CLAW DSL - Abstraction for Performance Portable Weather and Climate Models

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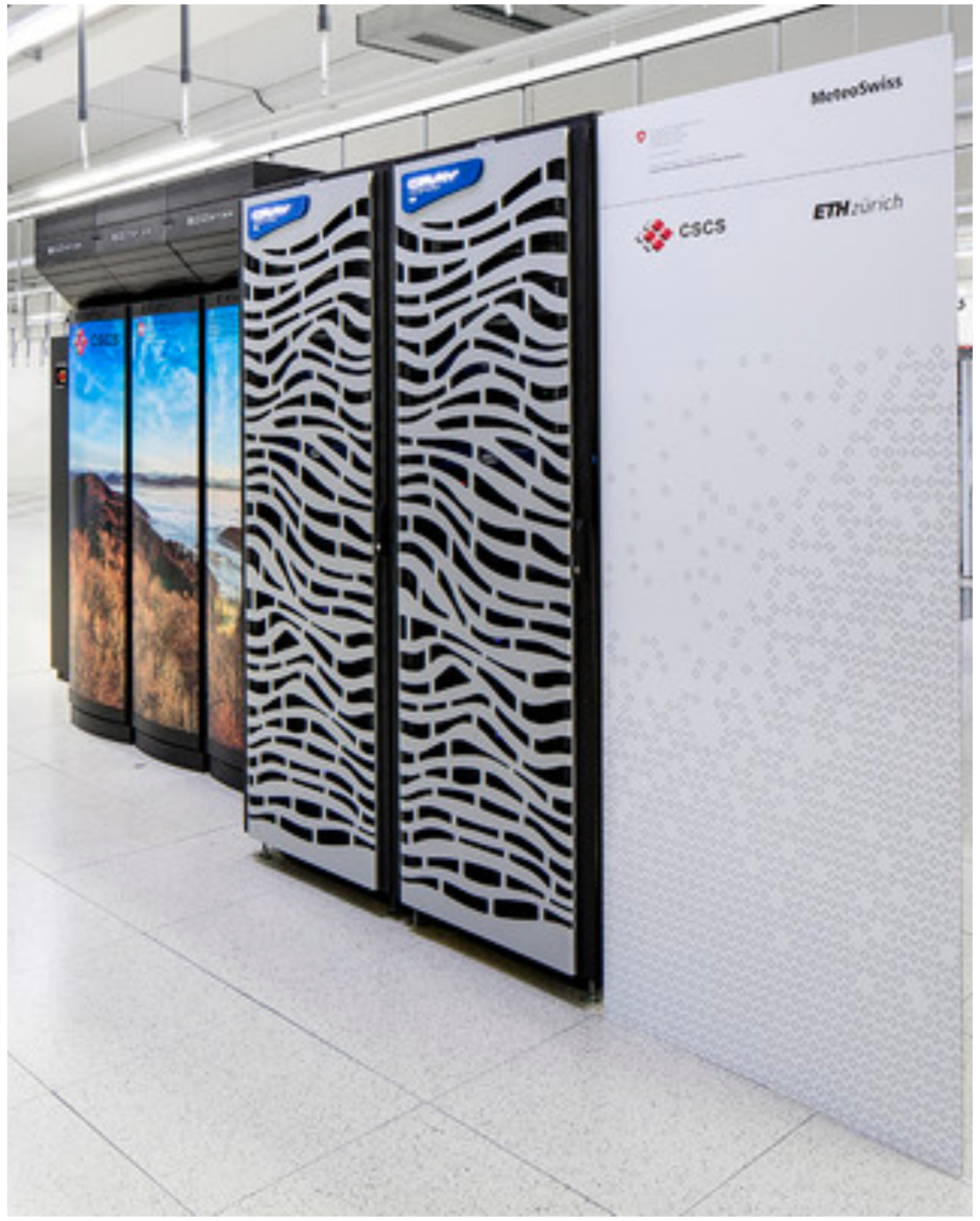
The Beginning - Performance Portability Problem

Porting COSMO to hybrid architecture



Twelve hybrid compute nodes with:

- 2 Intel Haswell E5-2690v3 2.6 GHz 12-core CPUs per node
- 8 NVIDIA Tesla K80 GPU devices per node
- 256 GB 2133 MHz DDR4 memory per node

