Task-graph-based applications, from theory to Exascale?

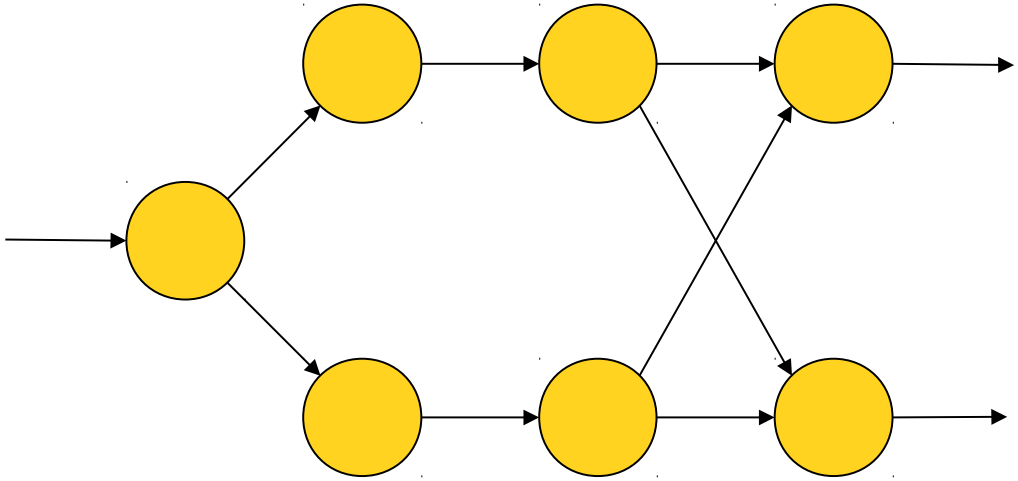
Olivier Aumage, Nathalie Furmento, Suraj Kumar,
Marc Sergent, Samuel Thibault
INRIA Storm Team-Project

INRIA Bordeaux, LaBRI, University of Bordeaux

Task graphs

- Well-studied expression of parallelism
- Departs from usual sequential programming

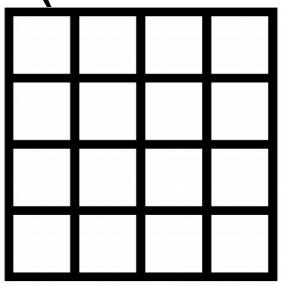
Really ?



Task management

Implicit task dependencies

- Right-Looking Cholesky decomposition (from PLASMA)



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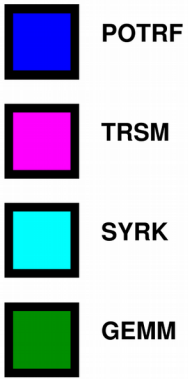

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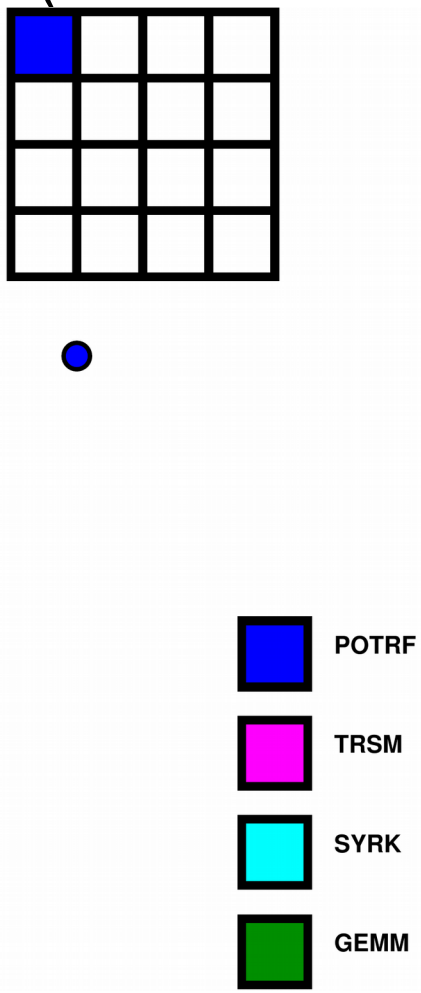

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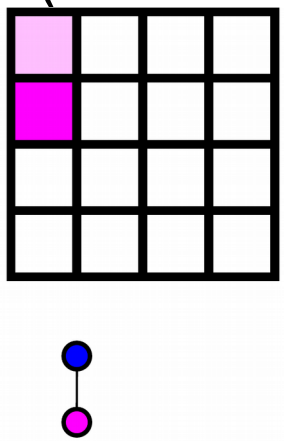

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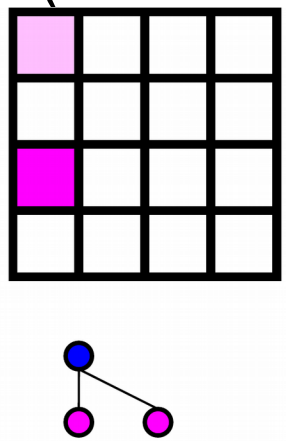

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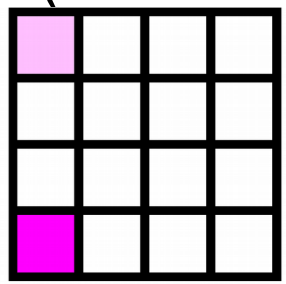

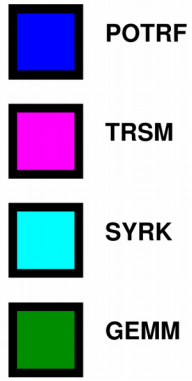

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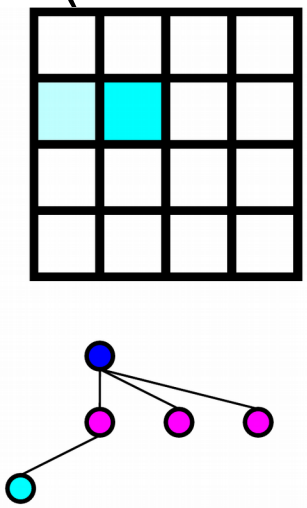

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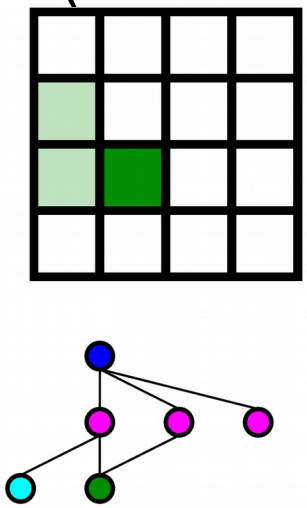

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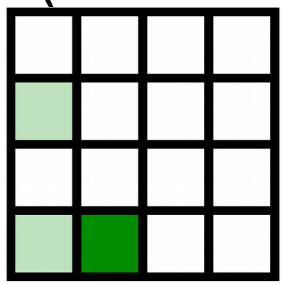

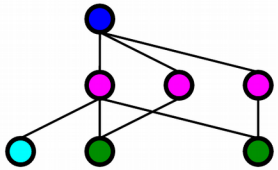

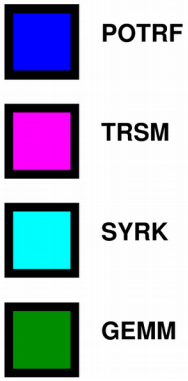

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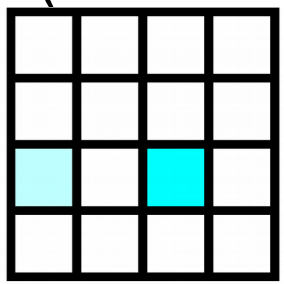

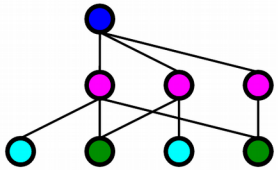

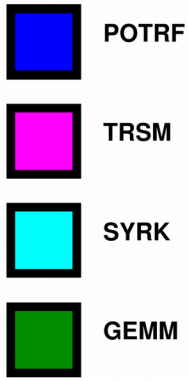

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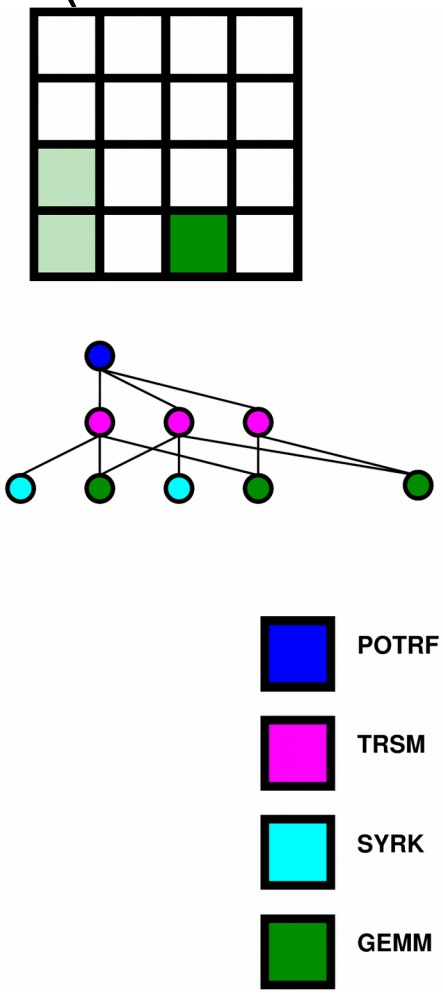

