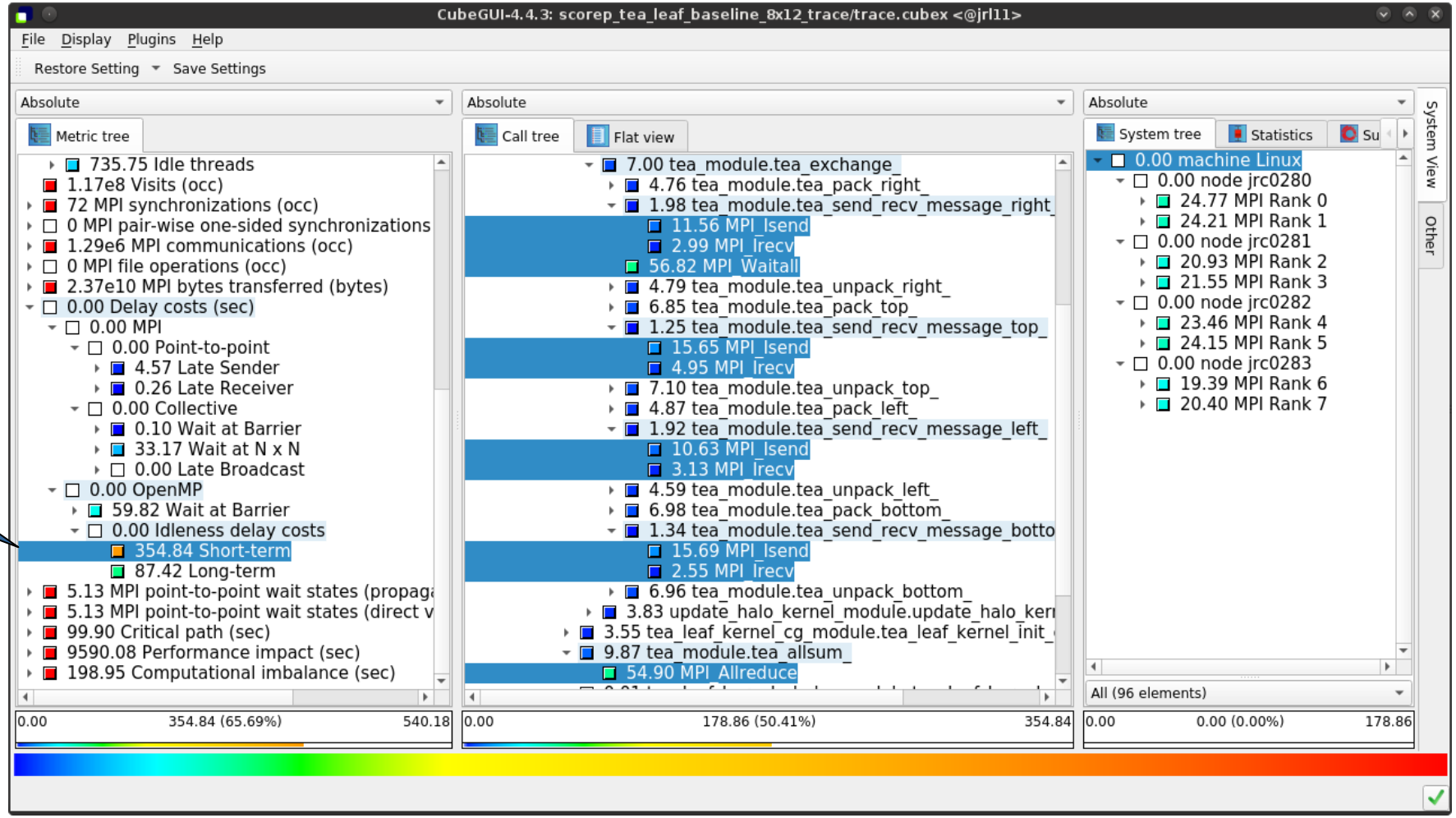
While MPI communication time and wait states are small (~0.6% of the total execution time)…



TeaLeaf Scalasca report analysis (II)

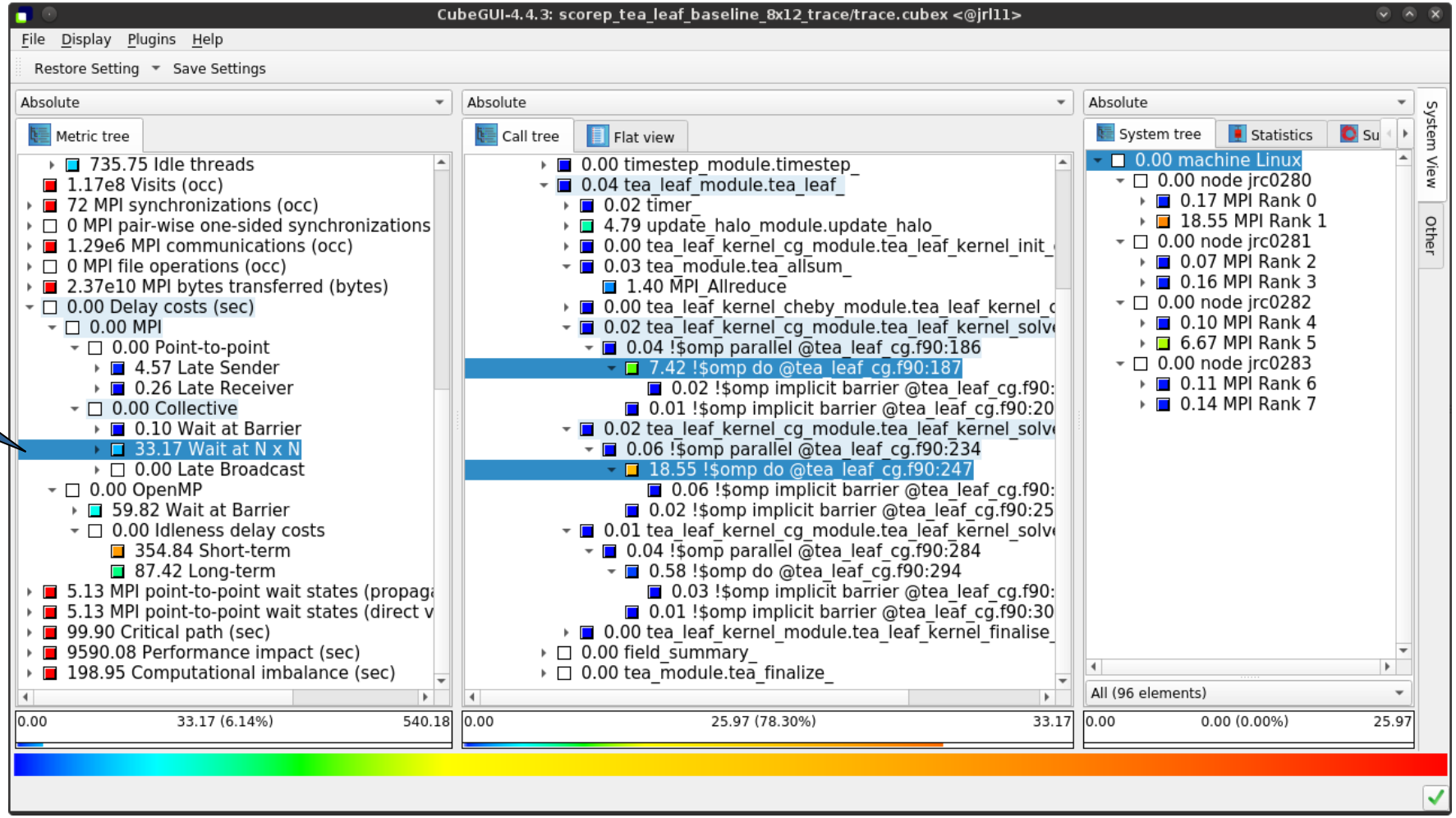


…they directly cause a significant amount of the OpenMP thread idleness

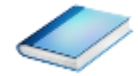


TeaLeaf Scalasca report analysis (III)