Porting COSMO to hybrid architecture

Initialization

Copy to accelerator

Δt

- Boundary conditions → OpenACC port
- Physics → OpenACC port

Interface

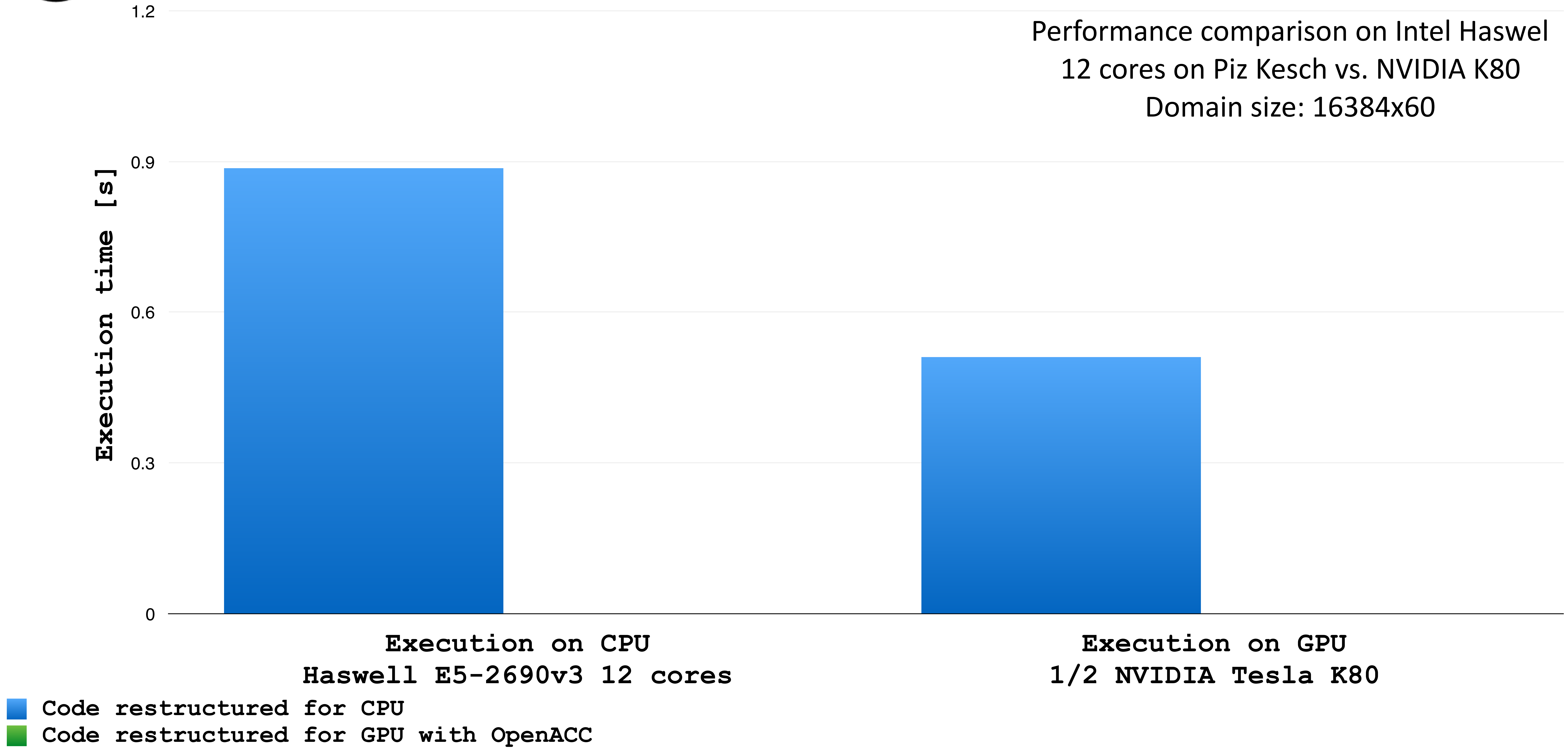
- Dynamics → C++ / DSL rewrite

Interface

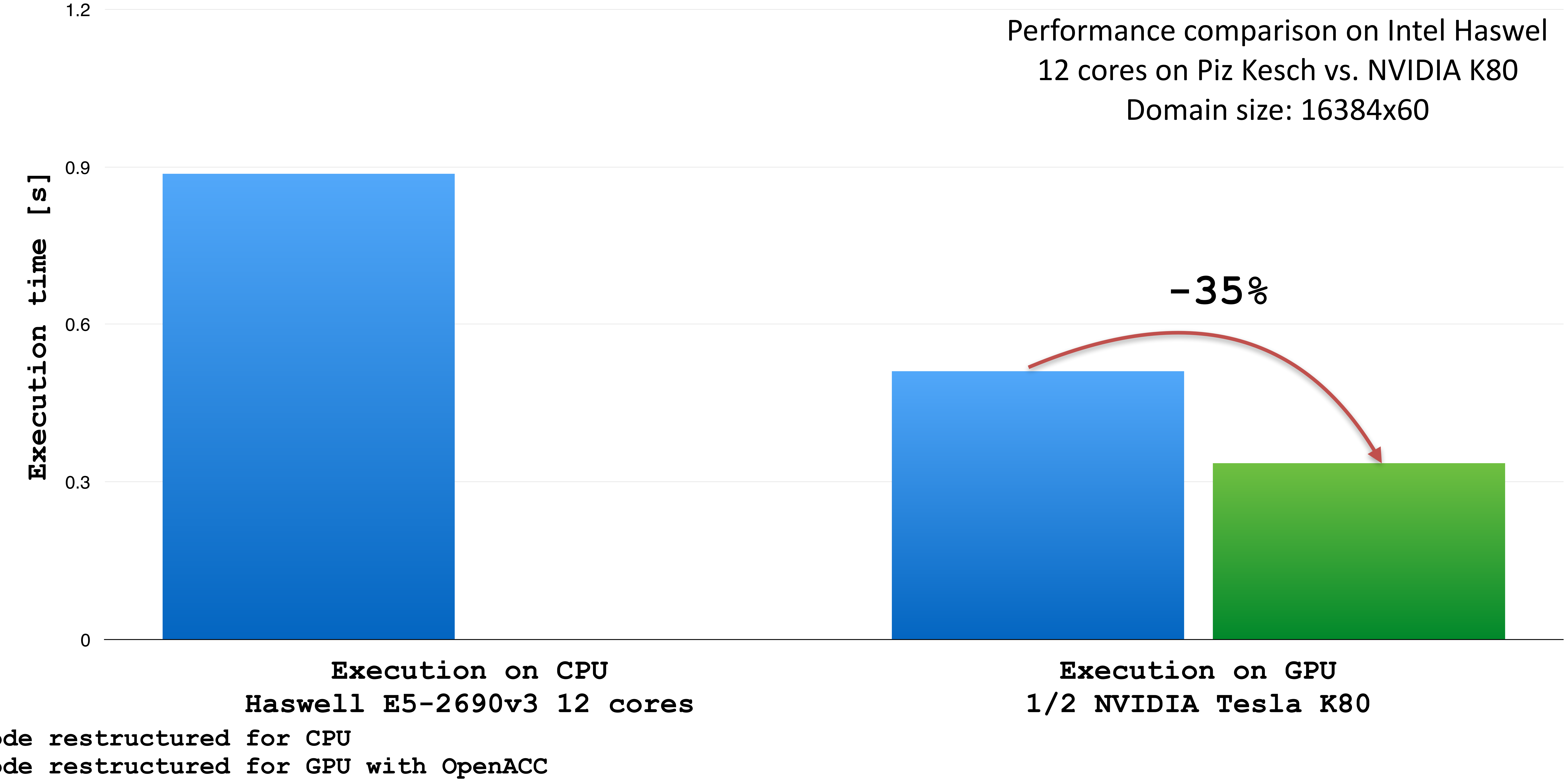
- Data assimilation → Mixed OpenACC / CPU
- Halo-update → Communication library (GCL)
- Diagnostics → OpenACC port
- Input / Output → Mixed OpenACC / CPU

Cleanup

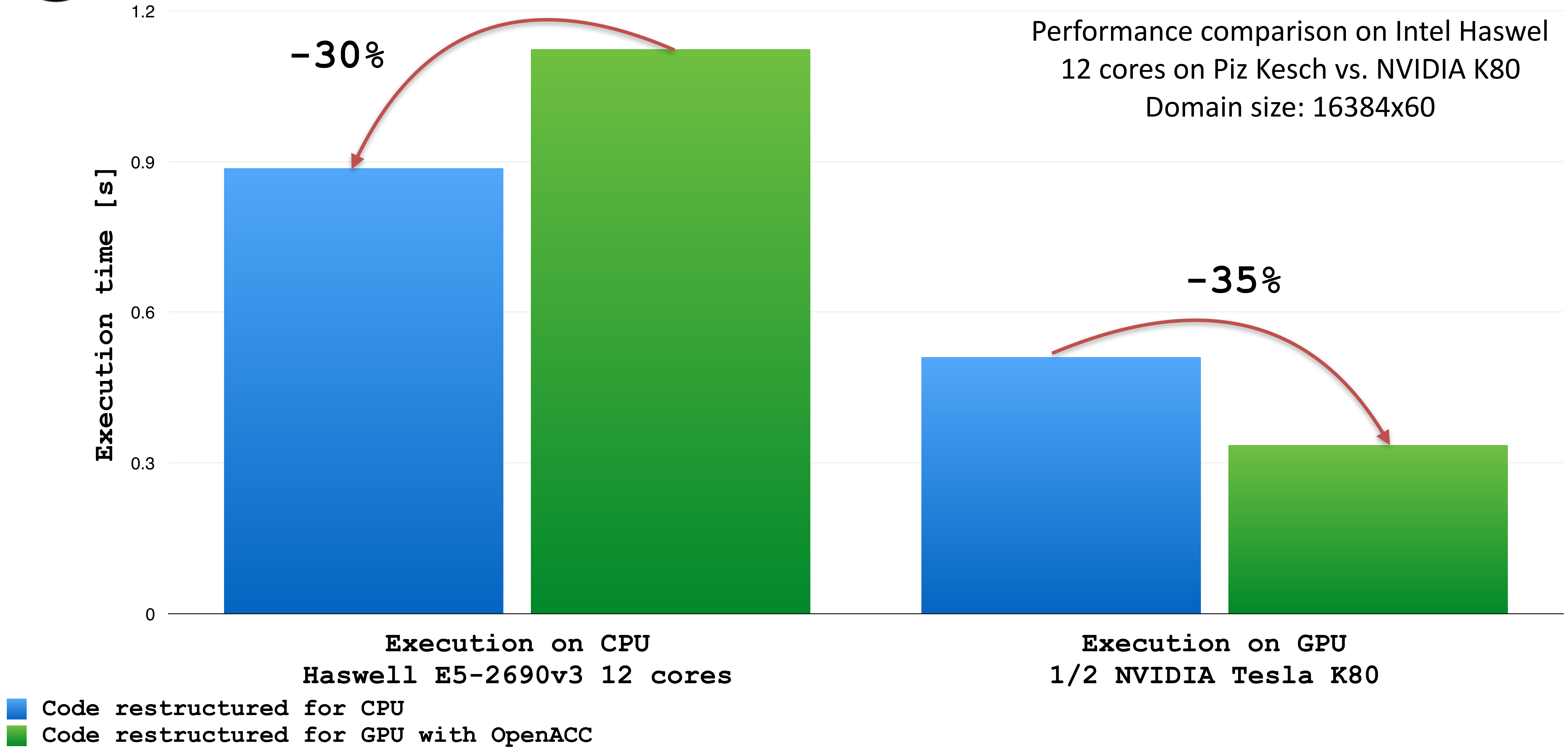
Performance portability problem - COSMO Radiation