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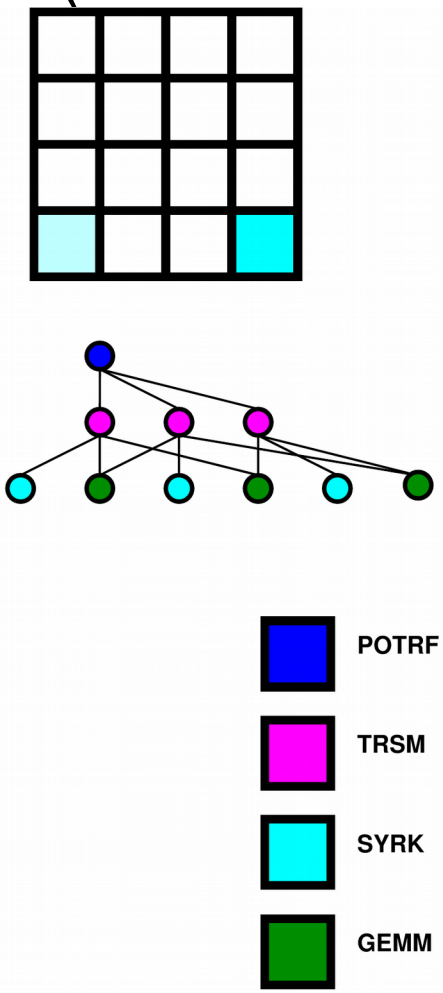

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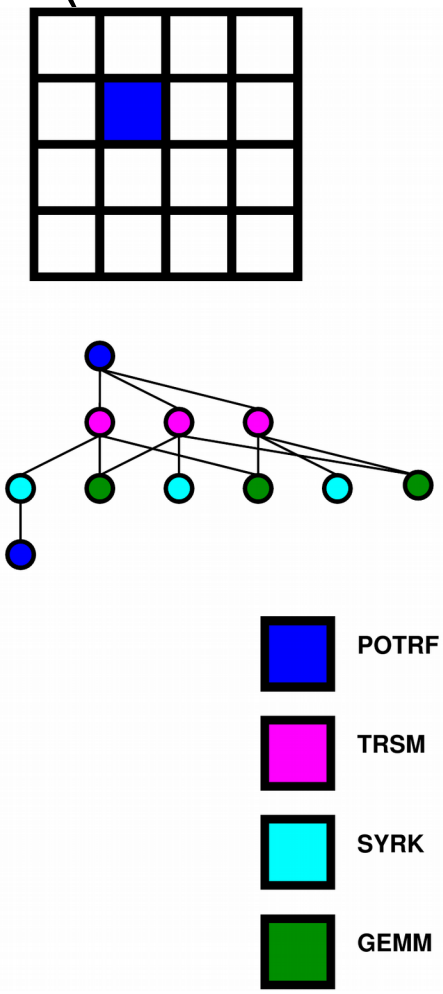

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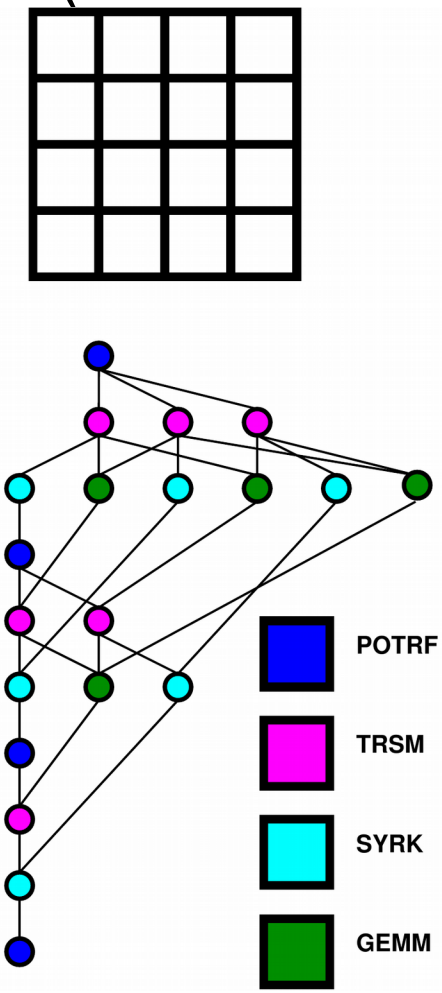


Write your application as a task graph

Even if using a sequential-looking source code

➔ Portable performance

Sequential Task Flow (STF)

- Algorithm remains the same on the long term
- Can debug the sequential version.
- Only kernels need to be rewritten
  - BLAS libraries, multi-target compilers
- Runtime will handle parallel execution

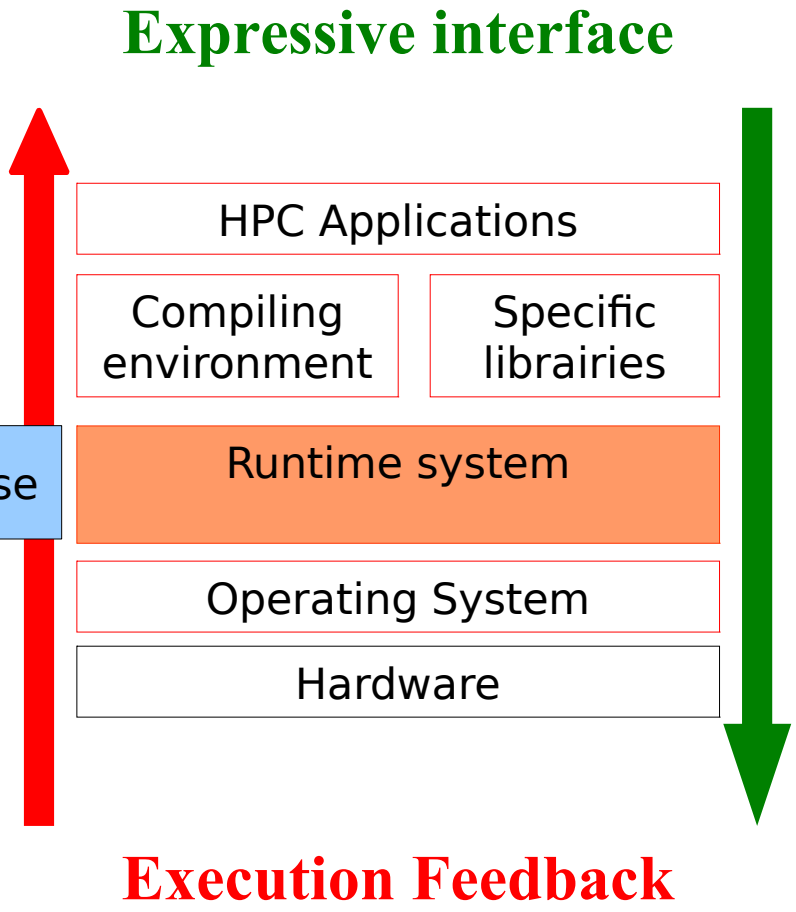
Task graphs everywhere

- OmpSs, PARSEC (aka Dague), StarPU, SuperGlue/DuctTeip, XKaapi...
- OpenMP4.0 introduced task dependencies
- Plasma/magma, state of the art dense linear algebra
- qr_mumps/PaStiX, state of the art sparse linear algebra
- ScalFMM-MORSE
- …
- Very portable

MORSE associate-team (Matrices Over Runtime Systems @ Exascale)

Challenging issues at all stages

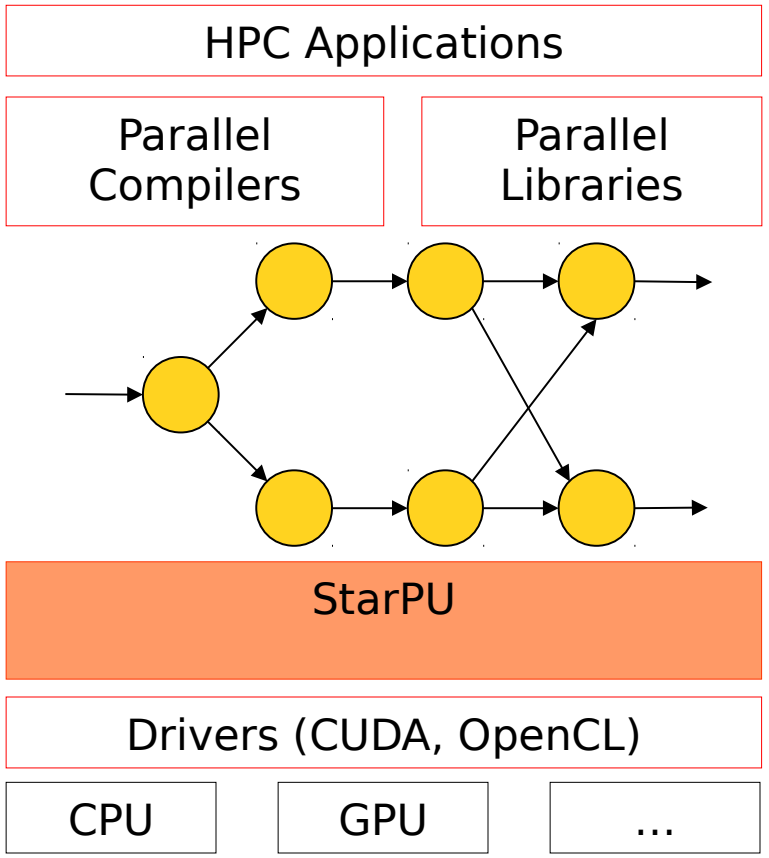
- Applications
  - Programming paradigm
  - BLAS kernels, FFT, …
- Compilers
  - Languages
  - Code generati
- Runtime systems
  - Resources management
  - Task scheduling
- Architecture
  - Memory interconnect



