clMAGMA: High Performance Dense Linear Algebra with OpenCL

Stan Tomov
C. Cao, J. Dongarra, P. Du, M. Gates, and P. Luszczek

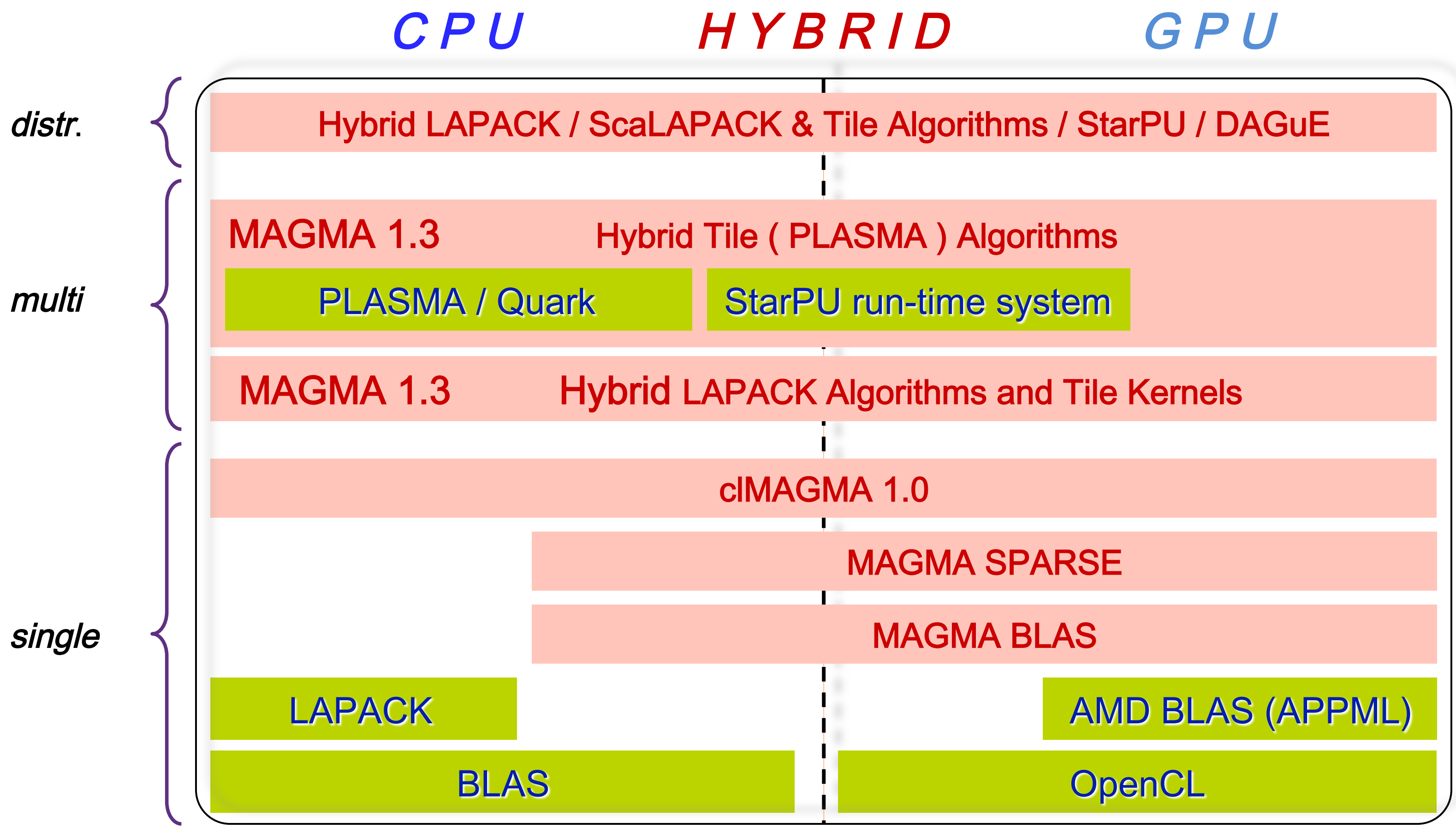
Innovative Computing Laboratory
University of Tennessee, Knoxville

1st International Workshop on OpenCL (IWOCL), May 13—14, 2013
Georgia Institute of Technology, Atlanta, GA