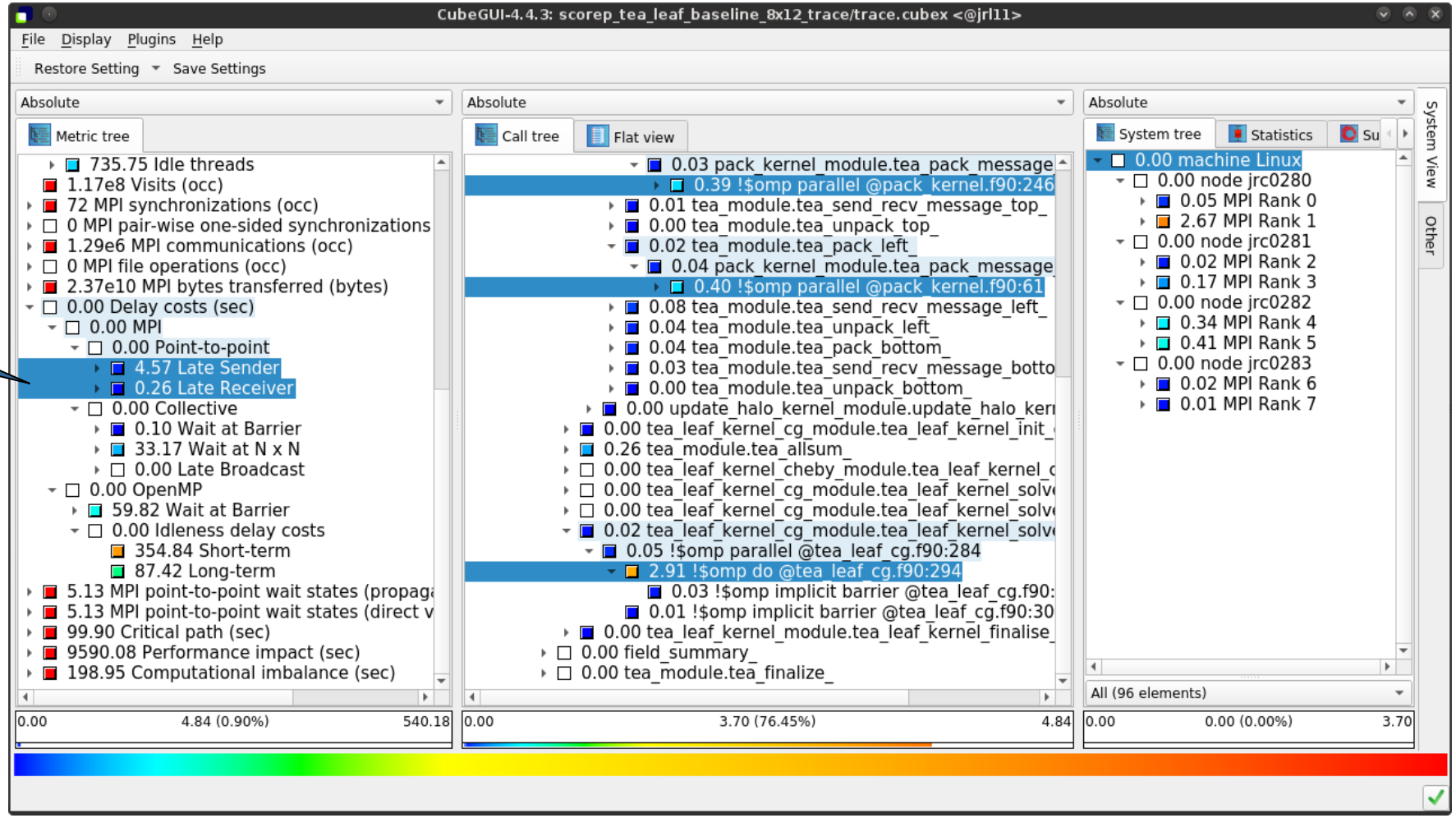
The “Wait at NxN” collective wait states are mostly caused by the first 2 OpenMP `do` loops of the solver (on ranks 5 & 1, resp.)…



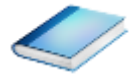
TeaLeaf Scalasca report analysis (IV)



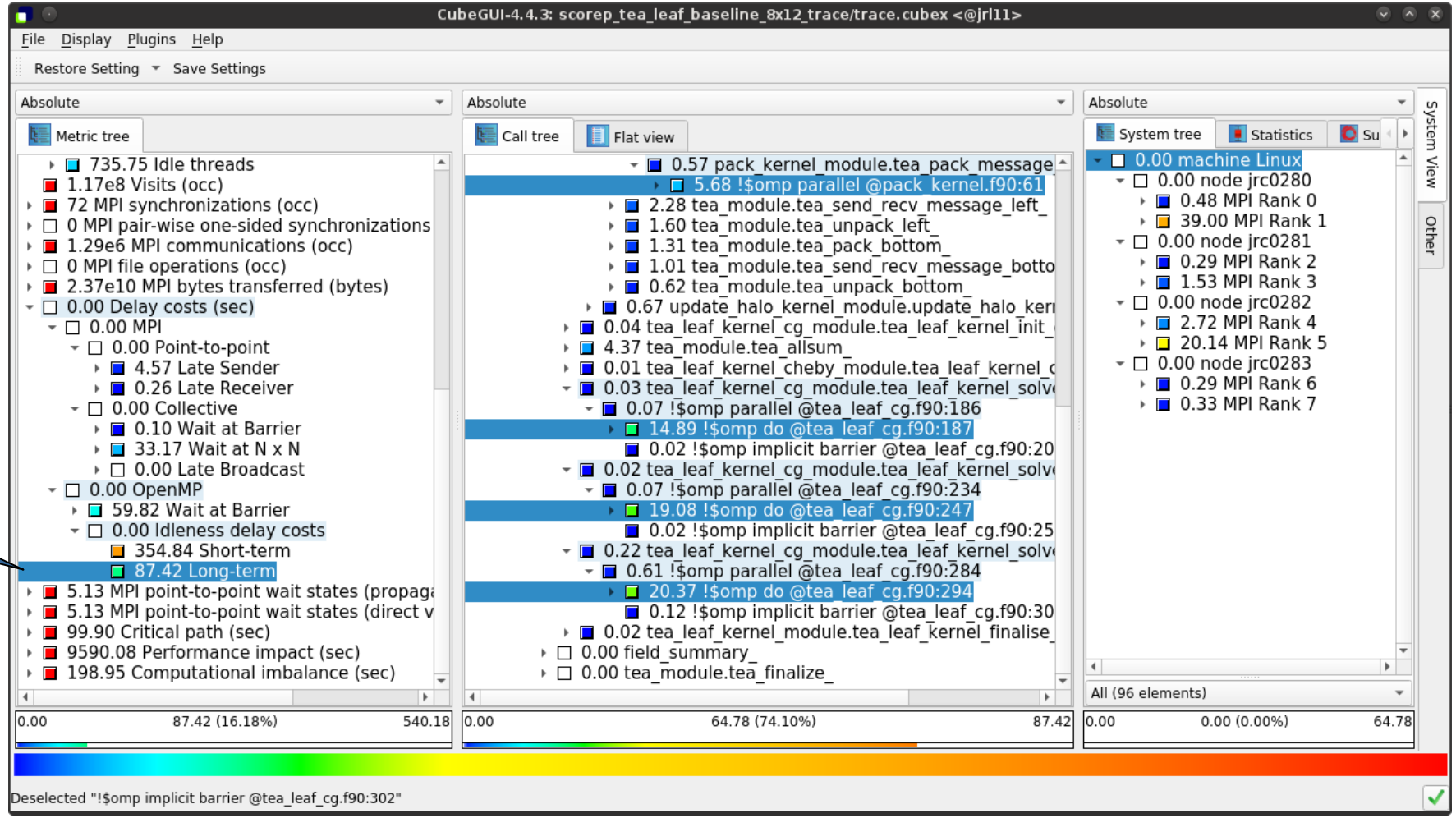
…while the MPI point-to-point wait states are caused by the 3rd solver `do` loop (on rank 1) and two loops in the halo exchange