Performance portability problem - COSMO Radiation



Performance portability problem - COSMO Radiation



Performance portability problem - COSMO Radiation

CPU structure

```
DO k=1,nz
  CALL fct()
  DO j=1,nproma
    ! 1st loop body
  END DO
  DO j=1,nproma
    ! 2nd loop body
  END DO
  DO j=1,nproma
    ! 3rd loop body
  END DO
END DO
```

GPU structure

```
!$acc parallel loop
DO j=1,nproma
  !$acc loop
  DO k=1,nz
    CALL fct()
    ! 1st loop body
    ! 2nd loop body
    ! 3rd loop body
  END DO
END DO
!$acc end parallel
```

Weather & Climate Models - One code, many users

- Several Institutes and Universities with different hardware
- Massive code base (200’000 to >1mio LOC)
  - Long development cycle
  - Several architecture specific optimization survive along the versions
  - Most of these code base are CPU optimized
    - Not suited for some architecture
    - Not suited for massive parallelism
  - Software engineering: few or no modularity
    - Physical parameterization hardly extractable to the main model

Performance portability problem - Keep two or more code?

```
#ifndef _OPENACC
DO k=1,nz
  CALL fct()
  DO j=1,nproma
    ! 1st loop body
  END DO
  DO j=1,nproma
    ! 2nd loop body
  END DO
  DO j=1,nproma
    ! 3rd loop body
  END DO
END DO
#else
!$acc parallel loop
DO j=1,nproma
  !$acc loop
  DO k=1,nz
    CALL fct()
    ! 1st loop body
    ! 2nd loop body
    ! 3rd loop body
  END DO
END DO
!$acc end parallel
#endif
```

CPU loop structure

GPU loop structure

- Multiple code paths
- Hard maintenance
- Error prone
- Domain scientists have to know well each target architectures

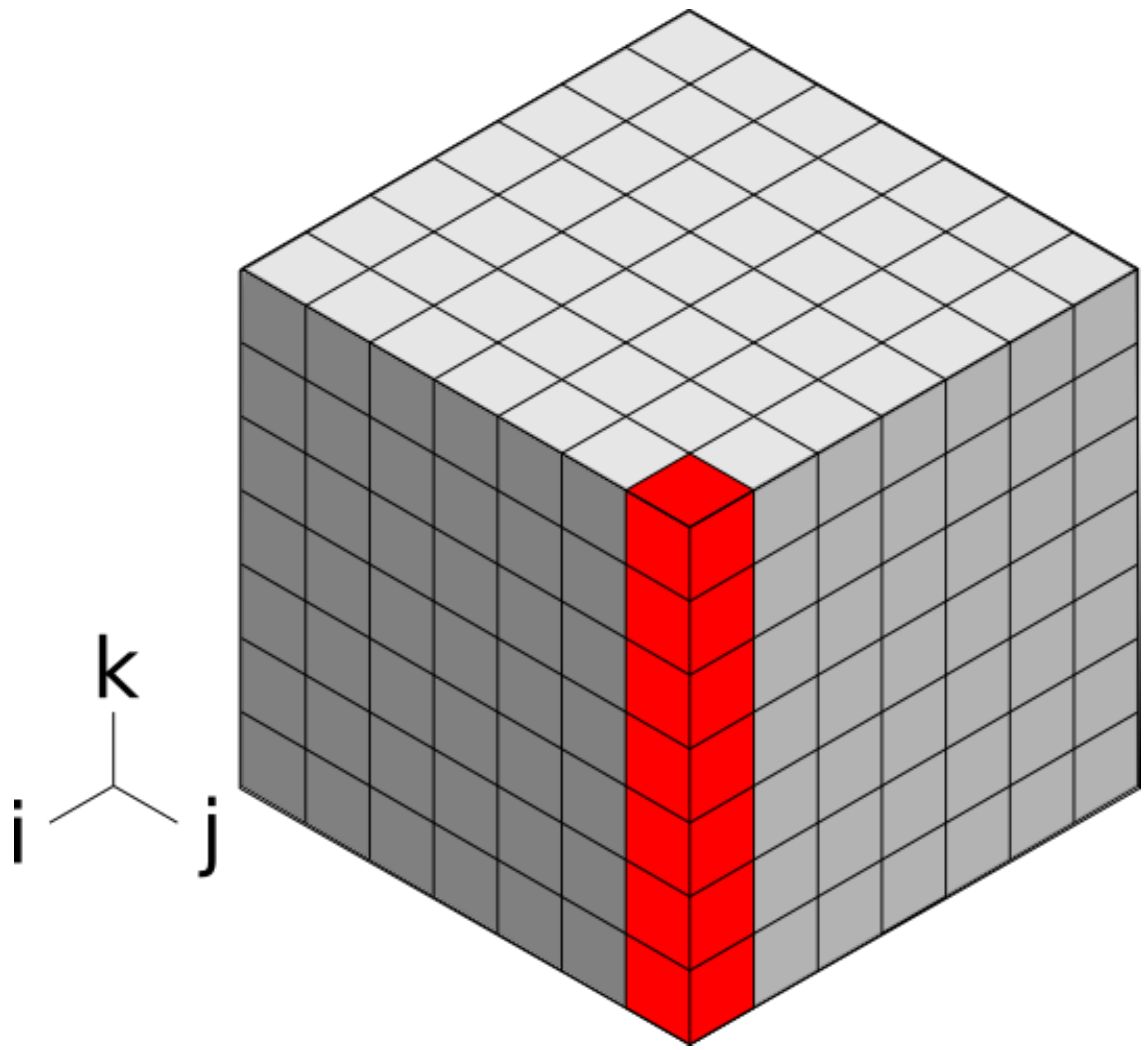
Performance portability from a single source code

- What is the best loop structure/data layout for next architecture?
- Do we want to rewrite the code each time?
- Do we have the resources to do that?
- Do we know exactly which architecture we will run on?
- Do we want to maintain a dedicated version for each architecture?

?

DSL - Single Column Abstraction

CLAW Single Column Abstraction (SCA)