The StarPU runtime system

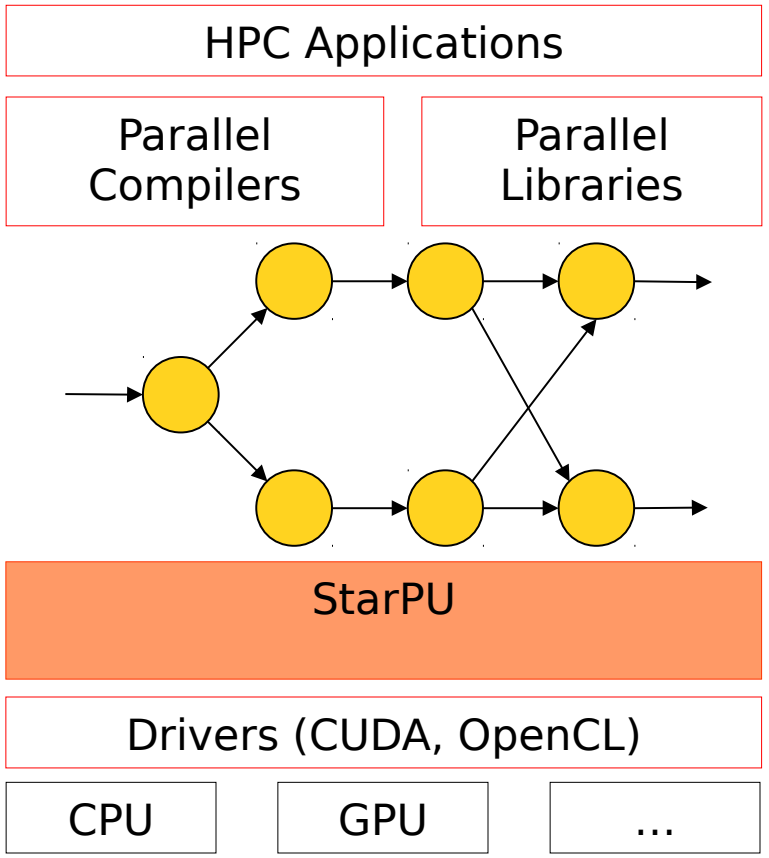
The need for runtime systems

- "do dynamically what can't be done statically anymore"
- Compilers and libraries generate (graphs of) tasks
  - Additional information is welcome!
- StarPU provides
  - Task scheduling
  - Memory management



Data management

- StarPU provides a Virtual Shared Memory (VSM) subsystem
  - Replication
  - Weak consistency
  - Single writer
    - Or reduction, ...
- Input & ouput of tasks = reference to VSM data

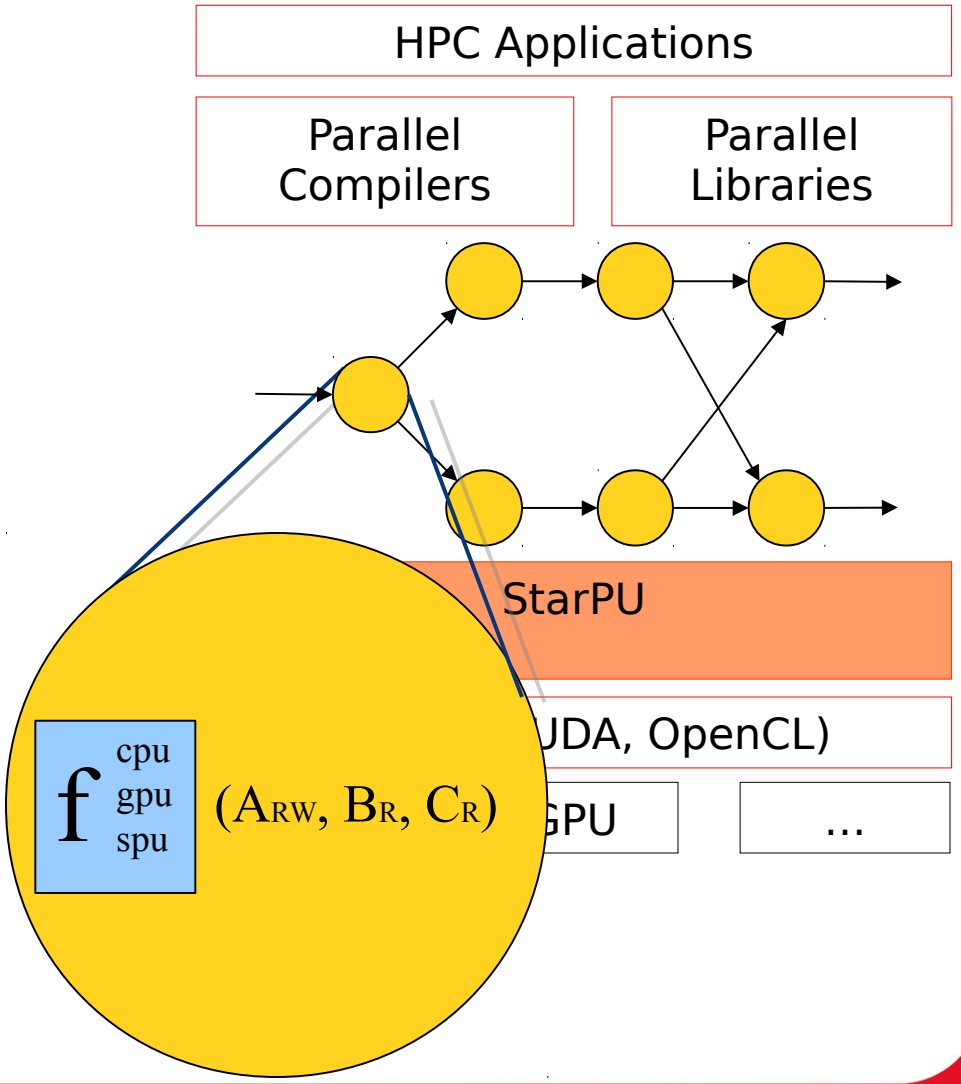


The StarPU runtime system

Task scheduling

- Tasks =
  - Data input & output
    - Reference to VSM data
  - Multiple implementations
    - E.g. CUDA + CPU implementation
  - Non-preemptible
  - Dependencies with other tasks

- StarPU provides an Open Scheduling platform
  - Scheduling algorithm = plug-ins



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Implicit task dependencies

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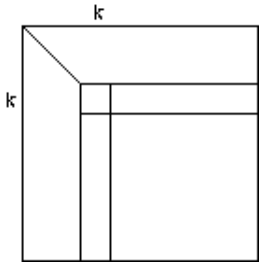

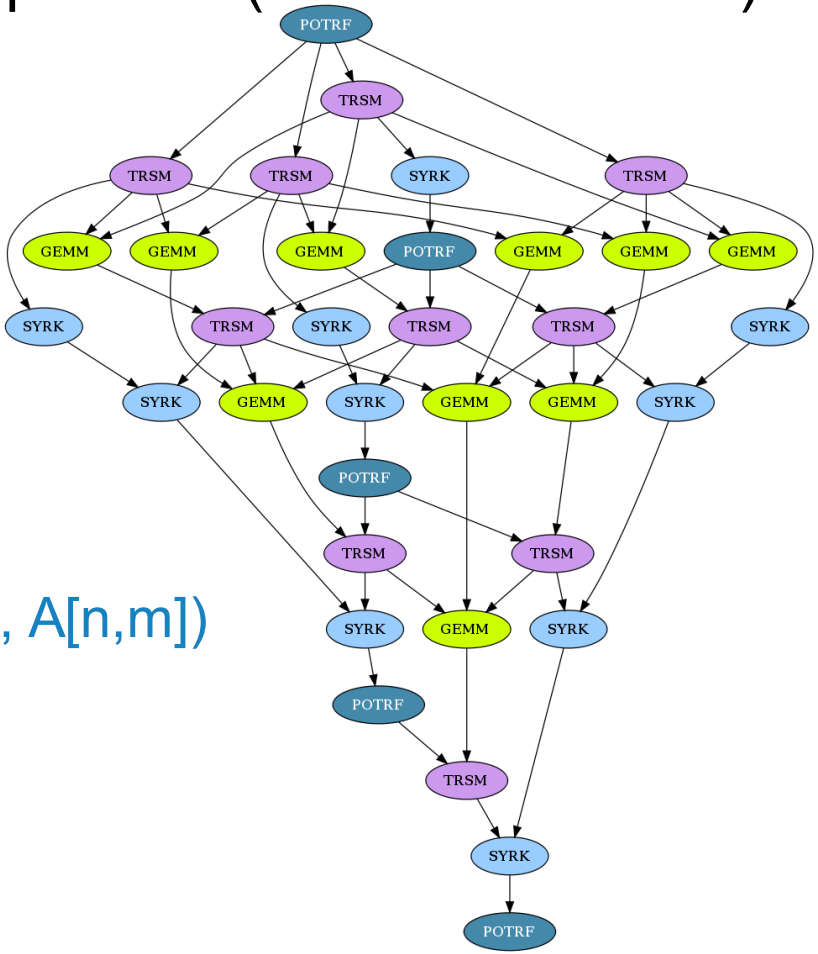

How to scale over MPI?

- (StarPU handles intra-MPInode scheduling fine)

- Splitting graph by hand
  - Complex, not flexible
- Master-Slave would not scale
  - ➔ Each node should determine its duty by itself
- Algebraic representation of e.g. Parsec
  - Difficult to write
  - Not flexible enough for any kind of application
- Recursive task graph unrolling
  - Complex

➔ Rather just unroll the whole task graph on each node

MPI VSM

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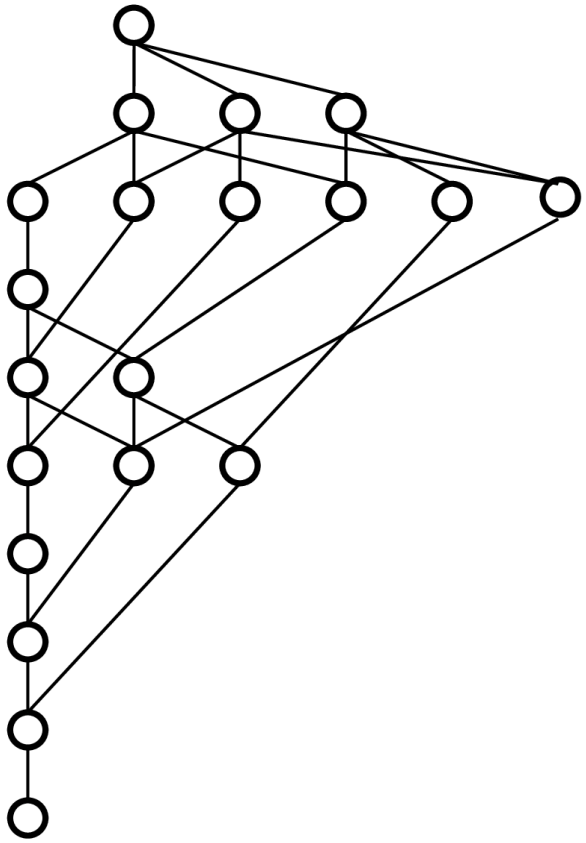