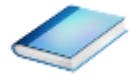
TeaLeaf Scalasca report analysis (V)



Various OpenMP `do` loops (incl. the solver loops) also cause OpenMP thread idleness on other ranks via propagation



TeaLeaf Scalasca report analysis (VI)



The Critical Path also highlights the three solver loops…

CubeGUI-4.4.3: scorep_tea_leaf_baseline_8x12_trace/trace.cubex <@jrl11>

File Display Plugins Help

Restore Setting Save Settings

Absolute | Absolute | Absolute

Metric tree | Call tree | Flat view | System tree | Statistics | Su

- 735.75 Idle threads
- 1.17e8 Visits (occ)
- 72 MPI synchronizations (occ)
- 0 MPI pair-wise one-sided synchronizations
- 1.29e6 MPI communications (occ)
- 0 MPI file operations (occ)
- 2.37e10 MPI bytes transferred (bytes)
- 0.00 Delay costs (sec)
  - 0.00 MPI
    - 0.00 Point-to-point
      - 4.57 Late Sender
      - 0.26 Late Receiver
    - 0.00 Collective
      - 0.10 Wait at Barrier
      - 33.17 Wait at N x N
      - 0.00 Late Broadcast
  - 0.00 OpenMP
    - 59.82 Wait at Barrier
    - 0.00 Idleness delay costs
      - 354.84 Short-term
      - 87.42 Long-term
- 5.13 MPI point-to-point wait states (propaga
- 5.13 MPI point-to-point wait states (direct v
- 99.90 Critical path (sec)
- 9590.08 Performance impact (sec)
- 198.95 Computational imbalance (sec)

- 0.00 timer_
- 0.00 set_field_module.set_field_
- 0.00 timestep_module.timestep_
- 0.08 tea_leaf_module.tea_leaf_
  - 0.03 timer_
  - 4.04 update_halo_module.update_halo_
  - 0.11 tea_leaf_kernel_cg_module.tea_leaf_kernel_init_
  - 0.84 tea_module.tea_allsum_
  - 0.01 tea_leaf_kernel_cheby_module.tea_leaf_kernel_c
  - 0.03 tea_leaf_kernel_cg_module.tea_leaf_kernel_solv
    - 0.15 !$omp parallel @tea_leaf_cg.f90:186
      - 37.74 !$omp do @tea_leaf_cg.f90:187
        - 0.06 !$omp implicit barrier @tea_leaf_cg.f90:
        - 0.02 !$omp implicit barrier @tea_leaf_cg.f90:20
  - 0.04 tea_leaf_kernel_cg_module.tea_leaf_kernel_solv
    - 0.29 !$omp parallel @tea_leaf_cg.f90:234
      - 38.10 !$omp do @tea_leaf_cg.f90:247
        - 0.07 !$omp implicit barrier @tea_leaf_cg.f90:
        - 0.03 !$omp implicit barrier @tea_leaf_cg.f90:25
  - 0.03 tea_leaf_kernel_cg_module.tea_leaf_kernel_solv
    - 0.25 !$omp parallel @tea_leaf_cg.f90:284
      - 17.22 !$omp do @tea_leaf_cg.f90:294
        - 0.07 !$omp implicit barrier @tea_leaf_cg.f90:
        - 0.03 !$omp implicit barrier @tea_leaf_cg.f90:30
  - 0.01 tea_leaf_kernel_module.tea_leaf_kernel_finalise_
- 0.00 field_summary_

- 0.00 machine Linux
  - 0.00 node jrc0280
    - 0.52 MPI Rank 0
    - 38.93 MPI Rank 1
  - 0.00 node jrc0281
    - 0.33 MPI Rank 2
    - 13.35 MPI Rank 3
  - 0.00 node jrc0282
    - 0.91 MPI Rank 4
    - 38.44 MPI Rank 5
  - 0.00 node jrc0283
    - 0.26 MPI Rank 6
    - 0.32 MPI Rank 7

System View | Other

All (96 elements)

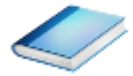
0.00 | 99.90 (100.00%) | 99.90

0.00 | 93.06 (93.16%) | 99.90

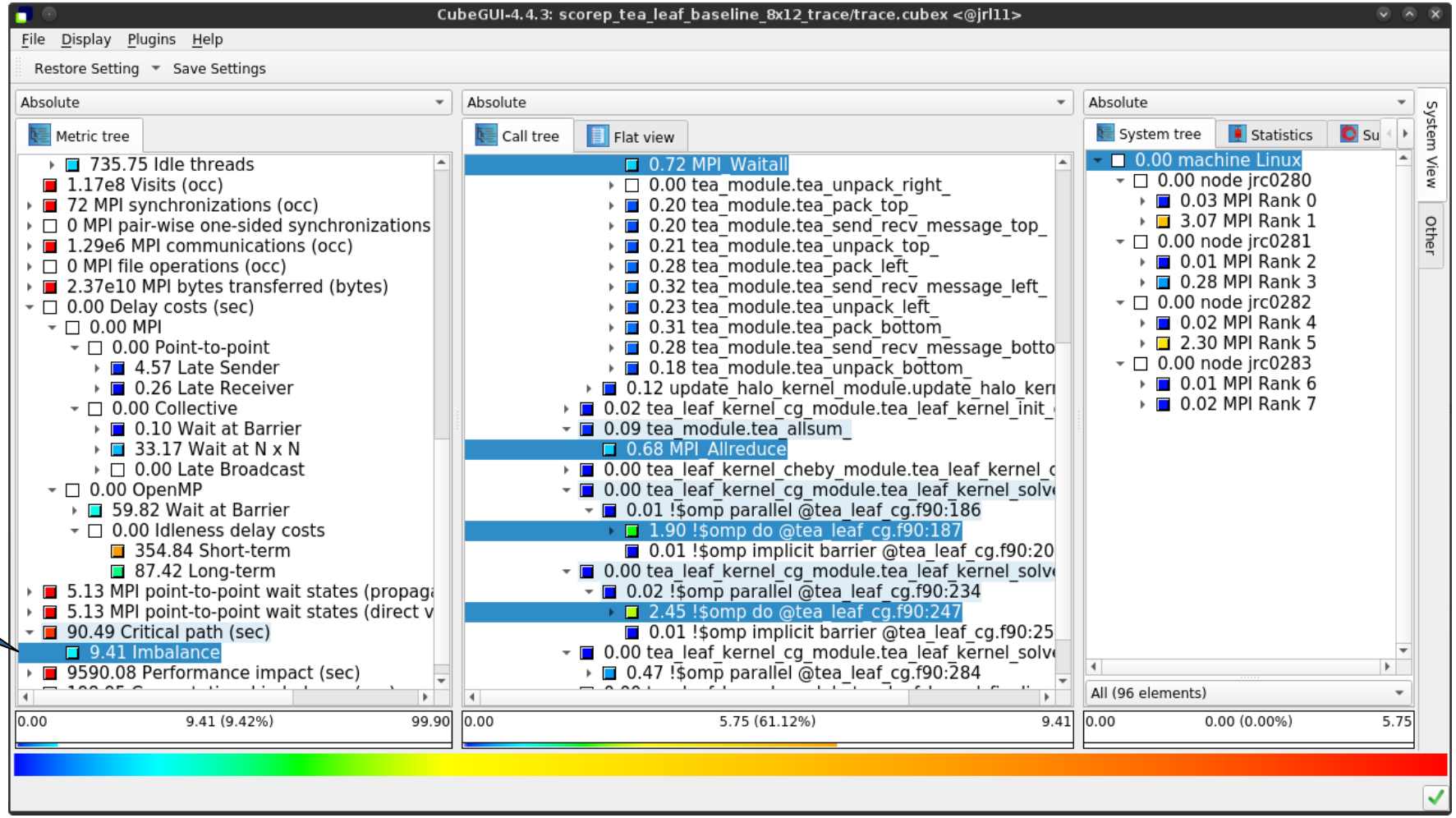
0.00 | 0.00 (0.00%) | 93.06

Ready

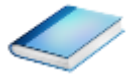
TeaLeaf Scalasca report analysis (VII)