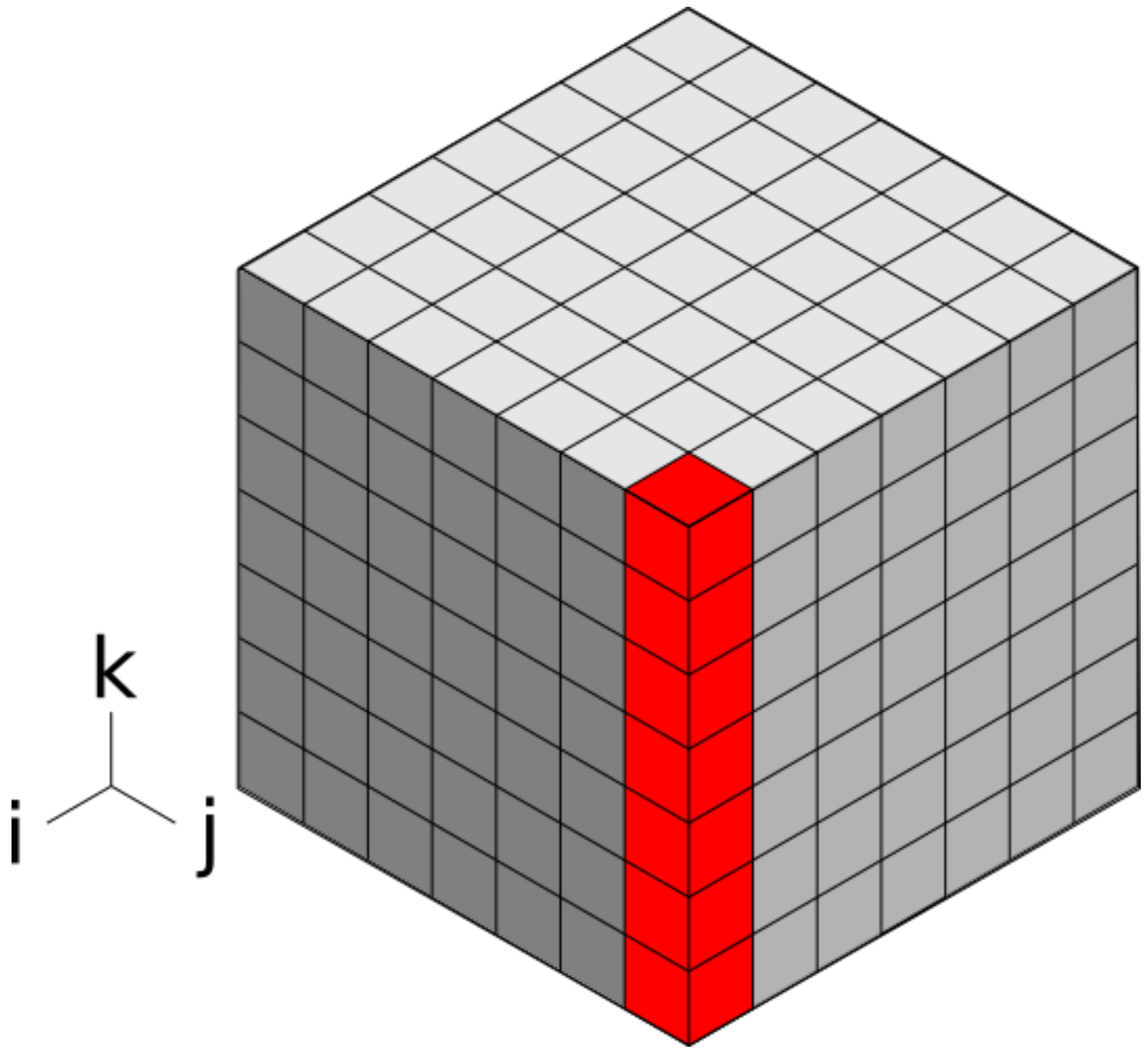
Targets physical parameterization

- Remove independent horizontal dimension
  - Remove do statements over horizontal
  - Demote arrays

Separation of concerns

- Domain scientists focus on their problem (1 column, 1 box)
- CLAW Compiler produce code for each target architecture and directive languages

RRTMGP Example - A nice modular code CPU structured



- F2003/F2008 Radiation Code
- From Robert Pincus and al. from AER University of Colorado
- Compute intensive part are well located in “kernel” module.
- Code is non-the-less CPU structured with horizontal loop as the inner most in every iteration.

RRTMGP Example - original code - CPU structured

Loop over spectral bands

Loop over vertical dimension

Loop over horizontal dimension

```
SUBROUTINE sw_solver(ngpt, nlay, tau, …)
 ! DECLARATION PART OMITTED
 DO igpt = 1, ngpt
    DO ilev = 1, nlay
      DO icol = 1, ncol
         tau_loc(icol,ilev) = max(tau(icol,ilev,igpt) …
         trans(icol,ilev) = exp(-tau_loc(icol,ilev))
      END DO
    END DO
    DO ilev = nlay, 1, -1
      DO icol = 1, ncol
         radn_dn(icol,ilev,igpt) = trans(icol,ilev) * radn_dn(icol,ilev+1,igpt) …
      END DO
    END DO
    DO ilev = 2, nlay + 1
      DO icol = 1, ncol
         radn_up(icol,ilev,igpt) = trans(icol,ilev-1) * radn_up(icol,ilev-1,igpt)
      END DO
    END DO
  END DO
  radn_up(:,:,:) = 2._wp * pi * quad_wt * radn_up(:,:,:)
  radn_dn(:,:,:) = 2._wp * pi * quad_wt * radn_dn(:,:,:)
END SUBROUTINE sw_solver
```

RRTMGP Example - Single Column Abstraction

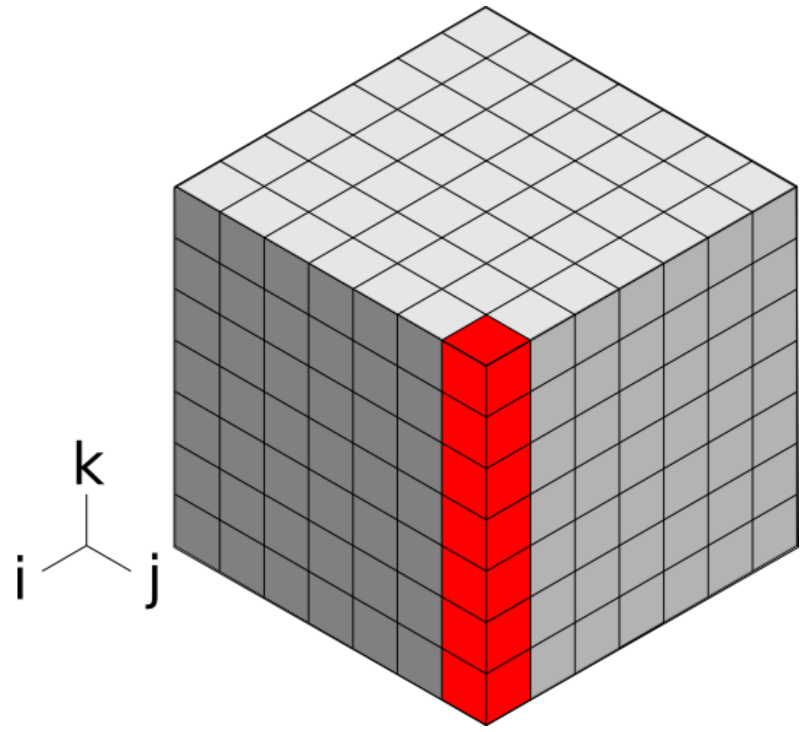
Only dependency on these iteration spaces

```
SUBROUTINE sw_solver(ngpt, nlay, tau, …)
  ! DECL: Fields don't have the horizontal dimension (demotion)
  DO igpt = 1, ngpt
    DO ilev = 1, nlay
      tau_loc(ilev) = max(tau(ilev,igpt) …
      trans(ilev) = exp(-tau_loc(ilev))
    END DO
    DO ilev = nlay, 1, -1
      radn_dn(ilev,igpt) = trans(ilev) * radn_dn(ilev+1,igpt) …
    END DO
    DO ilev = 2, nlay + 1
      radn_up(ilev,igpt) = trans(ilev-1) * radn_up(ilev-1,igpt)
    END DO
  END DO
  radn_up(:,:) = 2._wp * pi * quad_wt * radn_up(:,:)
  radn_dn(:,:) = 2._wp * pi * quad_wt * radn_dn(:,:)
END SUBROUTINE sw_solver
```

RRTMGP Example - CLAW code in subroutine

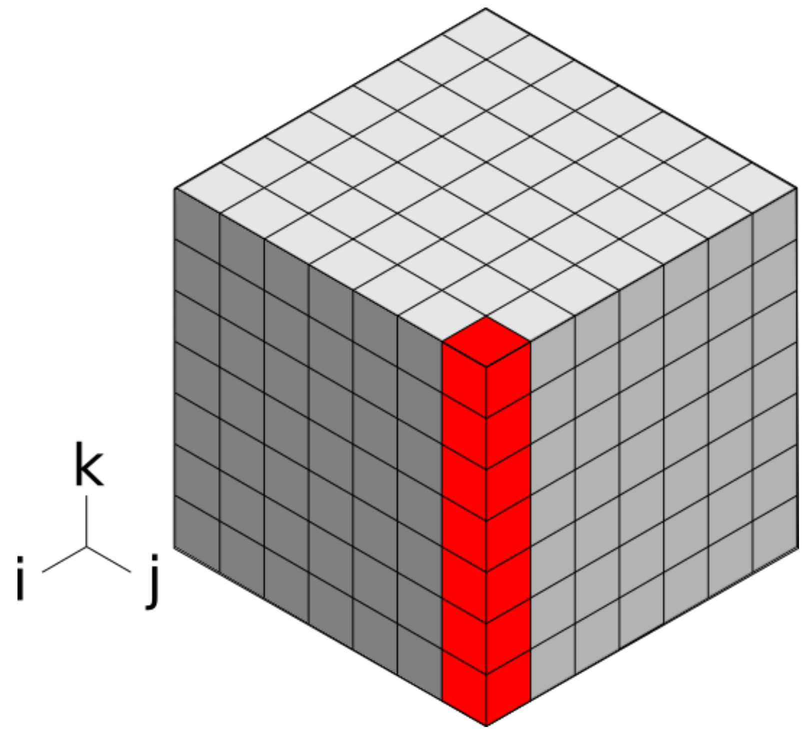
```
SUBROUTINE sw_solver(ngpt, nlay, tau, …)
 !$claw define dimension icol(1:ncol) &
 !$claw parallelize
 DO igpt = 1, ngpt
   DO ilev = 1, nlay
      tau_loc(ilev) = max(tau(ilev,igpt) …
      trans(ilev) = exp(-tau_loc(ilev))
    END DO
    DO ilev = nlay, 1, -1
      radn_dn(ilev,igpt) = trans(ilev) * radn_dn(ilev+1,igpt) …
    END DO
    DO ilev = 2, nlay + 1
      radn_up(ilev,igpt) = trans(ilev-1) * radn_up(ilev-1,igpt)
    END DO
  END DO
  radn_up(:,:) = 2._wp * pi * quad_wt * radn_up(:,:)
  radn_dn(:,:) = 2._wp * pi * quad_wt * radn_dn(:,:)
END SUBROUTINE sw_solver
```