MPI VSM

- Data mapping (e.g. 2D block-cyclic)

```
int get_rank(int m, int n) { return ((m%p)*q + n%q); }

For (m = 0 .. tiles – 1)
        For (n = m .. tiles – 1)
                set_rank(A[m,n], get_rank(m,n));

For (k = 0 .. tiles – 1) {
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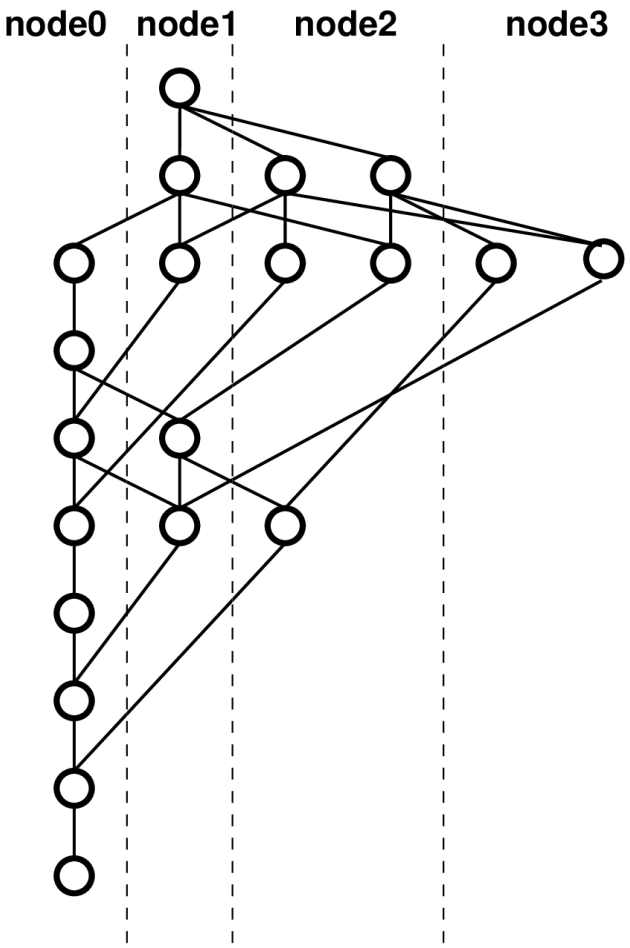
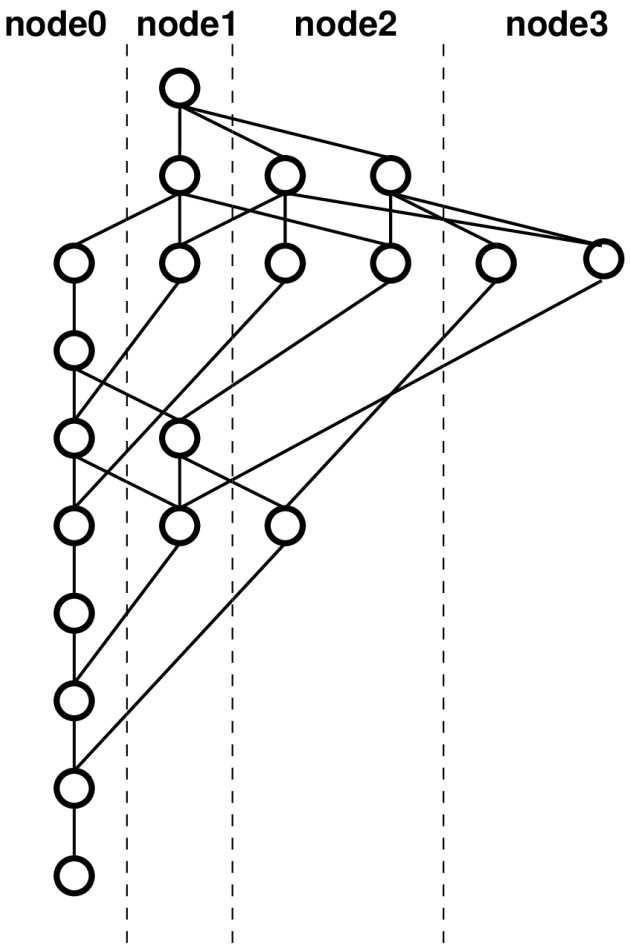


MPI VSM

- Each node unrolls the whole task graph
- Data ↔ node mapping
  - Provided by the application
  - E.g. 2D block-cyclic
- Task ↔ node mapping
  - Tasks move to data they modify
- MPI transfers
  - Automatically queued
- Local view of the computation
  - No synchronizations
  - No global scheduling



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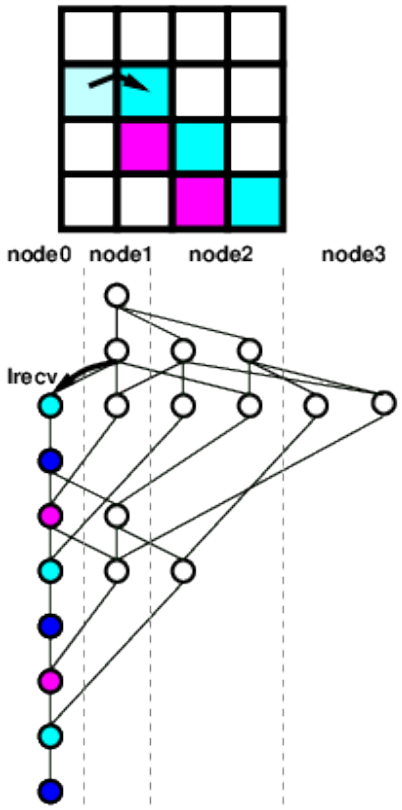
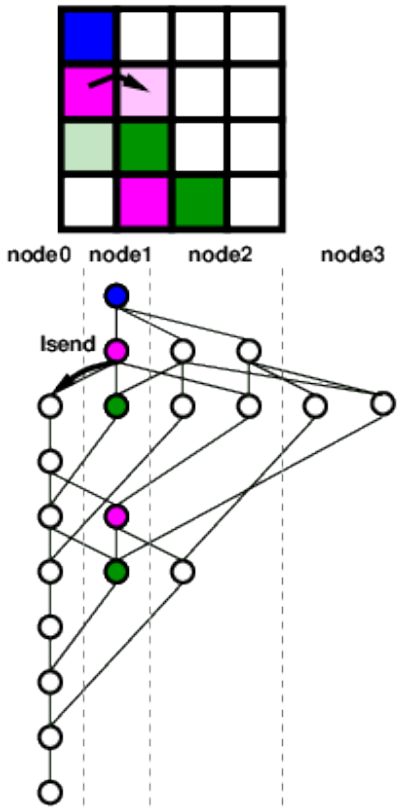


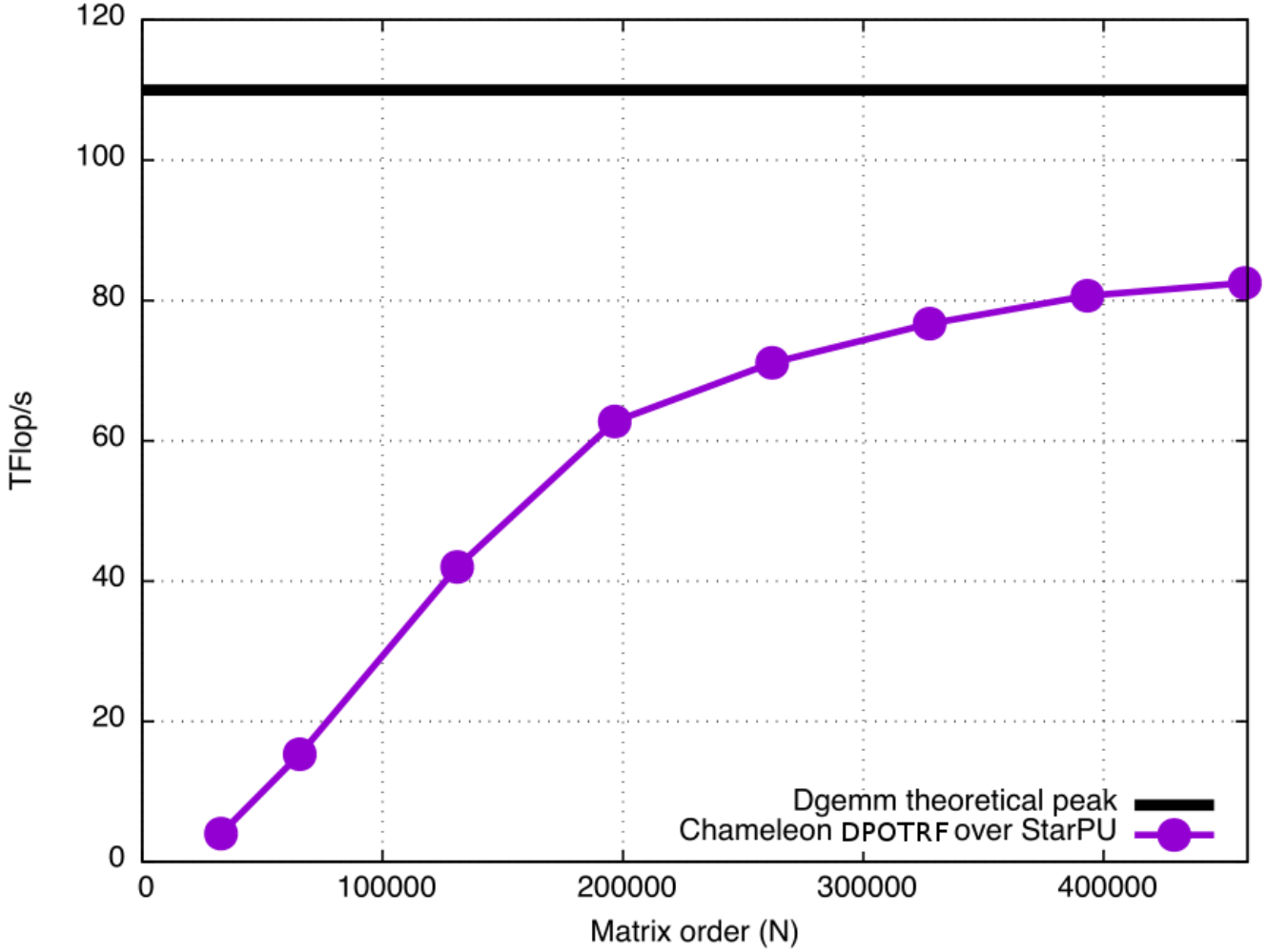
Node 0 execution



Node 1 execution

Cholesky cluster performance