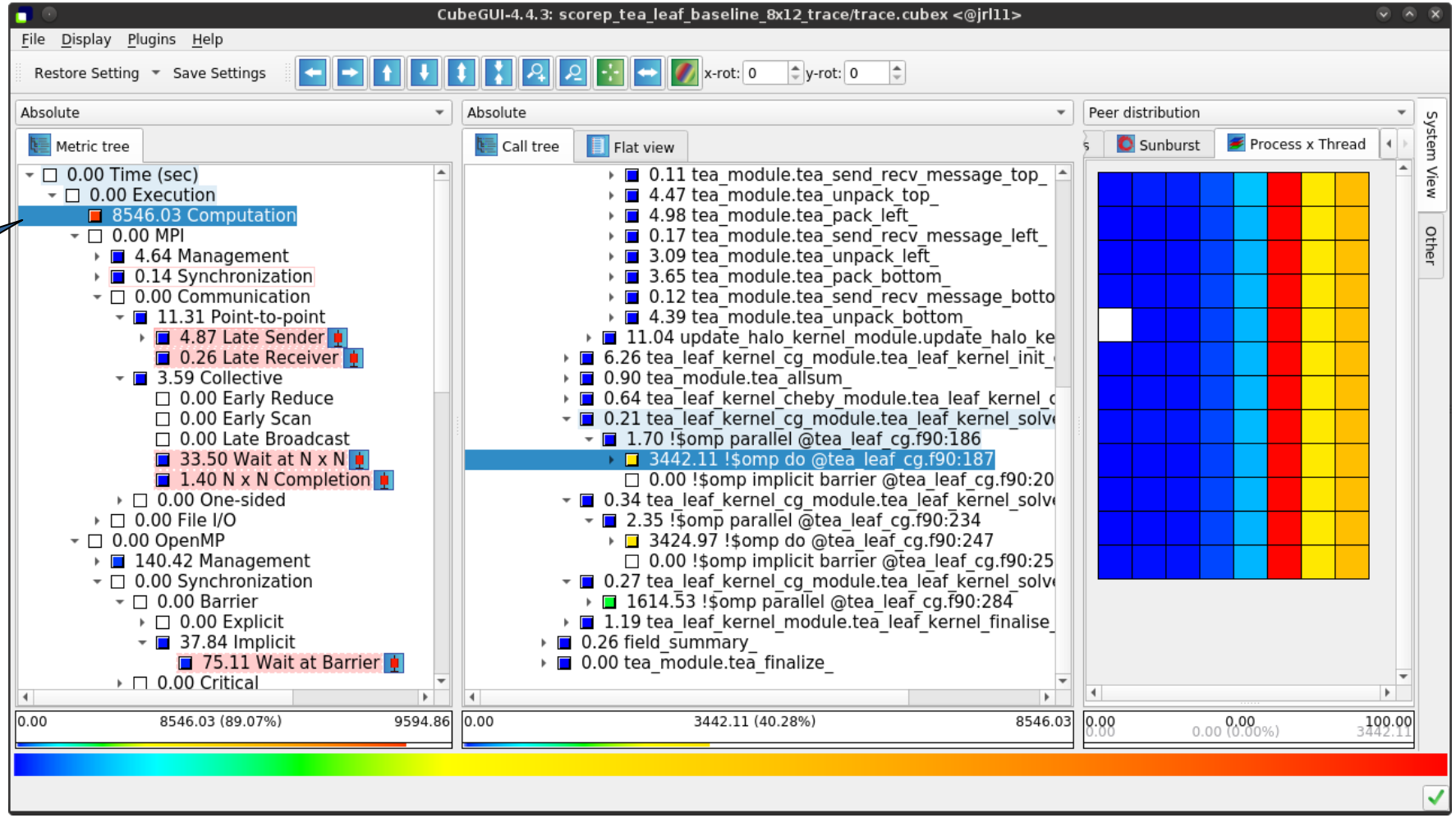
…with imbalance (time on critical path above average) mostly in the first two loops and MPI communication



TeaLeaf Scalasca report analysis (VIII)