Algorithm for one column only



Dependency on the vertical dimension only

RRTMGP Example - CLAW at call site




```
! Location in the model where the physical parameterization is
! plugged

!$claw parallelize forward
DO icol = 1, ncol
   CALL sw_solver(ngpt, nlay, tau(icol,:,:), …)
END DO
```

Fully working code if compiled with a standard compiler

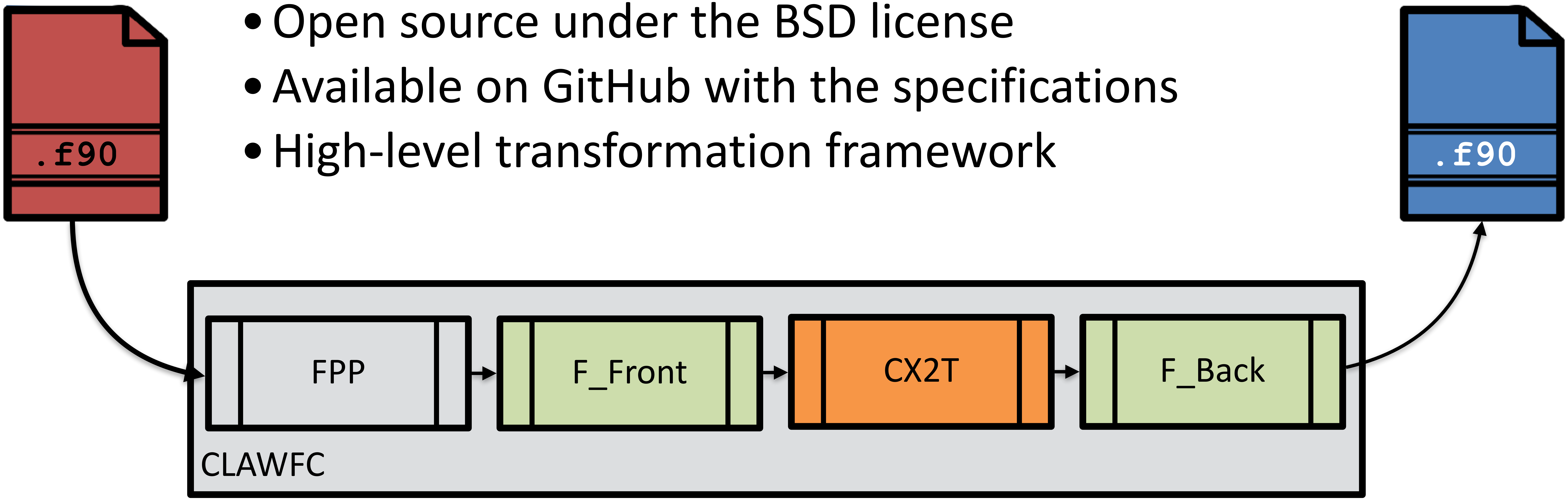
100% standard Fortran code

CLAW

The Compiler

What is the CLAW Compiler?

- Source-to-source translator
- Based on the OMNI Compiler Project
- Fortran 2008
- Open source under the BSD license
- Available on GitHub with the specifications
- High-level transformation framework



OMNI Compiler Project

F_Front F_Back

Sets of programs/libraries to build source-to-source compilers for C and Fortran via an XcodeML intermediate representation.

- XcalableMP (abstract inter-node communication), XcalableACC (XMP + OpenACC), OpenMP (implementation for C and Fortran), OpenACC (C implementation only)

Development team

- Programming Environments Research Team from the RIKEN Center for Computational Sciences (R-CCS), Kobe, Japan
- High Performance Computing System Lab, University of Tsukuba, Tsukuba
- CLAW Project is actively collaborating in this project

http://www.omni-compiler.org
https://github.com/omni-compiler

RIKEN R-CCS RIKEN Center for Computational Science

OMNI Compiler Project

F_Front

F_Back

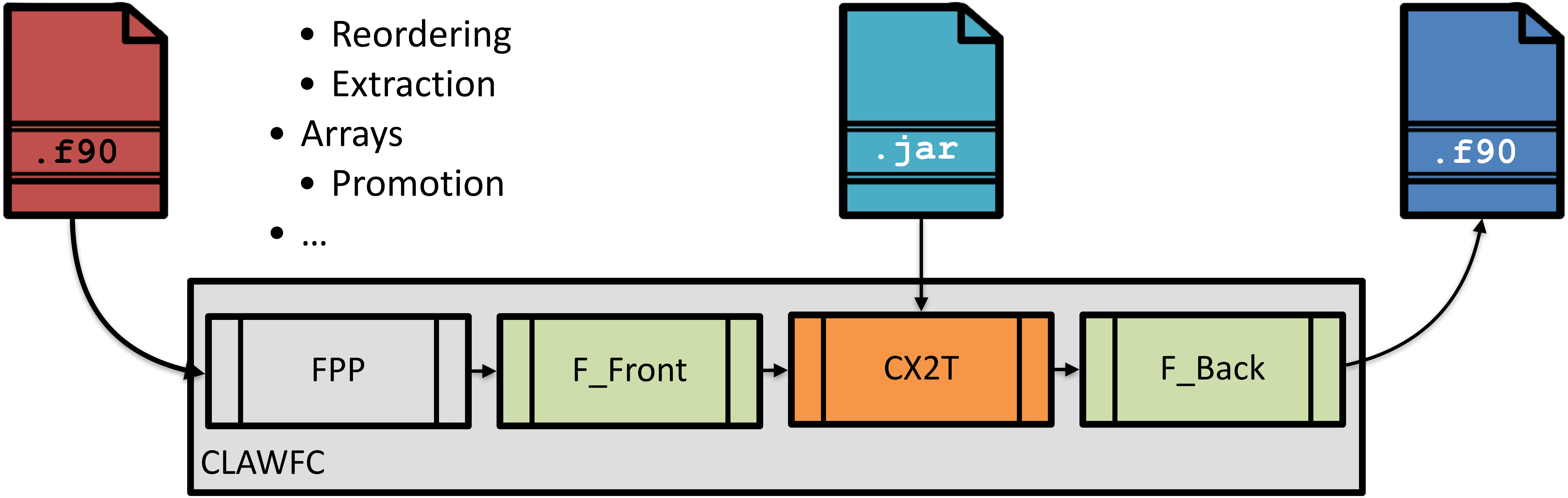
- Fortran front-end and back-end used in CLAW
- Transformations are applied on XcodeML IR
- > 100 PR contributed to OMNI Compiler from our CLAW
- Only open-source Fortran toolchain with high-level IR able to deal with the modern Fortran code found in ICON