@CEA: 144 nodes with 8 CPU cores (E5620) + 2 GPUs (M2090)



Cholesky cluster performance

@CEA: 144 nodes with 8 CPU cores (E5620) + 2 GPUs (M2090)

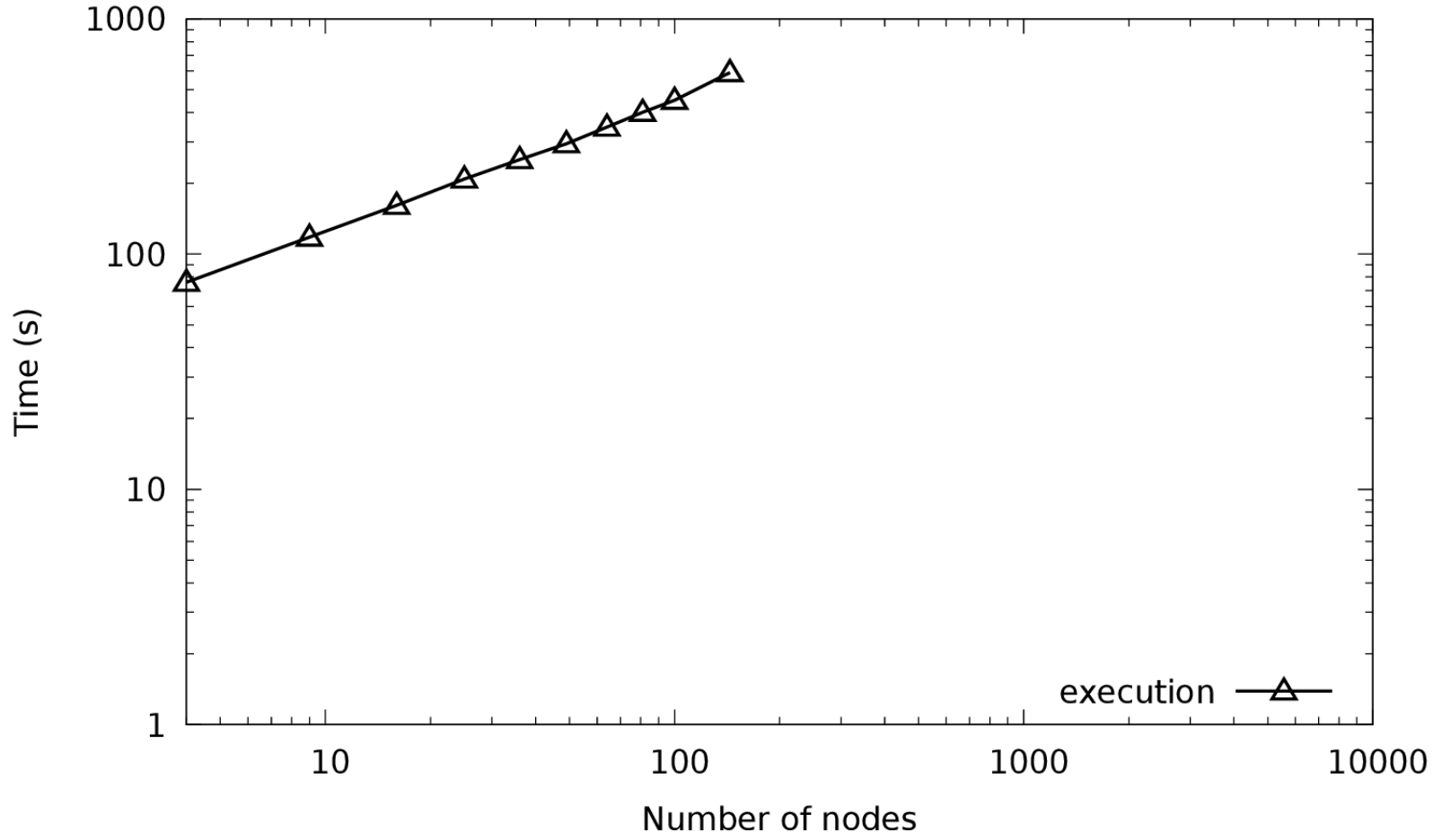
- ~500GFlops/node (vs 763GFlops DGEMM)
- Performance equivalent to
  - PARSEC
  - Hand-tuned CEA statically-distributed MPI+CUDA code
    - Actually brought ideas to improve it by pipelining more

How well will it scale?

- Submission of task graph is sequential on each node
  - Even if in parallel with execution on the node
- Submission loops over the whole graph, prune?
- Broadcasting values?

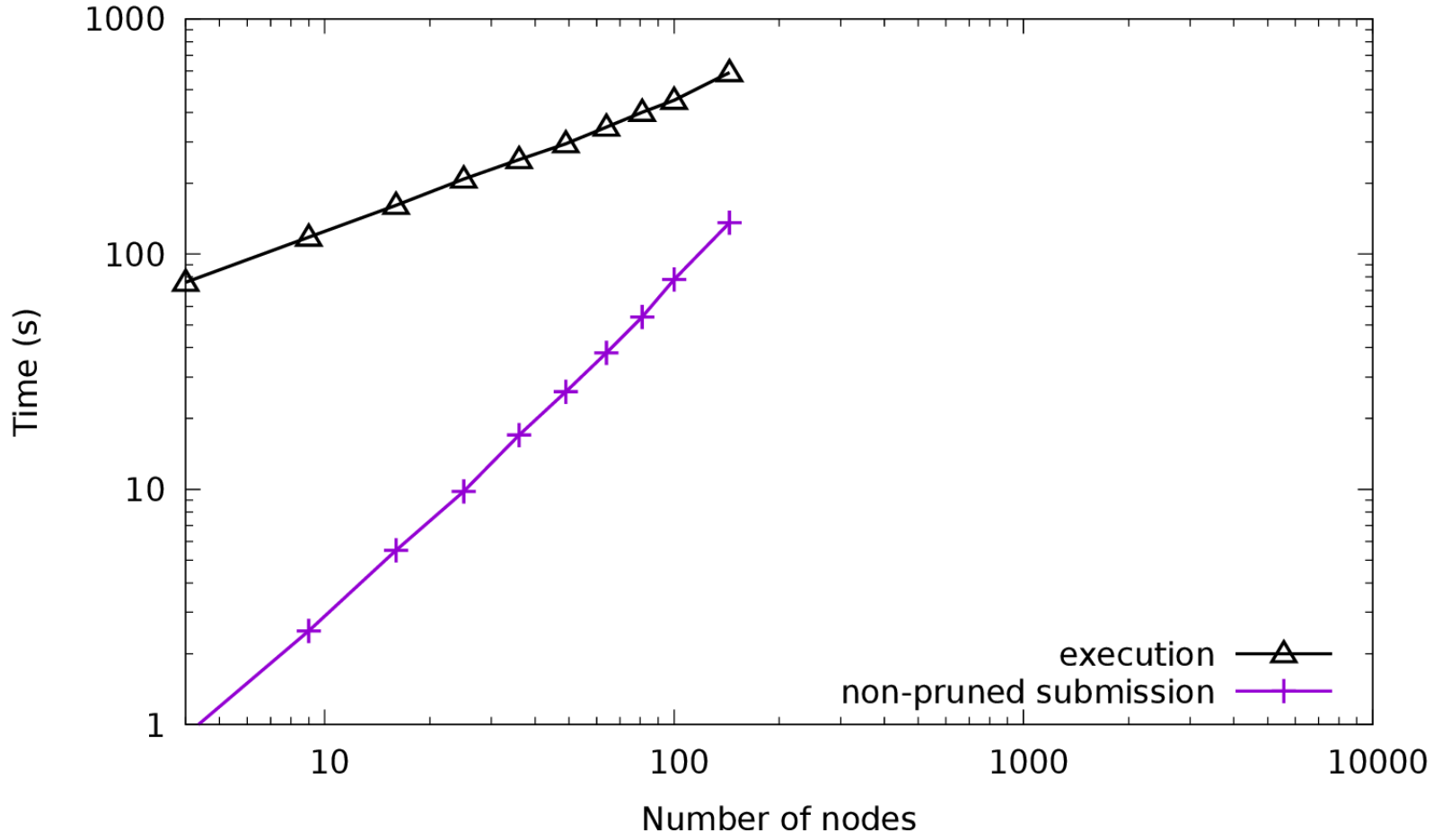
MPI VSM – pruning support

Weak scaling : 40960*40960 elements per node (80*80 tiles 512*512)



MPI VSM – pruning support

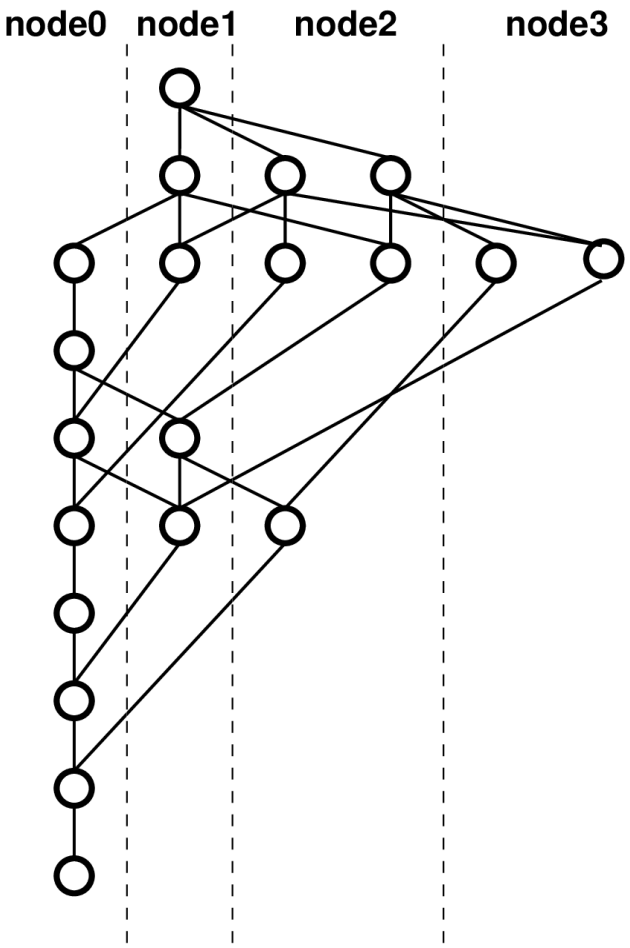
Weak scaling : 40960*40960 elements per node (80*80 tiles 512*512)



MPI VSM – pruning support

- Non-inlined pruning