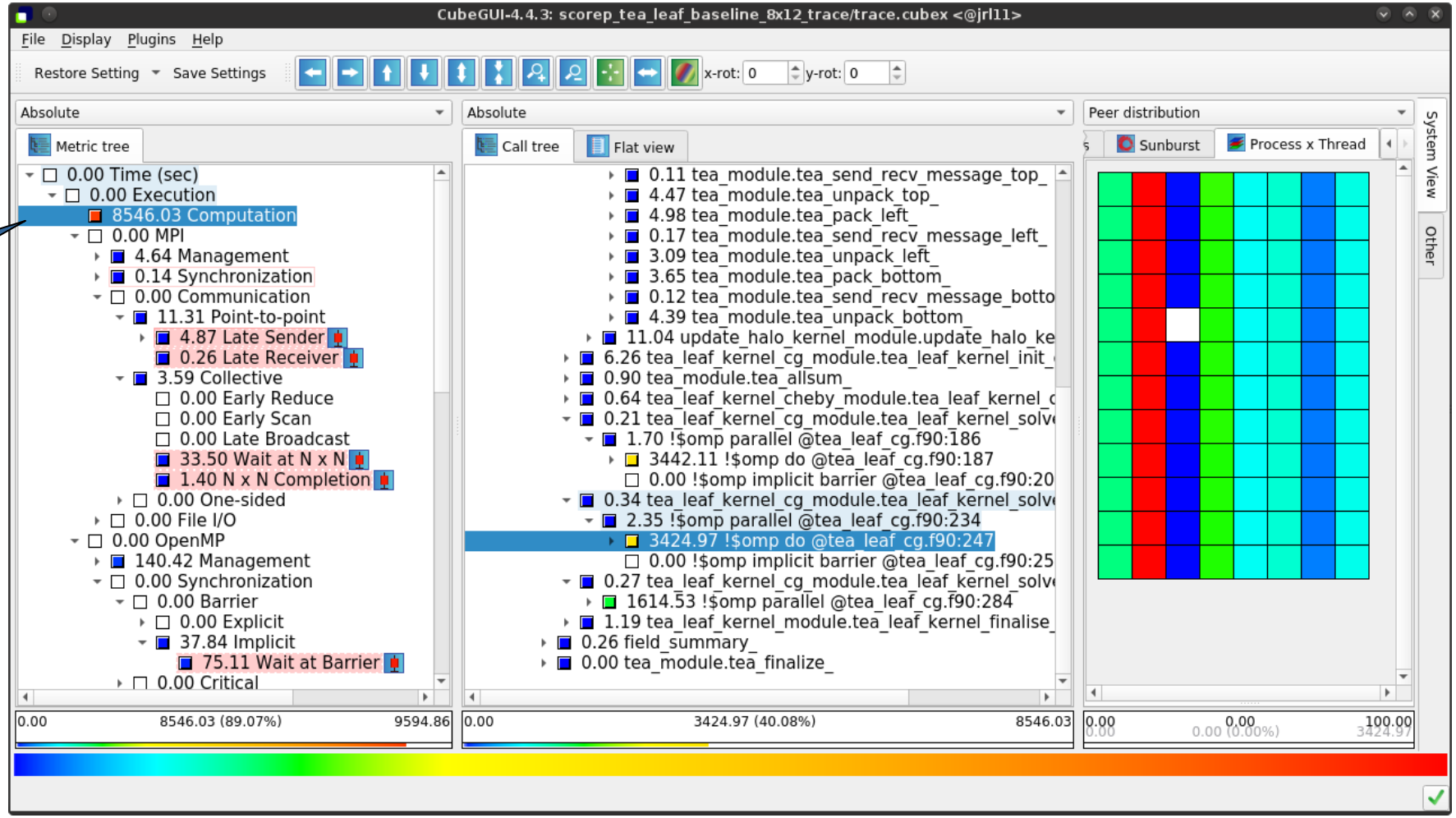


Computation time of 1st…



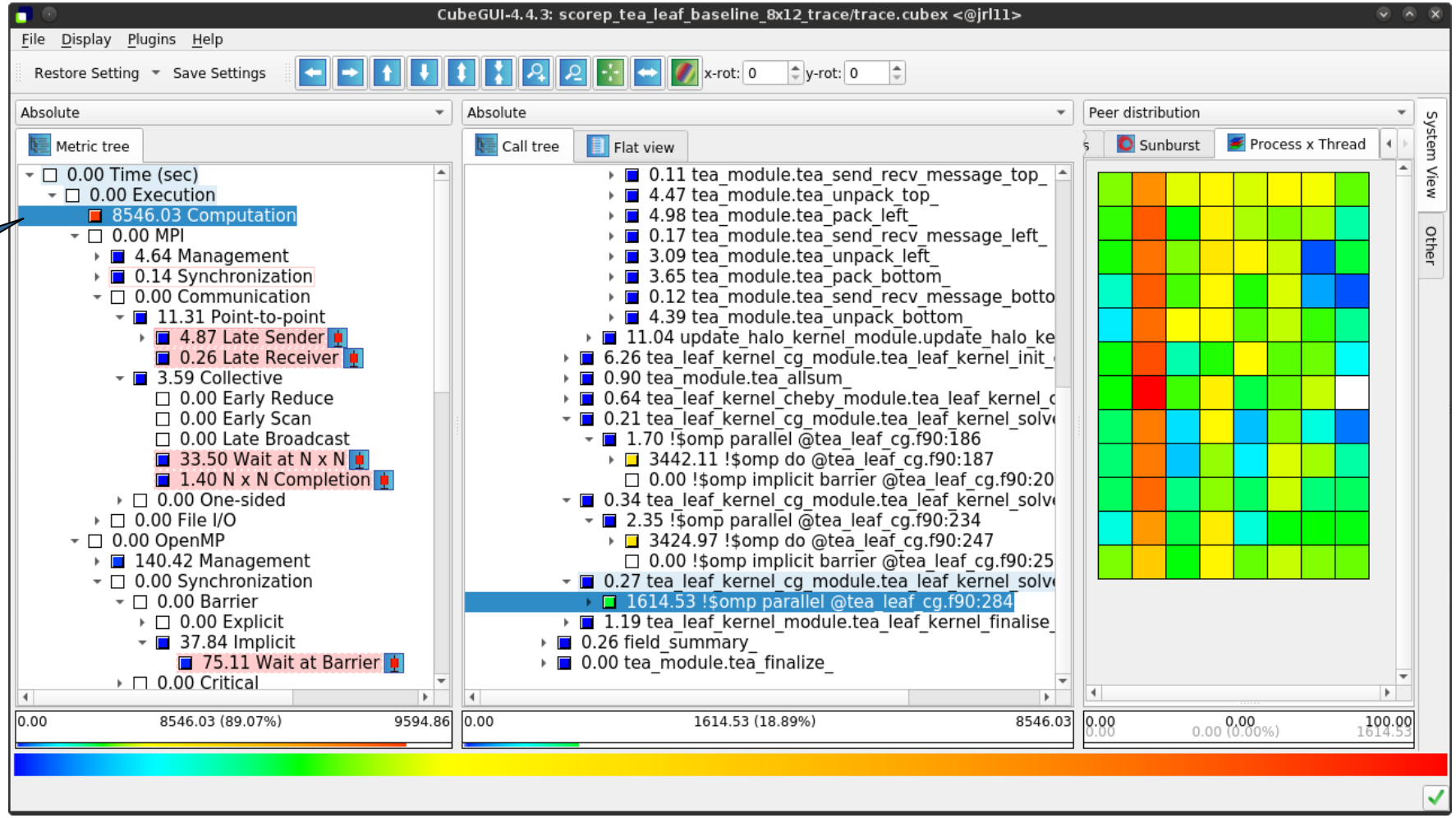
TeaLeaf Scalasca report analysis (IX)

…and 2nd `do` loop mostly balanced within each rank, but vary considerably across ranks…



TeaLeaf Scalasca report analysis (X)

…while the 3rd do loop also shows imbalance within each rank



TeaLeaf analysis summary

- The first two OpenMP do loops of the solver are well balanced within a rank, but are imbalanced across ranks
  - ➔ Requires a global load balancing strategy
- The third OpenMP do loop, however, is imbalanced within ranks,
  - causing direct "Wait at OpenMP Barrier" wait states,
  - which cause indirect MPI point-to-point wait states,
  - which in turn cause OpenMP thread idleness
  - ➔ Low-hanging fruit

- Adding a `SCHEDULE(guided)` clause reduced
  - the MPI point-to-point wait states by ~66%
  - the MPI collective wait states by ~50%
  - the OpenMP "Wait at Barrier" wait states by ~55%
  - the OpenMP thread idleness by ~11%
  - ➔ **Overall runtime (wall-clock) reduction by ~5%**

Scalasca Trace Tools: Further information

- Collection of trace-based performance tools
  - Specifically designed for large-scale systems
  - Features an automatic trace analyzer providing wait-state, critical-path, and delay analysis
  - Supports MPI, OpenMP, POSIX threads, and hybrid MPI+OpenMP/Pthreads
- Available under 3-clause BSD open-source license

- Documentation & sources:
  - https://www.scalasca.org
- Contact:
  - mailto: scalasca@fz-juelich.de

Reference material

Scalasca command – One command for (almost) everything

```
% scalasca
Scalasca 2.6.2
Toolset for scalable performance analysis of large-scale parallel applications
usage: scalasca [OPTION]... ACTION <argument>...
    1. prepare application objects and executable for measurement:
       scalasca -instrument <compile-or-link-command> # skin (using scorep)
    2. run application under control of measurement system:
       scalasca -analyze <application-launch-command> # scan
    3. interactively explore measurement analysis report:
       scalasca -examine <experiment-archive|report>  # square

Options:
   -c, --show-config     show configuration summary and exit
   -h, --help            show this help and exit
   -n, --dry-run         show actions without taking them
       --quickref        show quick reference guide and exit
       --remap-specfile  show path to remapper specification file and exit
   -v, --verbose         enable verbose commentary
   -V, --version         show version information and exit
```

- The ‘`scalasca -instrument`’ command is deprecated and will be remove in the next major release
  ⇨ use Score-P instrumenter directly

Scalasca convenience command: scan / scalasca -analyze

```
% scan
Scalasca 2.6.2: measurement collection & analysis nexus
usage: scan {options} [launchcmd [launchargs]] target [targetargs]
      where {options} may include:
  -h    Help       : show this brief usage message and exit.
  -v    Verbose    : increase verbosity.
  -n    Preview    : show command(s) to be launched but don't execute.
  -q    Quiescent  : execution with neither summarization nor tracing.
  -s    Summary    : enable runtime summarization. [Default]
  -t    Tracing    : enable trace collection and analysis.
  -a    Analyze    : skip measurement to (re-)analyze an existing trace.
  -e exptdir       : Experiment archive to generate and/or analyze.
                     (overrides default experiment archive title)
  -f filtfile      : File specifying measurement filter.
  -l lockfile      : File that blocks start of measurement.
  -R #runs         : Specify the number of measurement runs per config.
  -M cfgfile       : Specify a config file for a multi-run measurement.
  -P preset        : Specify a preset for a multi-run measurement, e.g., 'pop'.
  -L               : List available multi-run presets.
  -D cfgfile       : Check a multi-run config file for validity and dump
                   : the processed configuration for comparison.
```