Outline

- **Methodology overview**
  - ***Hybridization*** **of Linear Algebra Algorithms**
  - **Use both GPUs and multicore CPUs**
- **clMAGMA**
  - **OpenCL port of MAGMA**
  - **Performance results**
  - **Challenges and future directions**
- **Conclusions**

clMAGMA Software Stack



Linux, Windows, Mac OS X | C/C++, Fortran | Matlab, Python

[**AMD APPML** -- Accelerated Parallel Processing Math Libraries
http://developer.amd.com/libraries/appmathlibs/]

clMAGMA 1.0

MAGMA

icl.cs.utk.edu/magma/news/news.html?id=303

MAGMA

News

- Home
- Overview
- News
- Downloads
- Publications
- People
- Partners
- Documentation
- User Forum

clMAGMA 1.0 Released

2012-10-24

clMAGMA 1.0 is now available. clMAGMA is an OpenCL port of the MAGMA library. This release adds the following new functionalities:

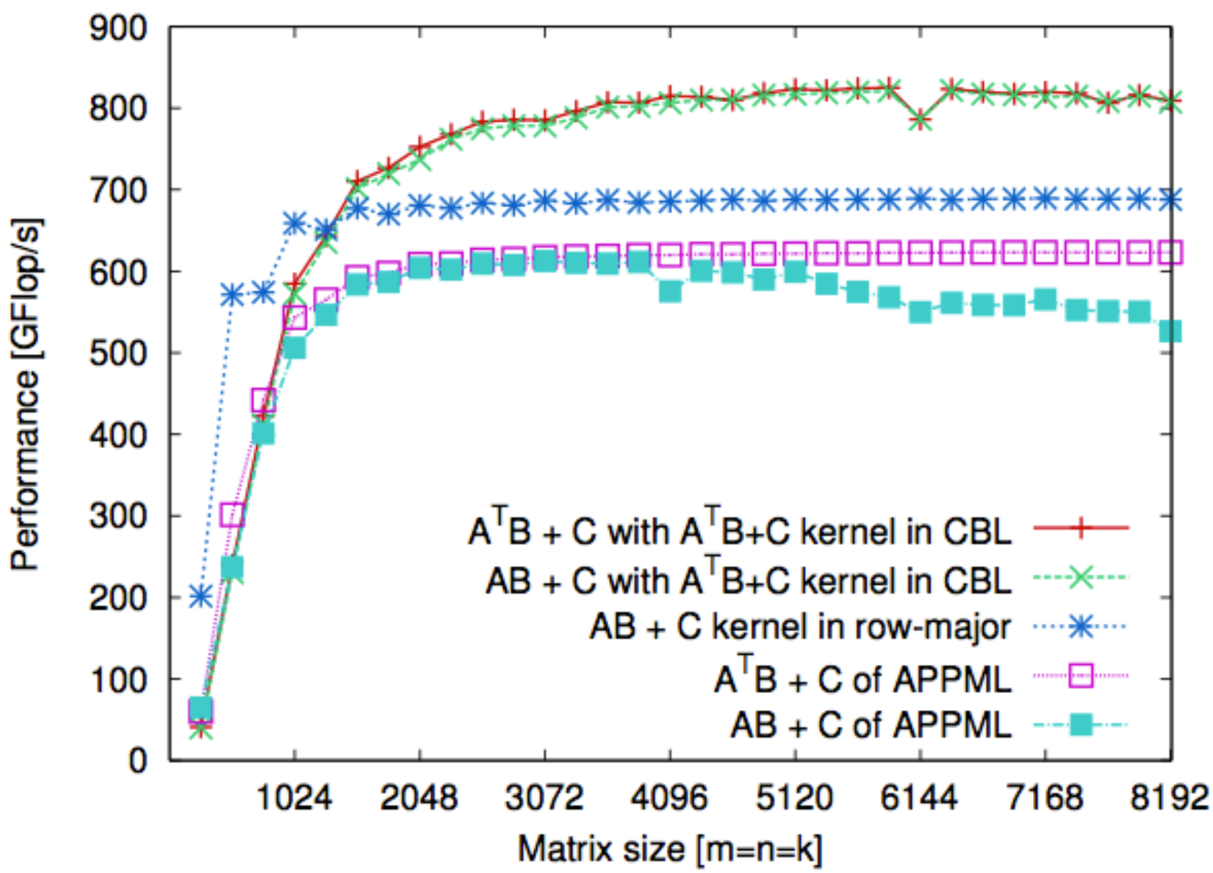
- Eigen and singular value problem solvers in both real and complex arithmetic, single and double (routines magma_zlc}heevd, magma_{dls}syevd, magma_{zlcldls}geev, and magma_{zlcldls}gesvd);
- Matrix inversion routines (routines magma_{zlcldls}trtri_gpu, magma_{zlcldls}getri_gpu, magma_{zlcldls}potri_gpu);
- Orthogonal transformations routines ({zlc}unmqr_gpu, {dls}ormqr_gpu, {zlc}ungqr, {dls}orgqr, {zlc}unmtr, {dls}ormtr, {zlc}unmqr, {dls}ormqr, {zlc}unmql, {dls}ormql, {zlc}unghr, and {dls}orghr).