```
POTRF(tile A) {
        if (get_rank(A) != self)
                return;
        starpu_task_insert(…);
}
...
For (k = 0 .. tiles – 1) {
        POTRF(A[k,k])
        for (m = k+1 .. tiles – 1)
                TRSM(A[k,k], A[m,k])
        for (m = k+1 .. tiles – 1) {
                SYRK(A[m,k], A[m,m])
                for (n = m+1 .. tiles – 1)
                        GEMM(A[m,k], A[n,k], A[n,m])
        }
}
```



MPI VSM – pruning support

- Inlined pruning

```
#define get_rank(m, n) ((m%p)*q + n%q);

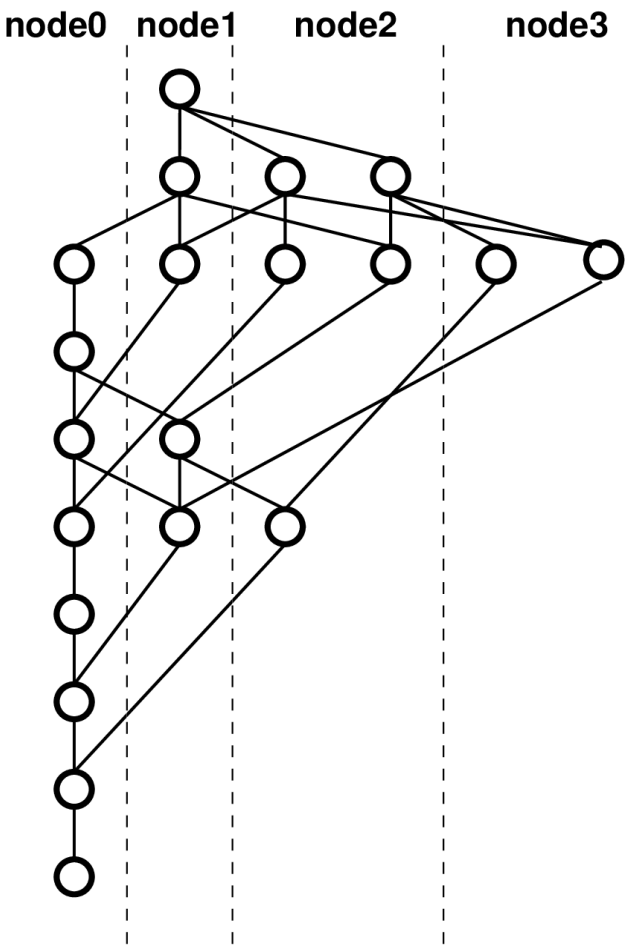
#define POTRF(A) do {
        if (get_rank(A) == self)
                POTRF(A);

} while (0)

...

For (k = 0 .. tiles – 1) {
        POTRF(A[k,k]);
        for (m = k+1 .. tiles – 1)
                TRSM(A[k,k], A[m,k]);
        for (m = k+1 .. tiles – 1) {
                SYRK(A[m,k], A[m,m]);
                for (n = m+1 .. tiles – 1)
                        GEMM(A[m,k], A[n,k], A[n,m]);
        }

}
```



MPI VSM – pruning support

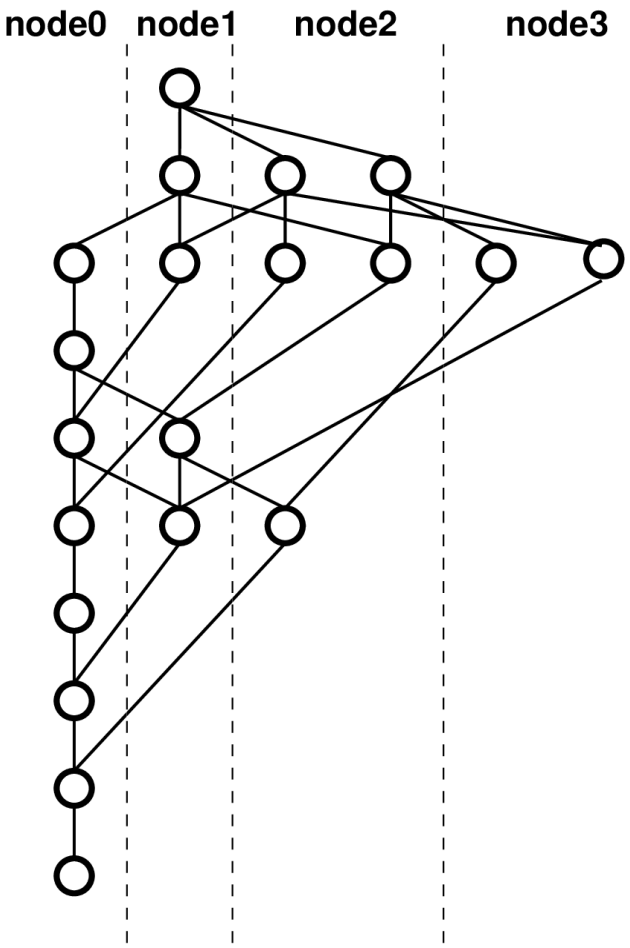
- Inlined const pruning

```
#define get_rank(m, n) ((m%P)*Q + n%Q);

#define POTRF(A) do {
        if (get_rank(A) == self)
                POTRF(A);
} while (0)

...

For (k = 0 .. tiles – 1) {
        POTRF(A[k,k]);
        for (m = k+1 .. tiles – 1)
                TRSM(A[k,k], A[m,k]);
        for (m = k+1 .. tiles – 1) {
                SYRK(A[m,k], A[m,m]);
                for (n = m+1 .. tiles – 1)
                        GEMM(A[m,k], A[n,k], A[n,m]);
        }
}
```



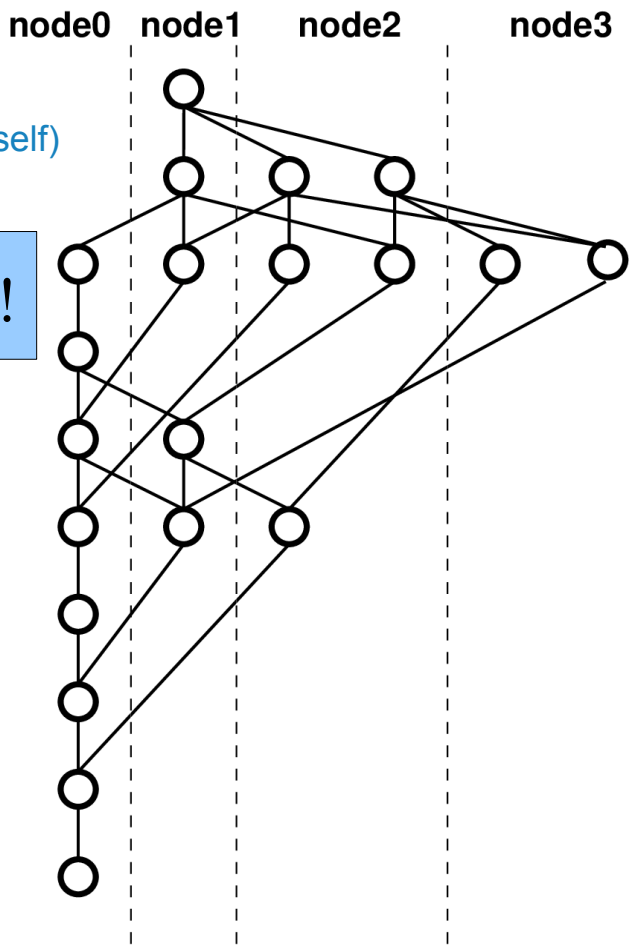
MPI VSM – pruning support

- Inlined const pruning

```
#define get_rank(m, n) ((m%P)*Q + n%Q);

#define GEMM(A, B, C) do {
        if (get_rank(A) == self || get_rank(B) == self || get_rank(C) == self)
                GEMM(A, B, C);
} while (0)
...
For (k = 0 .. tiles – 1) {
        POTRF(A[k,k]);
        for (m = k+1 .. tiles – 1)
                TRSM(A[k,k], A[m,k]);
        for (m = k+1 .. tiles – 1) {
                SYRK(A[m,k], A[m,m]);
                for (n = m+1 .. tiles – 1)
                        GEMM(A[m,k], A[n,k], A[n,m]);
        }
}
```

Loops can be compiler-optimized!



MPI VSM – pruning support

- Loop optimization

```
...
For (k = 0 .. tiles – 1) {
        ...
        for (m = k+1 .. tiles – 1) {
                ...
                for (n = m+1 .. tiles – 1)
                        if ((k%P)*Q + m%Q == self)
                         ||((k%P)*Q + n%Q == self)
                         ||((m%P)*Q + n%Q == self)
                        GEMM(A[m,k], A[n,k], A[n,m]);
        }
}
```

MPI VSM – pruning support

- Loop optimization (simplified)