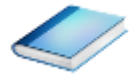
- Scalasca measurement collection & analysis nexus

Scalasca convenience command: square / scalasca -examine

```
% square
Scalasca 2.6.2: analysis report explorer
usage: square [OPTIONS] <experiment archive | cube file>
  -C <none | quick | full> : Level of sanity checks for newly created reports
  -c <number>              : Consider number of counters when doing scoring (-s)
  -F                       : Force remapping of already existing reports
  -f filtfile              : Use specified filter file when doing scoring (-s)
  -s                       : Skip display and output textual score report
  -v                       : Enable verbose mode
  -n                       : Do not include idle thread metric
  -S <mean | merge>        : Aggregation method for summarization results of
                             each configuration (default: merge)
  -T <mean | merge>        : Aggregation method for trace analysis results of
                             each configuration (default: merge)
  -A                       : Post-process every step of a multi-run experiment
  -I                       : Ignore structural sanity checks and force aggregation
                             of measurements in a multi-run experiment
  -x <scorep-score opt>    : Pass option(s) to scorep-score
```

- Scalasca analysis report explorer (Cube)

Scalasca advanced command: scout - Scalasca automatic trace analyzer

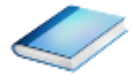


```
% scout.hyb --help
SCOUT   (Scalasca 2.6.2)
Copyright (c) 1998-2022 Forschungszentrum Juelich GmbH
Copyright (c) 2014-2021 RWTH Aachen University
Copyright (c) 2009-2014 German Research School for Simulation Sciences GmbH

Usage: <launchcmd> scout.hyb [OPTION]... <ANCHORFILE | EPIK DIRECTORY>
Options:
  --statistics       Enables instance tracking and statistics [default]
  --no-statistics    Disables instance tracking and statistics
  --critical-path    Enables critical-path analysis [default]
  --no-critical-path Disables critical-path analysis
  --rootcause        Enables root-cause analysis [default]
  --no-rootcause     Disables root-cause analysis
  --single-pass      Single-pass forward analysis only
  --time-correct     Enables enhanced timestamp correction
  --no-time-correct  Disables enhanced timestamp correction [default]
  --verbose, -v      Increase verbosity
  --help             Display this information and exit
```

- Provided in serial (.ser), OpenMP (.omp), MPI (.mpi) and MPI+OpenMP (.hyb) variants

Scalasca advanced command: clc_synchronize

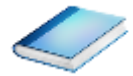


- Scalasca trace event timestamp consistency correction

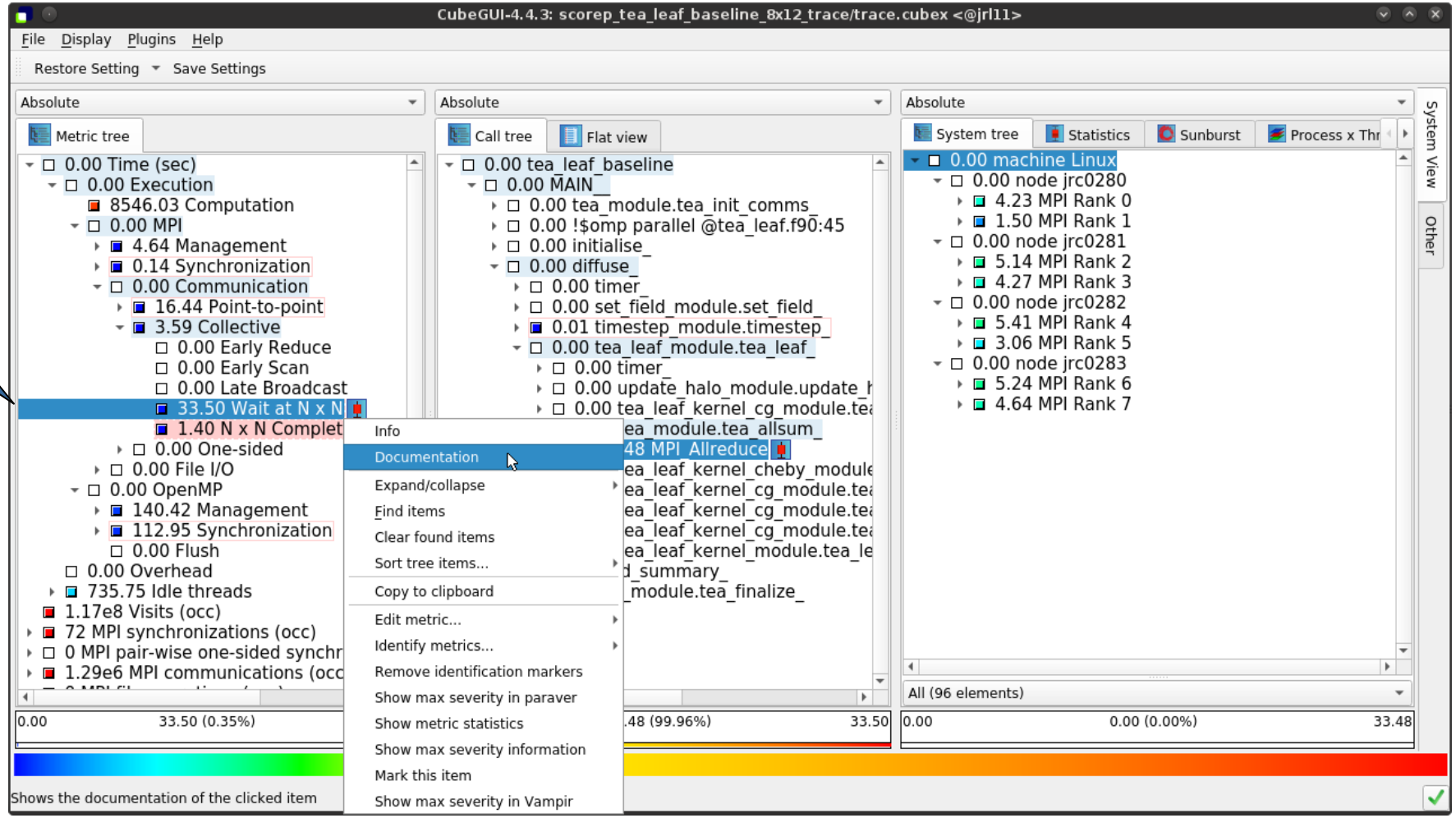
```
Usage: <launchcmd> clc_synchronize.hyb <ANCHORFILE | EPIK_DIRECTORY>
```

  - Provided in MPI (.mpi) and MPI+OpenMP (.hyb) variants
  - Takes as input a trace experiment archive where the events may have timestamp inconsistencies
    - E.g., multi-node measurements on systems without adequately synchronized clocks on each compute node
  - Generates a new experiment archive (always called ./clc_sync) containing a trace with event timestamp inconsistencies resolved
    - E.g., suitable for detailed examination with a time-line visualizer