See the MAGMA software homepage for a **download link**.

Sponsored By: Industry Support From: AMD intel Microsoft NVIDIA

DGEMM in OpenCL

Kazuya Matsumoto, Naohito Nakasato, Stanislav G.Sedukhin, *Implementing a Code Generator for Fast Matrix Multiplication in OpenCL on the GPU*, University of Aizu, Japan, July 2, 2012.



DGEMM

GPU: Tahiti (AMD Radeon HD 7900)
264 GB/s memory bandwidth
3.79 Tflop/s SP, 947 Gflop/s DP
32 x 64 (2048 stream proc.)

MAGMA Methodology

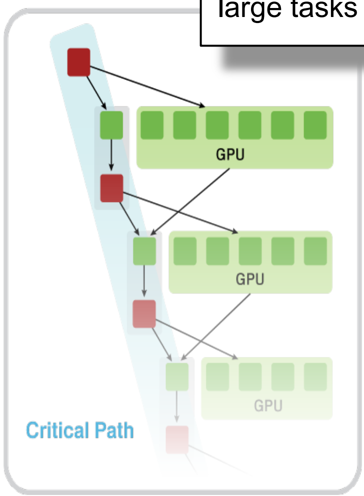
A methodology to use all available resources:

- MAGMA uses HYBRIDIZATION methodology based on
  - Representing linear algebra algorithms as collections of TASKS and DATA DEPENDENCIES among them
  - Properly SCHEDULING tasks' execution over multicore and GPU hardware components

- Successfully applied to fundamental linear algebra algorithms
  - One and two-sided factorizations and solvers
  - Iterative linear and eigen-solvers

- Productivity
  - 1) High-level; 2) Leveraging prior developments; 3) Exceeding in performance homogeneous solutions

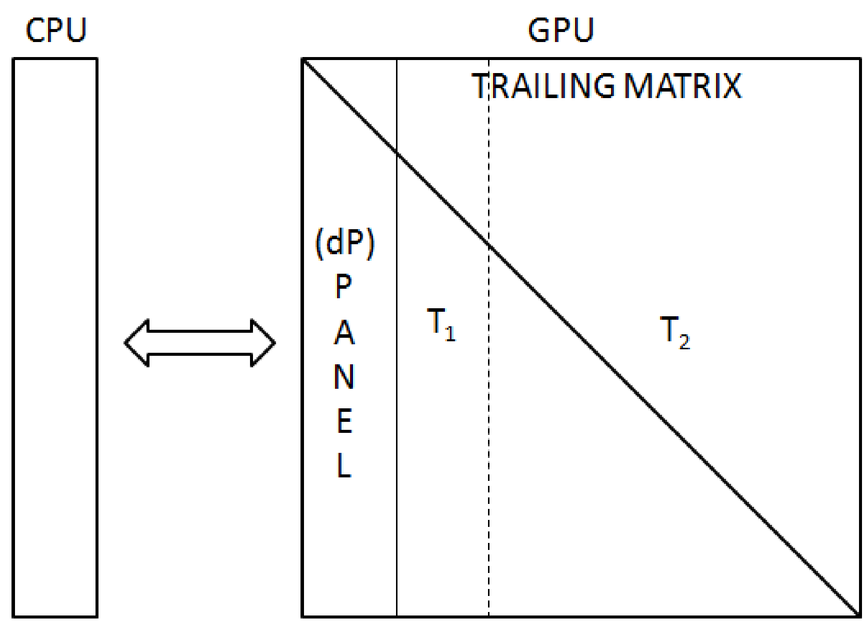
Hybrid CPU+GPU algorithms (small tasks for multicores and large tasks for GPUs)