```
...
For (k = 0 .. tiles – 1) {
        ...
        for (m = k+1 .. tiles – 1) {
                ...
                for (n = m+1 .. tiles – 1)
                        if (cst + n%Q == self) {
                                …
                        }
        }
}
```

MPI VSM – pruning support

- Loop optimization (simplified)

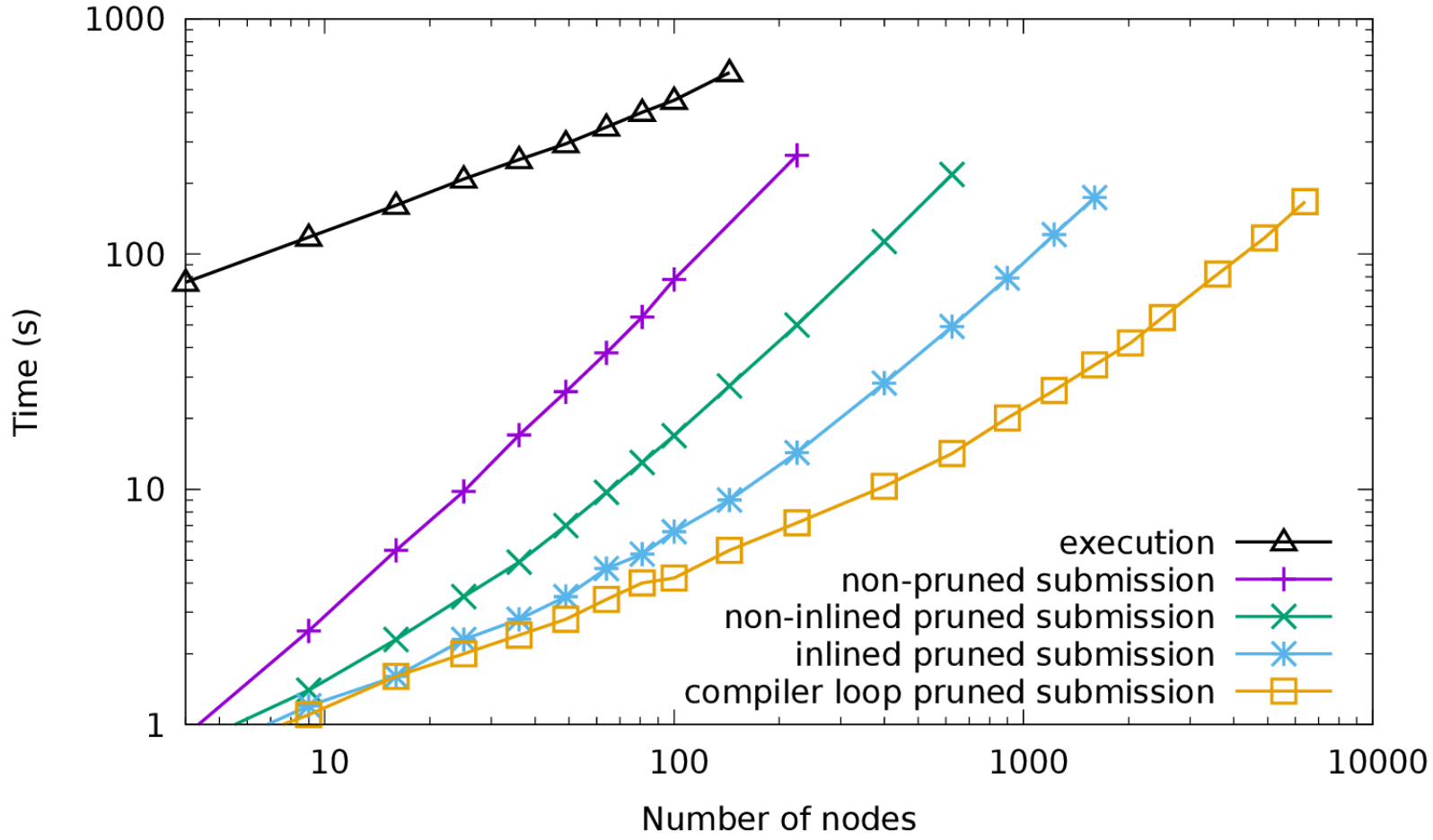
```
...
For (k = 0 .. tiles – 1) {
        ...
        for (m = k+1 .. tiles – 1) {
                ...
                for (n = m+1 + xxx .. tiles – 1 step Q)
                        /* if (cst + n%Q == self) */ {
                                …
                        }
        }
}
```

- And similar for the rest

  → Very reduced loop nest cost, not O(tiles^3) any more, but O(tiles^3/Q)

MPI VSM – pruning support

Weak scaling : 40960*40960 elements per node (80*80 tiles 512*512)

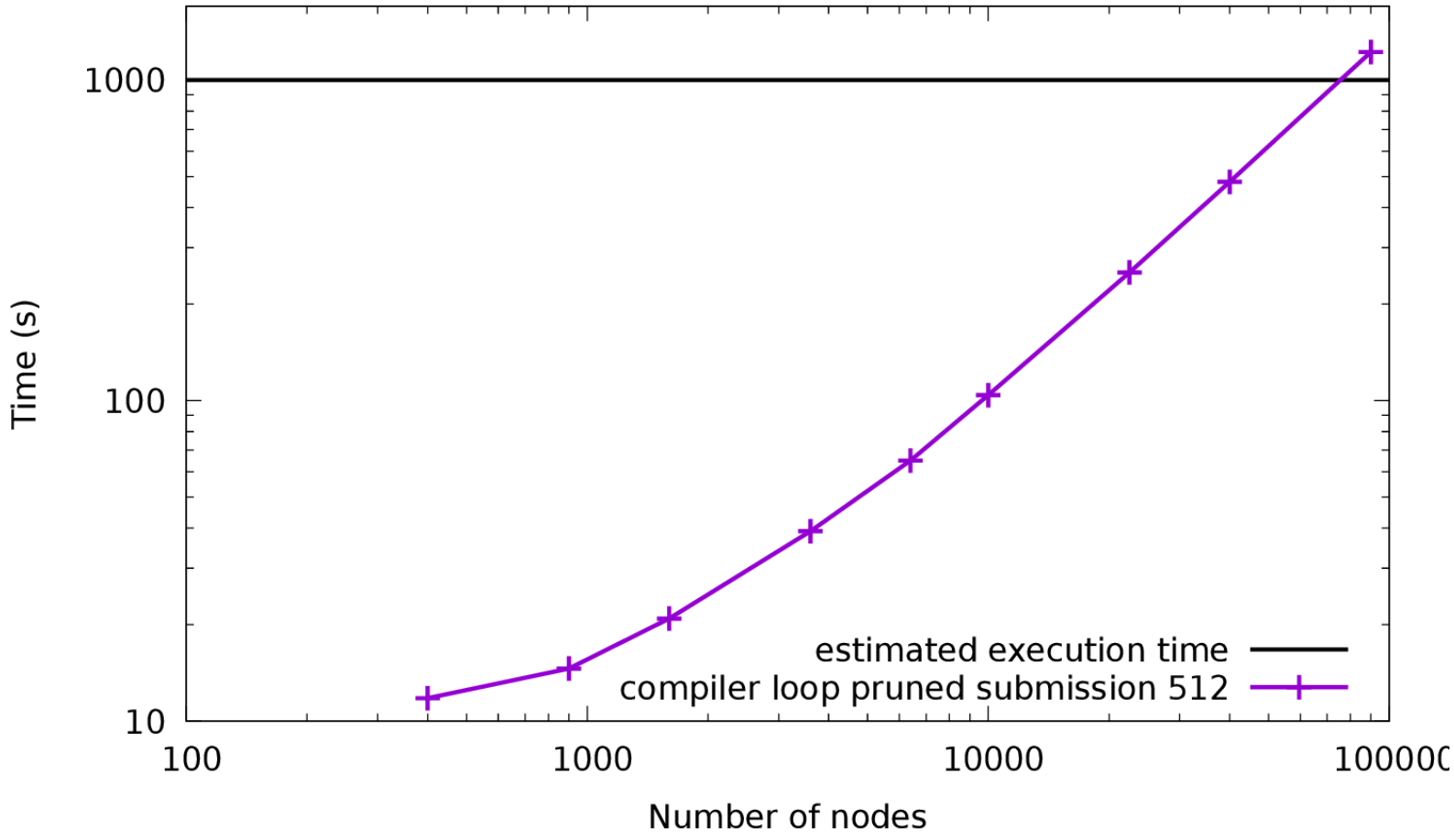


How well would it continue?

- At 400 nodes
  - 20*40960 matrix
  - 500GFlops per node (~5yr old machine)
  - ~500,000GFlop per node to compute
  - ~1000 seconds execution time
  - ~10 seconds compiler loop pruned submission time
- Let's continue weak scaling from there
  - But now fix 500,000 Gflop per node
  - I.e. keep 1000 seconds execution time

How well would it continue?

Weak scaling : 500,000 GFlop per node (~1000s execution), tile 512



How well would it continue?

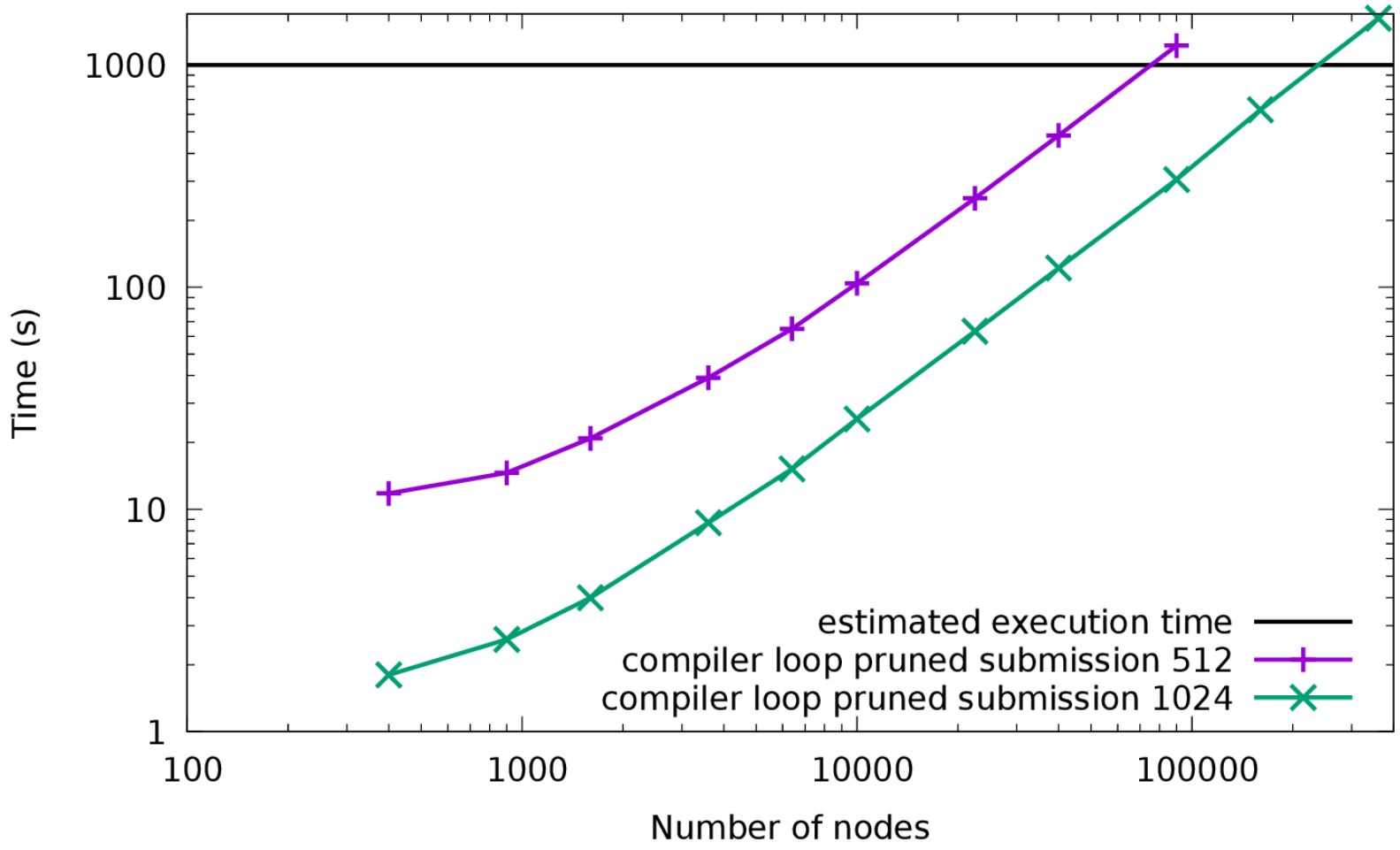
Crosses around 75,000 nodes

- Same result with other weak scaling choices
- With old 500GFlops nodes, would be 37PFlops, i.e. #2!

- Bigger tasks (parallel tasks?)
  - Way fewer tasks
  - Way smaller submission time
  - 1024 tile size

How well would it continue? (2)

Weak scaling : 500,000 GFlop per node (~1000s execution), tile 1024



How well would it continue? (2)

Now crosses around 250,000 nodes

- With 4TFlops nodes, would be 1EFlops

Further work include

- Using parallel tasks in Chameleon
- Compiler pruning of loops
- Automatic rewrite of the loop nest through polyhedral analysis
- Communication-avoidance algorithms

MPI VSM – diffusion

- Diffusion to lots of nodes
  - Bottleneck

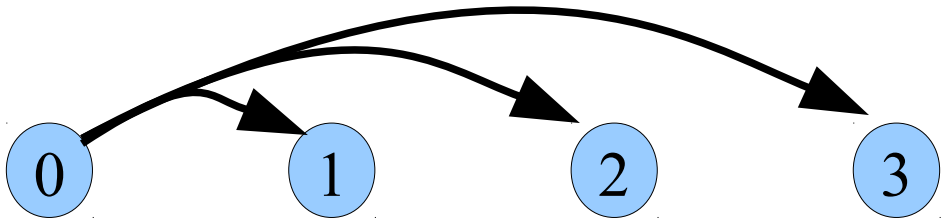
```
For (k = 0 .. tiles – 1) {
        POTRF(A[k,k]);