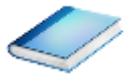
Online metric description



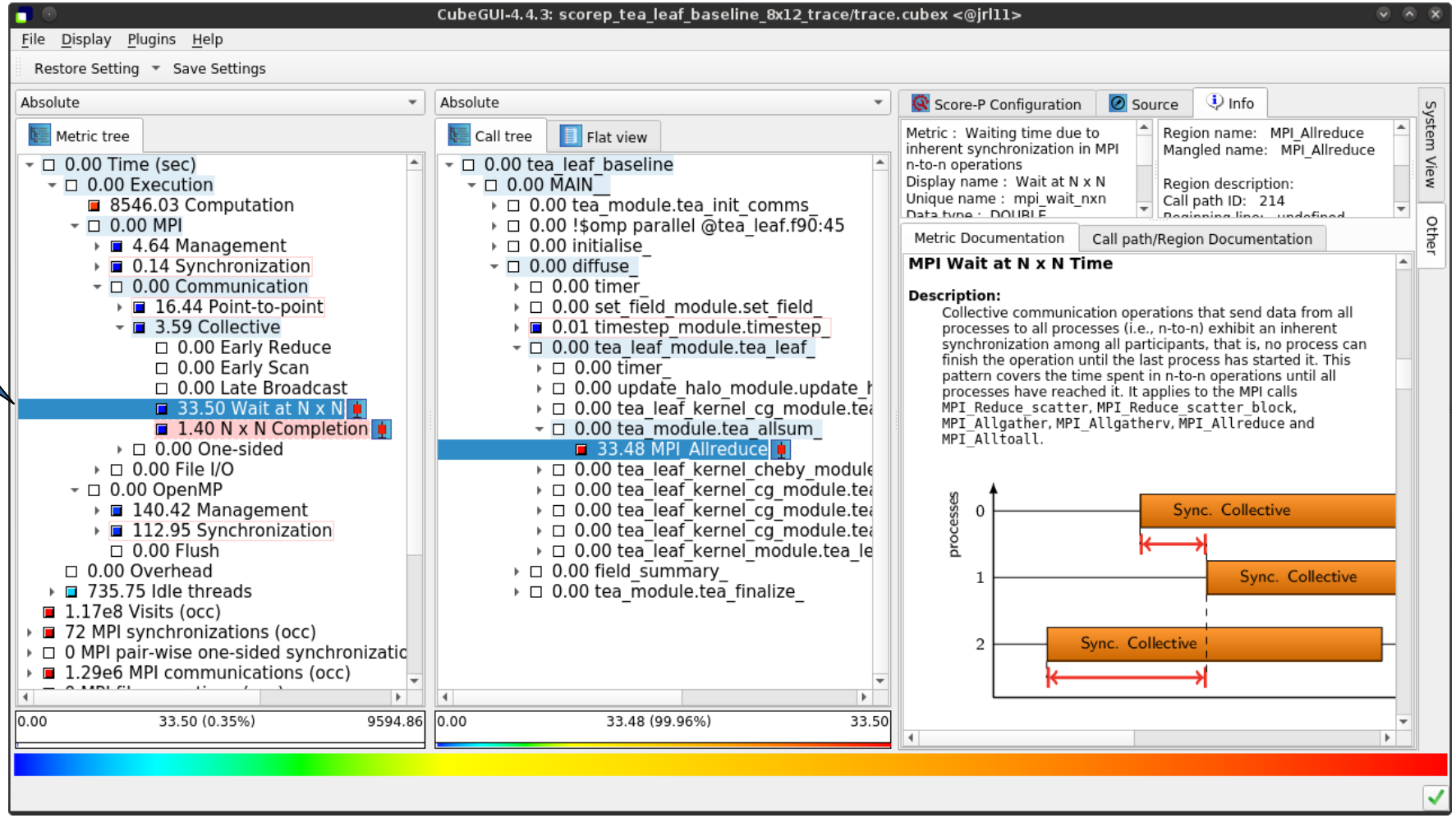
Access online metric description via context menu (right-click)



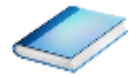
Online metric description (cont.)



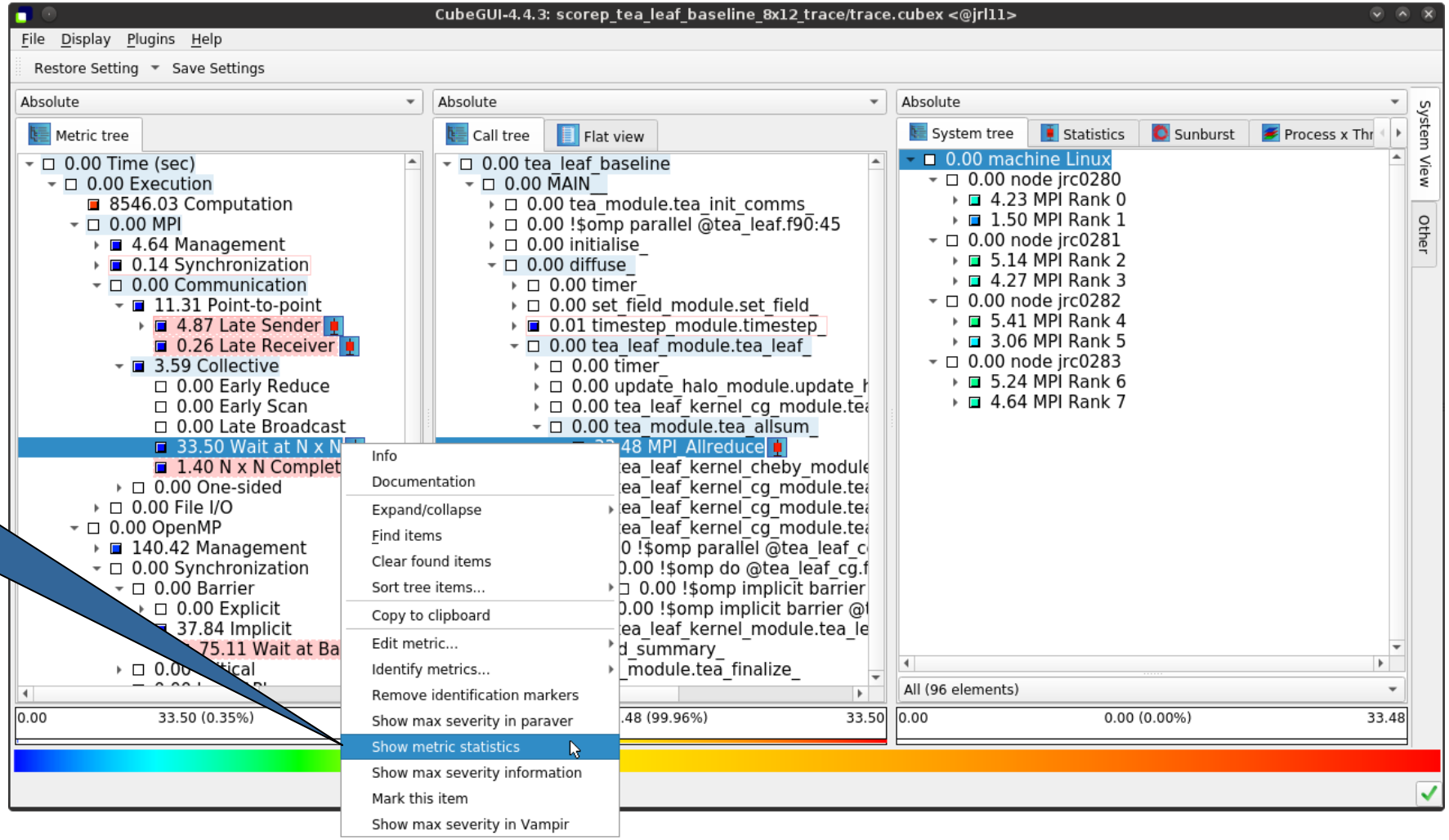
Selection of different metric automatically updates description