RIKEN Center for Computational Science

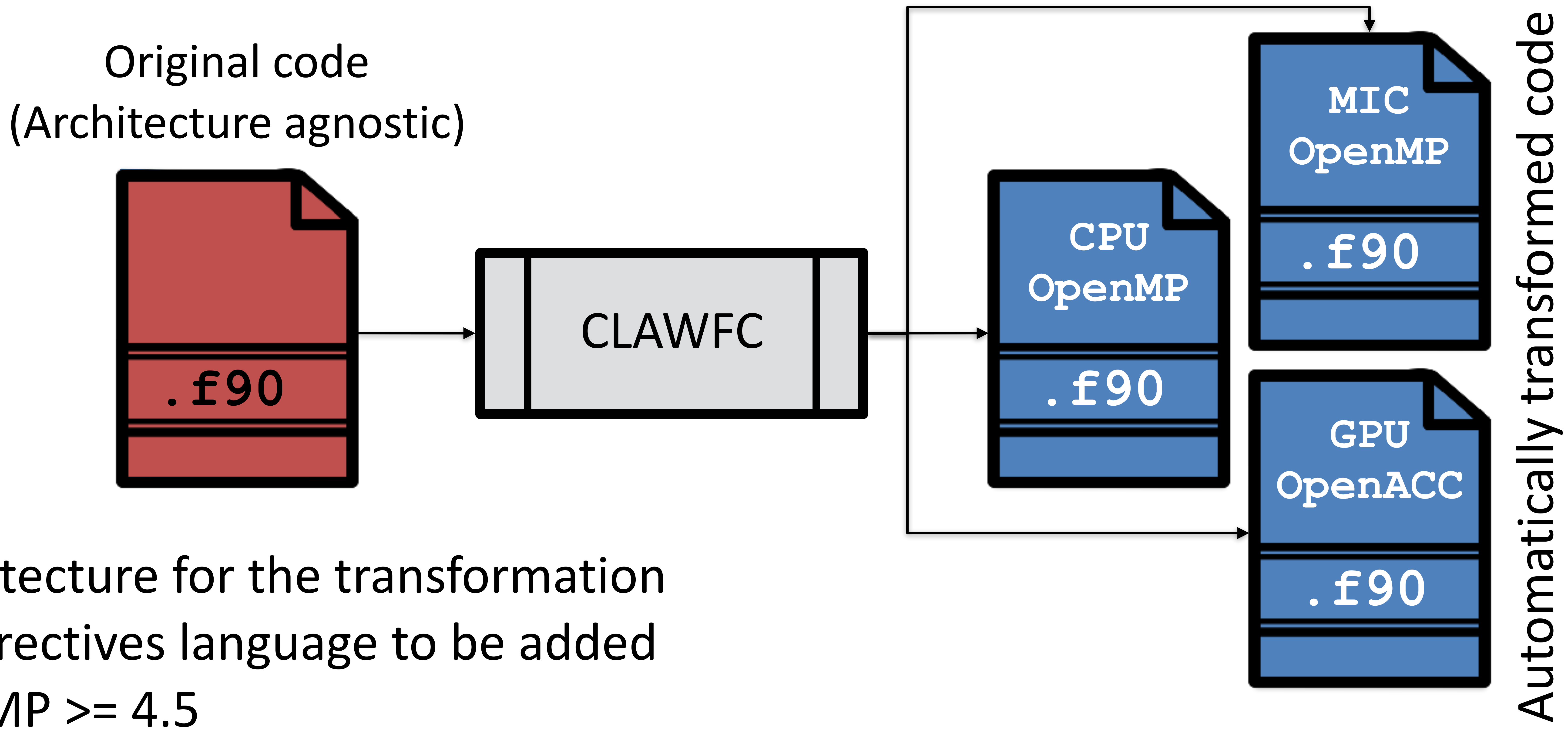
CLAW CX2T - External transformation

Easy integration of new transformation build on top of “building blocks”

- Primitive transformation
  - Loops
    - Fusion
    - Reordering
    - Extraction
  - Arrays
    - Promotion
  - …



RRTMGP Example - CLAW transformation



- A single source code
- Specify a target architecture for the transformation
- Specify a compiler directives language to be added
  - OpenACC or OpenMP >= 4.5

```
clawfc --directive=openacc --target=gpu -o mo sw solver.acc.f90 mo sw solver.f90
```

```
clawfc --directive=openmp --target=cpu -o mo_sw_solver.omp.f90 mo_sw_solver.f90
```

```
clawfc --directive=openmp --target=mic -o mo_sw_solver.mic.f90 mo_sw_solver.f90
```

CLAW SCA to target specific code - recipe

- Data dependency analysis for promotion and generation of directive
  - Potentially collapsing loops
  - Generate data transfer if wanted
- Adapt data layout
  - Promotion of scalar and arrays to fit model dimensions
- Detect unsupported statements for OpenACC/OpenMP
- Insertion of do statements to iterate of new dimensions
- Insertion of directives (OpenMP/OpenACC)

CLAW Compiler has various options - example for GPU

- **Local array strategy** for Accelerator transformation
  - **Private** - issue a copy of the array for each “thread”
  - **Promote** - promote the array and keep a unique copy for all the “thread”

- **Data movement strategy** for Accelerator transformation
  - **Present** - assume that data are present on the device, no data transfer
  - **Kernel** - data movement is generated for each kernel
  - **None** - no data region generated