        for (m = k+1 .. tiles – 1) {
                TRSM(A[k,k], A[m,k]);

        }
        for (m = k+1 .. tiles – 1) {
                SYRK(A[m,k], A[m,m]);
                for (n = m+1 .. tiles – 1)
                        GEMM(A[m,k], A[n,k], A[n,m]);
        }
}
```

MPI VSM – diffusion

- Diffusion to lots of nodes
  - Bottleneck
    - E.g. node 0 sends results to a series of nodes



MPI VSM – diffusion

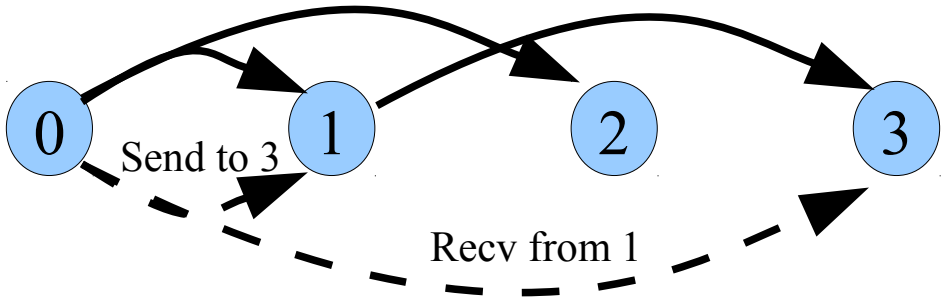
- Diffusion to lots of nodes
  - Explicit Bcast (or generated by polyhedral analysis)

```
For (k = 0 .. tiles – 1) {
        POTRF(A[k,k]);
        Bcast(A[k,k]);
        for (m = k+1 .. tiles – 1) {
                TRSM(A[k,k], A[m,k]);
                Bcast(A[m,k]);
        }
        for (m = k+1 .. tiles – 1) {
                SYRK(A[m,k], A[m,m]);
                for (n = m+1 .. tiles – 1)
                        GEMM(A[m,k], A[n,k], A[n,m]);
        }
}
```

MPI VSM – diffusion

- Diffusion to lots of nodes
  - Bottleneck

- Can also use a diffusion tree
  - Sends result to some nodes
  - Tells them to forward
  - Tells others to receive from them



MPI VSM – diffusion

- Diffusion to lots of nodes
  - Bottleneck
- Can also use a diffusion tree
  - Sends result to some nodes
  - Tells them to forward
  - Tells others to receive from them
- No need for other nodes to have global view
  - Only node 0 etc. need to compute diffusion tree

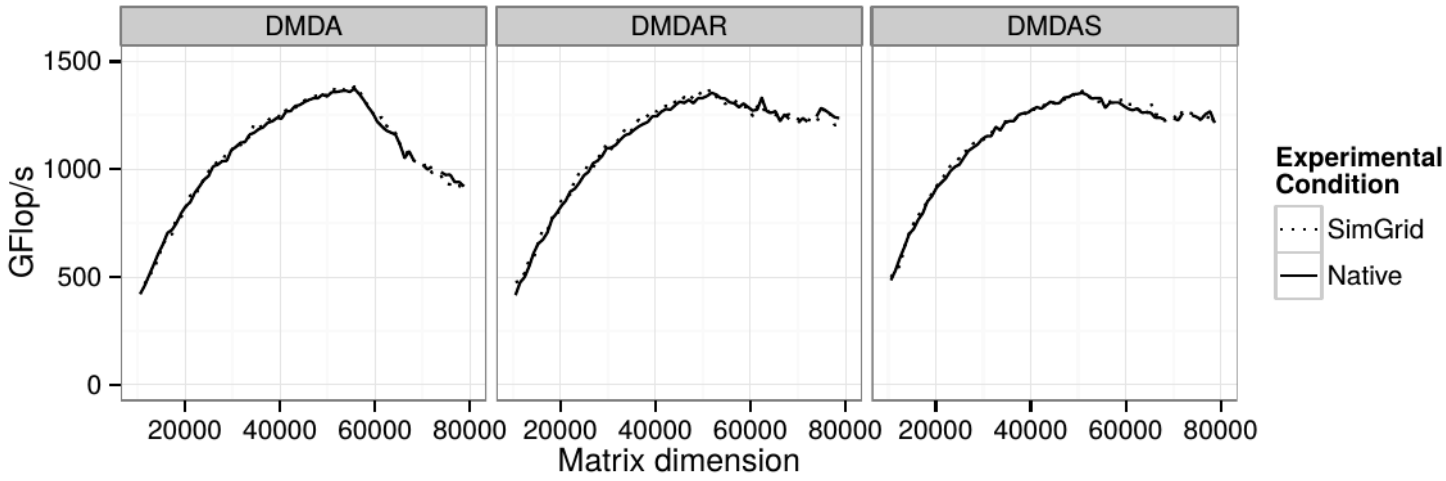
→ End-result equivalent to manual optimization

Simulation with SimGrid

- Run application natively on target system
  - Records performance models
- Rebuild application against simgrid-compiled StarPU
- Run again
  - Uses performance model estimations instead of actually executing tasks

- Way faster execution time
- Reproducible experiments
- No need to run on target system
- Can change system architecture

Simulation with SimGrid



- Way faster execution time
- Reproducible experiments
- No need to run on target system
- Can change system architecture

MPI VSM

- Will be also simulable with simgrid-MPI
  - Experimental for now, PostDoc L. Stanisic working on it

Conclusion

Summary

Tasks

- Nice programming model
  - Keep sequential program!
- Scales to large platforms
- Runtime playground
- Scheduling playground
- Algorithmic playground
- Used for various computations
  - Cholesky/QR/LU (dense/sparse), FFT, stencil, CG, FMM…

Scheduling expertise

http://starpu.gforge.inria.fr