Hybrid Algorithms

One-sided factorizations (LU, QR, Cholesky)

- **Hybridization**
  - **Panels (Level 2 BLAS) are factored on CPU using LAPACK**
  - **Trailing matrix updates (Level 3 BLAS) are done on the GPU using "look-ahead"**



A Hybrid Algorithm Example

- Left-looking hybrid Cholesky factorization in clMAGMA

```
1   for ( j=0; j<n; j += nb)  {
2       jb = min(nb, n – j);
3       magma_zherk( MagmaUpper, MagmaConjTrans, jb, j, m_one, dA(0, j), ldda, one, dA(j, j), ldda, queue );
4       magma_zgetmatrix_async( jb, jb, dA(j,j), ldda, work, 0, jb, queue, &event );
5       if ( j+jb < n )
6           magma_zgemm( MagmaConjTrans, MagmaNoTrans, jb, n-j-jb, j, mz_one,
7                        dA(0, j ), ldda, dA(0, j+jb), ldda, z_one,  dA(j, j+jb), ldda, queue );
8       magma_event_sync( event );
9       lapackf77_zpotrf( MagmaUpperStr, &jb, work, &jb, info );
10      if ( *info != 0 )
11           *info += j;
12      magma_zsetmatrix_async( jb, jb, work, 0, jb, dA(j,j), ldda, queue, &event );
13      if ( j+jb < n ) {
12          magma_event_sync( event );
13          magma_ztrsm( MagmaLeft, MagmaUpper, MagmaConjTrans, MagmaNonUnit,
14                       jb, n-j-jb, z_one, dA(j, j), ldda, dA(j, j+jb), ldda, queue );
15       }
16  }
```

- The difference with LAPACK – the 4 additional lines in red
- Line 9 (done on CPU) is overlapped with work on the GPU (from line 6)

Programming model

Host program

```
for ( j=0; j<n; j += nb) {
     jb = min(nb, n – j);
     magma_zherk( MagmaUpper, MagmaConjTrans,
                          jb, j, m_one, dA(0, j), ldda, one, dA(j, j), ldda, queue );
     magma_zgetmatrix_async( jb, jb, dA(j,j), ldda, work, 0, jb, queue, &event );
     if ( j+jb < n )
         magma_zgemm( MagmaConjTrans, MagmaNoTrans, jb, n-j-jb, j, mz_one,
                              dA(0, j ), ldda, dA(0, j+jb), ldda, z_one,  dA(j, j+jb), ldda, queue );
     magma_event_sync( event );
     lapackf77_zpotrf( MagmaUpperStr, &jb, work, &jb, info );
     if ( *info != 0 )
          *info += j;
     magma_zsetmatrix_async( jb, jb, work, 0, jb, dA(j,j), ldda, queue, &event );
     if ( j+jb < n ) {
         magma_event_sync( event );
         magma_ztrsm( MagmaLeft, MagmaUpper, MagmaConjTrans, MagmaNonUnit,
                             jb, n-j-jb, z_one, dA(j, j), ldda, dA(j, j+jb), ldda, queue );
     }
}
```