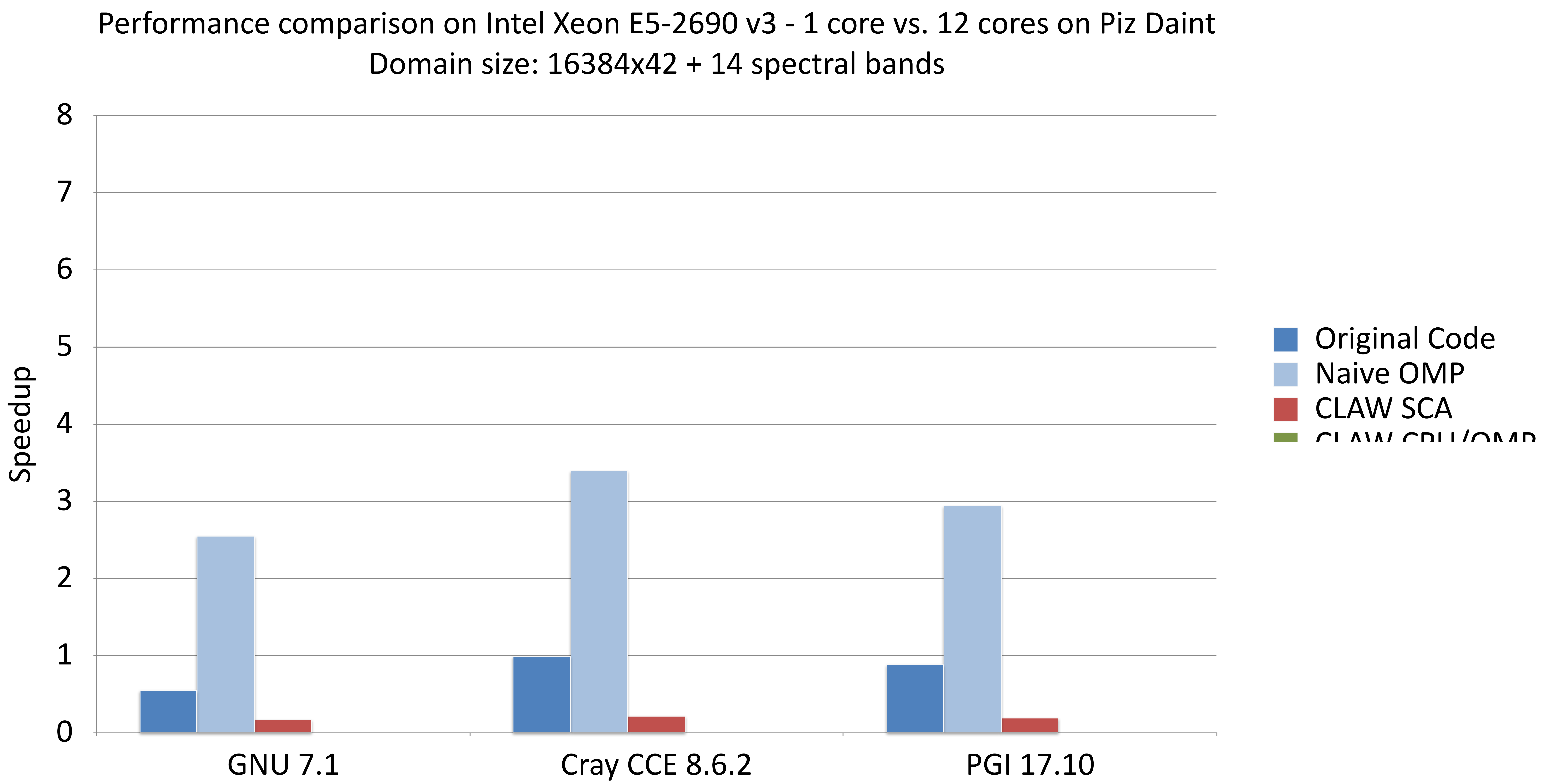
- **Collapse strategy** - true/false

Performance Results

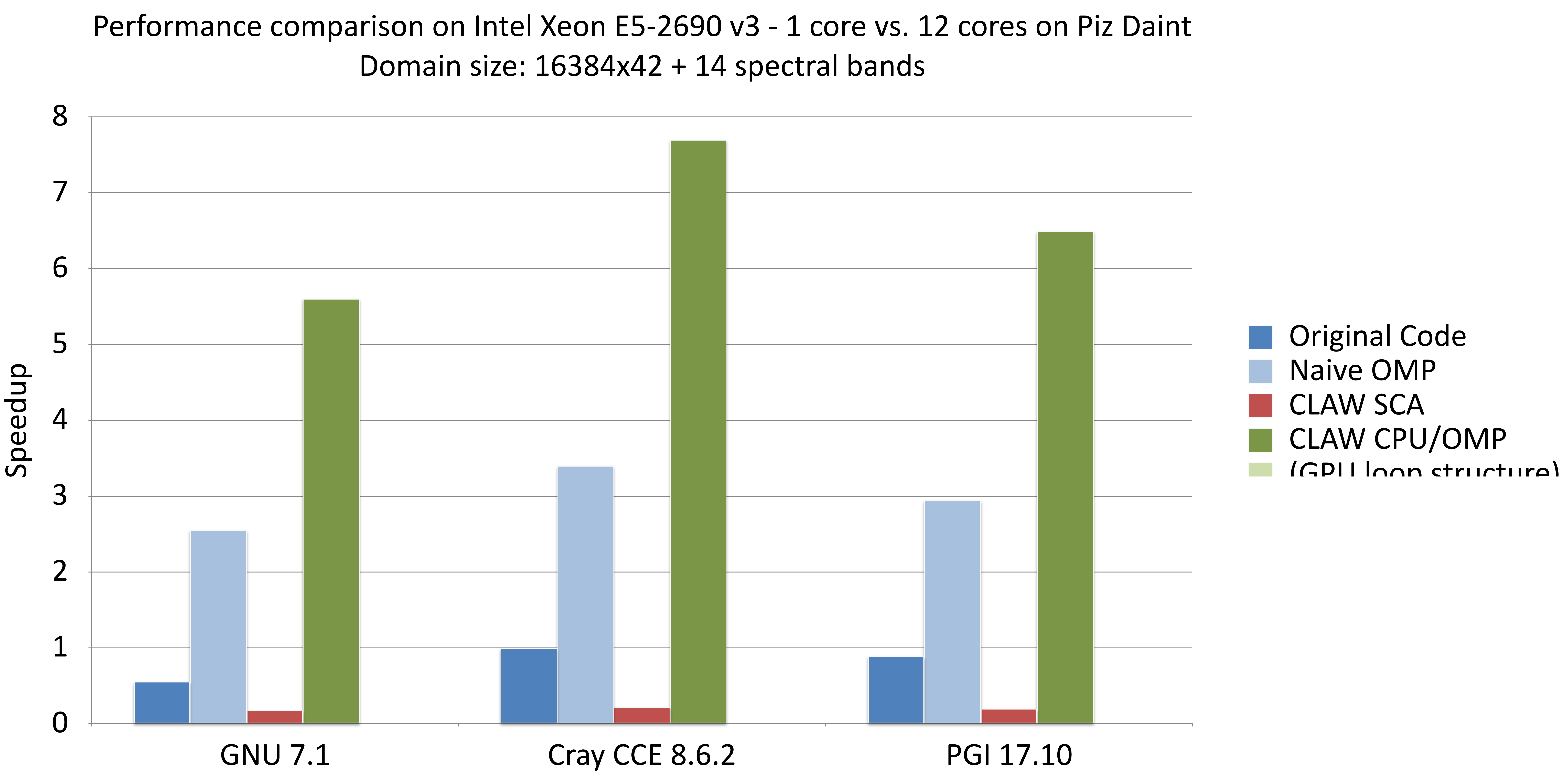
RRTMGP Example - CLAW target=gpu directive=openacc

```
SUBROUTINE sw_solver(ngpt, nlay, tau, …)
! DECL: Fields promoted accordingly to usage
!$acc data present(…)
!$acc parallel
!$acc loop gang vector private(…) collapse(2)
DO icol = 1 , ncol , 1
  DO igpt = 1 , ngpt , 1
    !$acc loop seq
    DO ilev = 1 , nlay , 1
      tau_loc(ilev) = max(tau(icol,ilev,igpt)
      trans(ilev) = exp(-tau_loc(ilev))
    END DO
    !$acc loop seq
    DO ilev = nlay , 1 , (-1)
      radn_dn(icol,ilev,igpt) = trans(ilev) * radn_dn(icol,ilev+1,igpt)
    END DO
    !$acc loop seq
    DO ilev = 2 , nlay + 1 , 1
      radn_up(icol,ilev,igpt) = trans(ilev-1)*radn_up(icol,ilev-1,igpt)
    END DO
  END DO
  !$acc loop seq
  DO igpt = 1 , ngpt , 1
    !$acc loop seq
    DO ilev = 1 , nlay + 1 , 1
      radn_up(icol,igpt,ilev) = 2._wp * pi * quad_wt * radn_up(icol,igpt,ilev)
      radn_dn(icol,igpt,ilev) = 2._wp * pi * quad_wt * radn_dn(icol,igpt,ilev)
    END DO
  END DO
END DO
!$acc end parallel
!$acc end data
END SUBROUTINE sw_solver
```