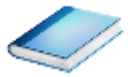
Metric statistics



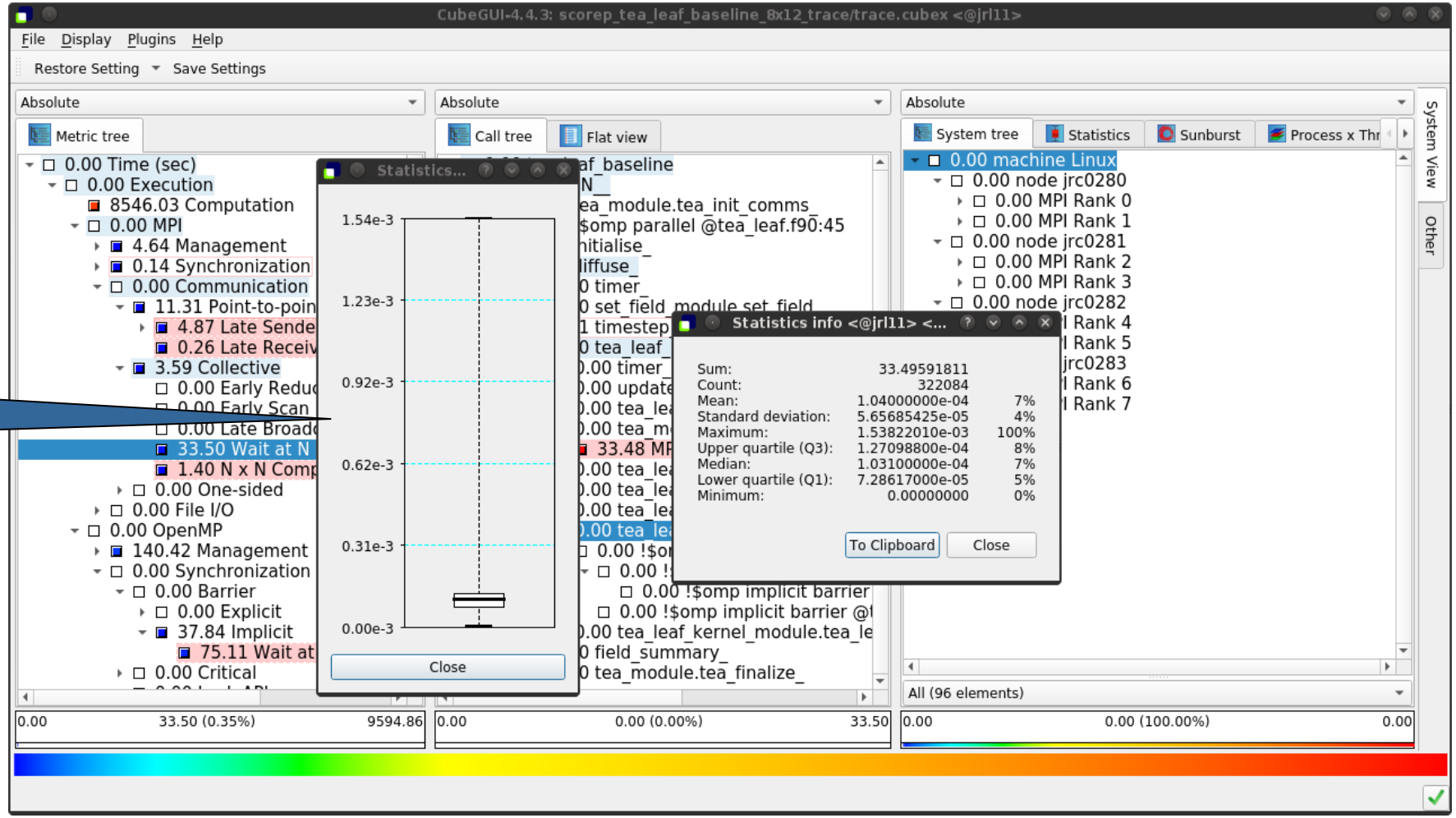
Access metric statistics for metrics marked with box plot icon from context menu



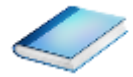
Metric statistics (cont.)



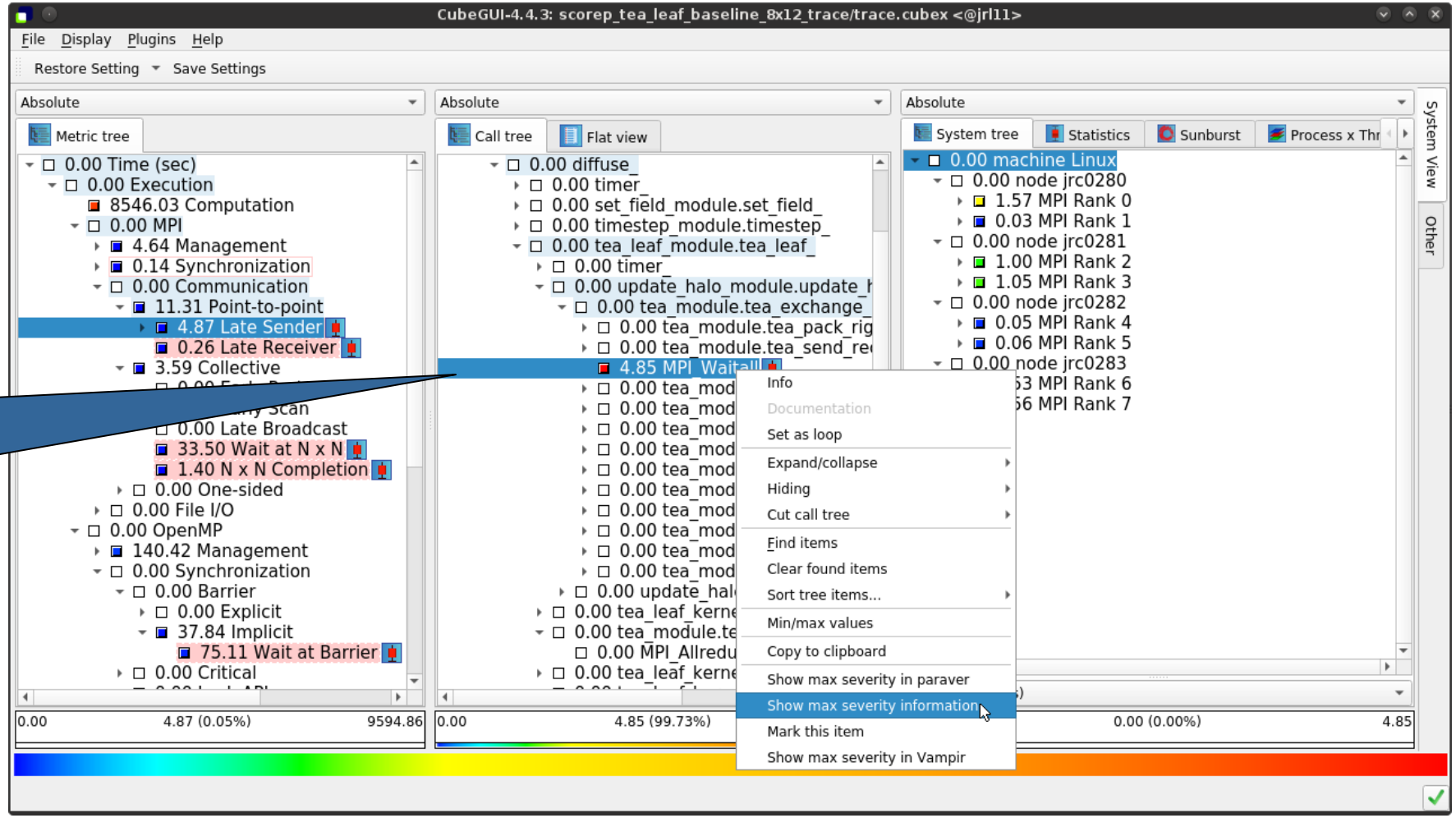
Shows instance statistics box plot, click to get details



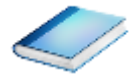
Metric instance statistics



Access most-severe instance information for call paths marked with box plot icon via context menu



Metric instance statistics (cont.)



Shows instance details