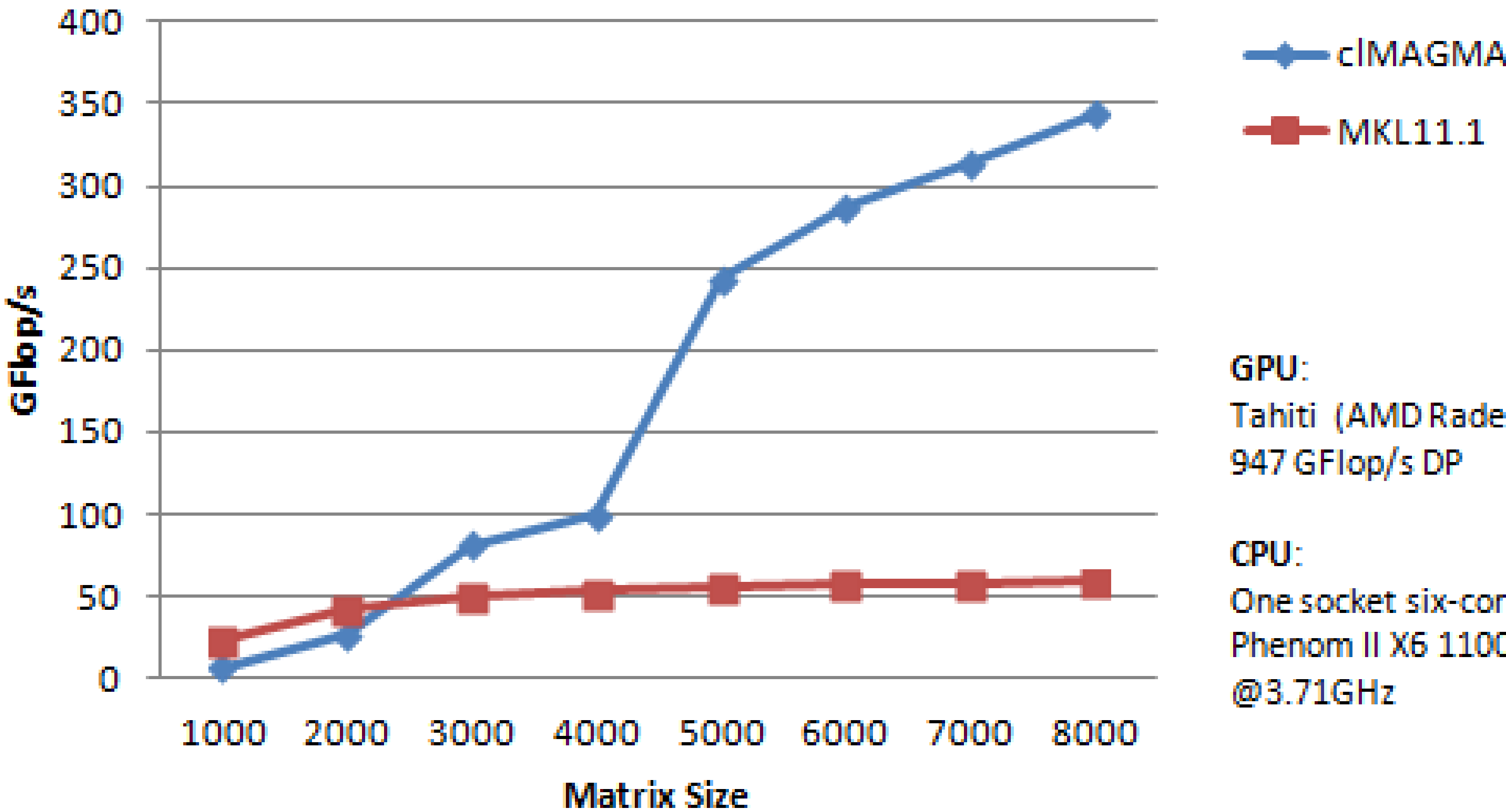
OpenCL interface – communications

```
magma_err_t
magma_zgetmatrix_async(
    magma_int_t m, magma_int_t n,
    magmaDoubleComplex_const_ptr dA_src, size_t dA_offset, magma_int_t
    magmaDoubleComplex*          hA_dst, size_t hA_offset, magma_int_t
    magma_queue_t queue, magma_event_t *event )
{
    size_t buffer_origin[3] = { dA_offset*sizeof(magmaDoubleComplex),
    size_t host_orig[3]     = { 0, 0, 0 };
    size_t region[3]        = { m*sizeof(magmaDoubleComplex), n, 1 };
    cl_int err = clEnqueueReadBufferRect(
        queue, dA_src, CL_FALSE,  // non-blocking
        buffer_origin, host_orig, region,
        ldda*sizeof(magmaDoubleComplex), 0,
        ldha*sizeof(magmaDoubleComplex), 0,
        hA_dst, 0, NULL, event );
```

OpenCL interface – AMD APPML BLAS

```
magma_zherk(
    magma_uplo_t uplo, magma_trans_t trans,
    magma_int_t n, magma_int_t k,
    double alpha, magmaDoubleComplex_const_ptr dA, size_t dA_offset,
    double beta,  magmaDoubleComplex_ptr       dC, size_t dC_offset,
    magma_queue_t queue )
{
    cl_int err = clAmdBlasZherk(
        clAmdBlasColumnMajor,
        amdblas_uplo_const( uplo ),
        amdblas_trans_const( trans ),
        n, k,
        alpha, dA, dA_offset, lda,
        beta,  dC, dC_offset, ldc,
        1, &queue, 0, NULL, NULL );
    return err;
}
```