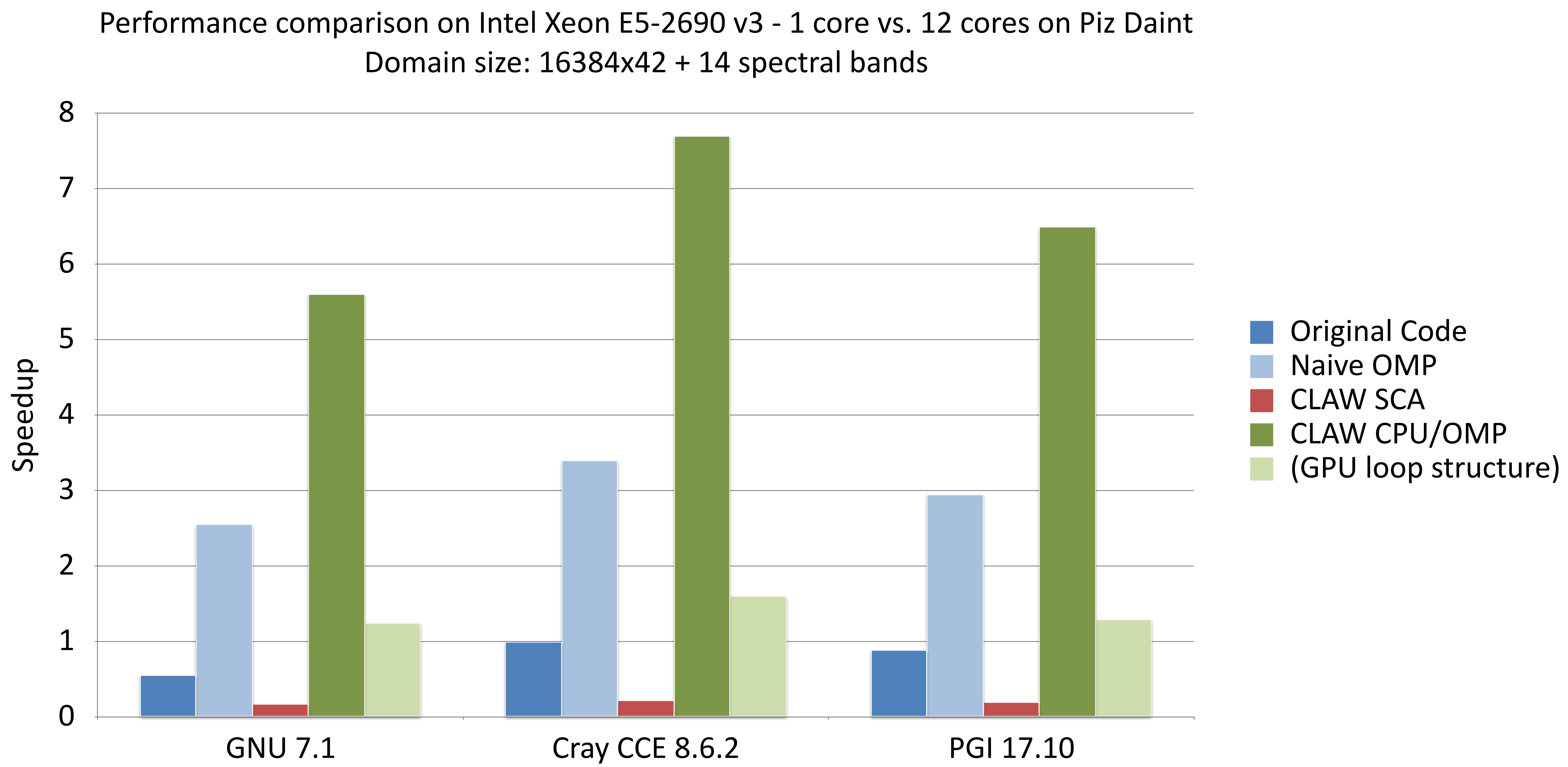
RRTMGP Example - Speedup on CPU



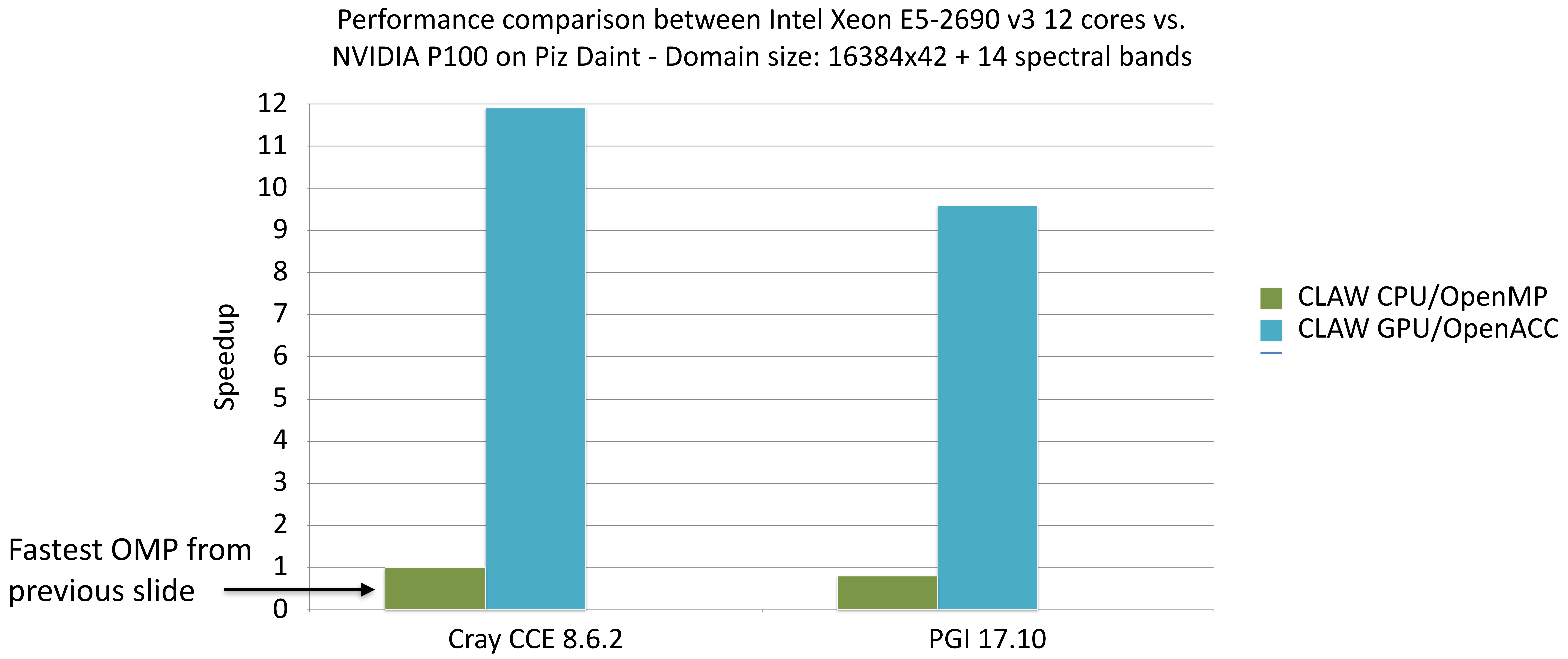
RRTMGP Example - Speedup on CPU



RRTMGP Example - Speedup on CPU



RRTMGP Example - Speedup CPU vs. GPU



RRTMGP Example - Speedup CPU vs. GPU

Code metrics

	sw_solver
Demoted Arrays	35
Removed do statments	15
CLAW directive	3

81% of the code is kept from original

Applied in micro-physics from ICON

CLAW GPU/OpenACC and CLAW CPU/OpenMP versions reach similar performance from an hand-written one

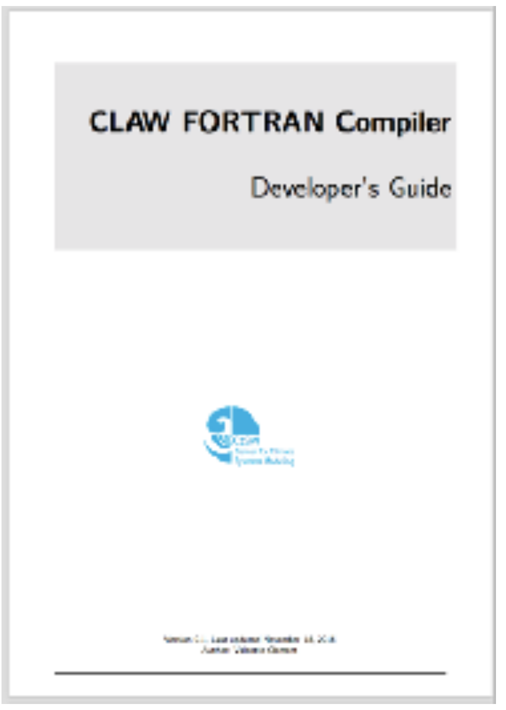
PASC ENIAC Project (2017-2020)

- Enabling ICON model on heterogenous architecture
  - Port to OpenACC
  - GridTools for stencil computation (DyCore)
  - Looking at performance portability in Fortran code
    - Enhance CLAW Compiler capabilities
    - Apply SCA on some physical parameterization
    - Enhance transformation for x86, XeonPhi and GPUs

CLAW Compiler & Directives - Resources

`https://claw-project.github.io`

`https://github.com/omni-compiler`



CLAW Compiler developer’s guide

Summary

- Single source code with high-level of abstraction
- Domain scientist can focus on their problem
- Little to no change in current code
- Standard Fortran
- Open source project
- CLAW is easily extensible to new architecture or new transformation

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