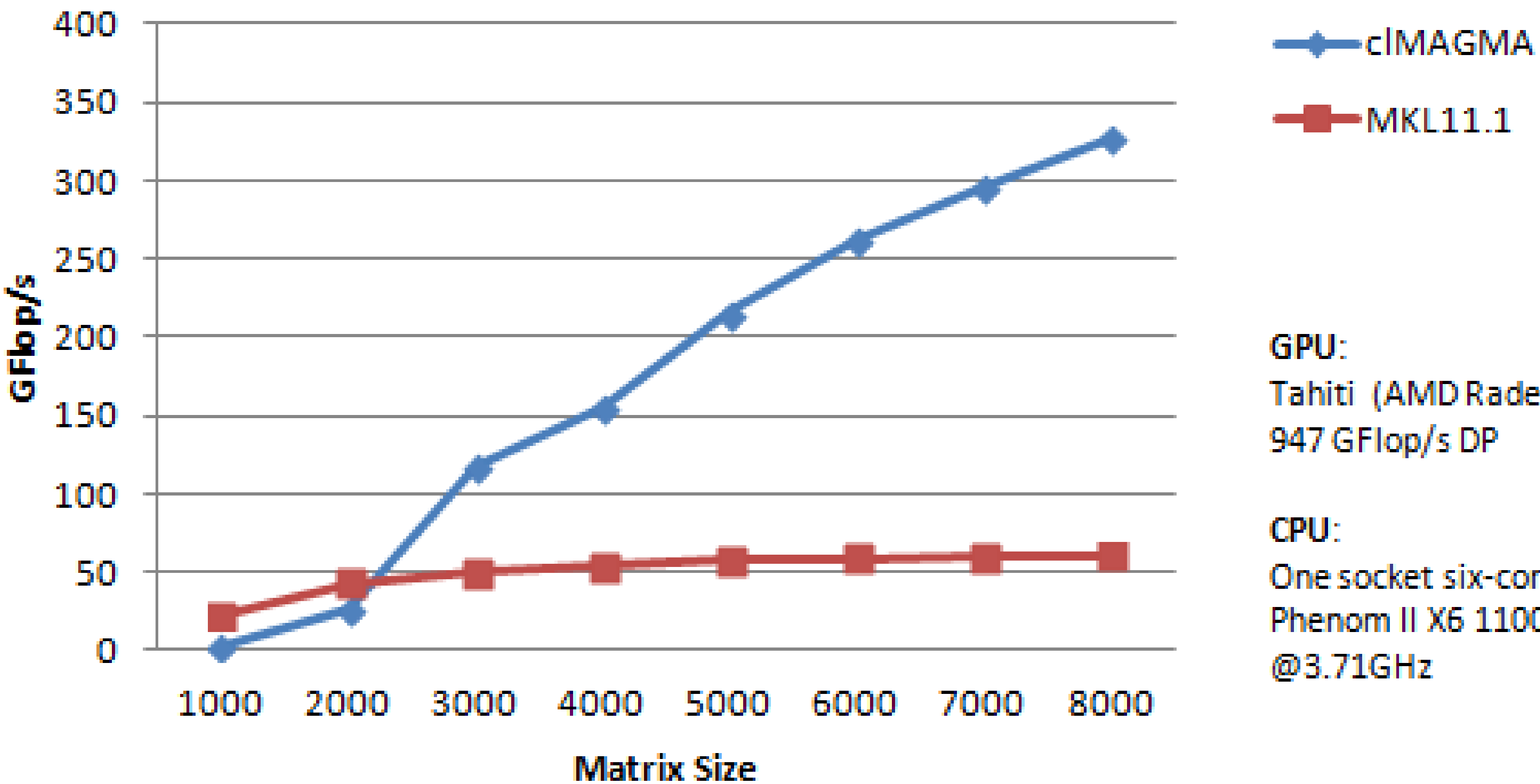
Performance of clMAGMA Cholesky Factorization in double precision



GPU:
Tahiti (AMD Radeon 7970)
947 GFlop/s DP

CPU:
One socket six-core AMD
Phenom II X6 1100T
@3.71GHz

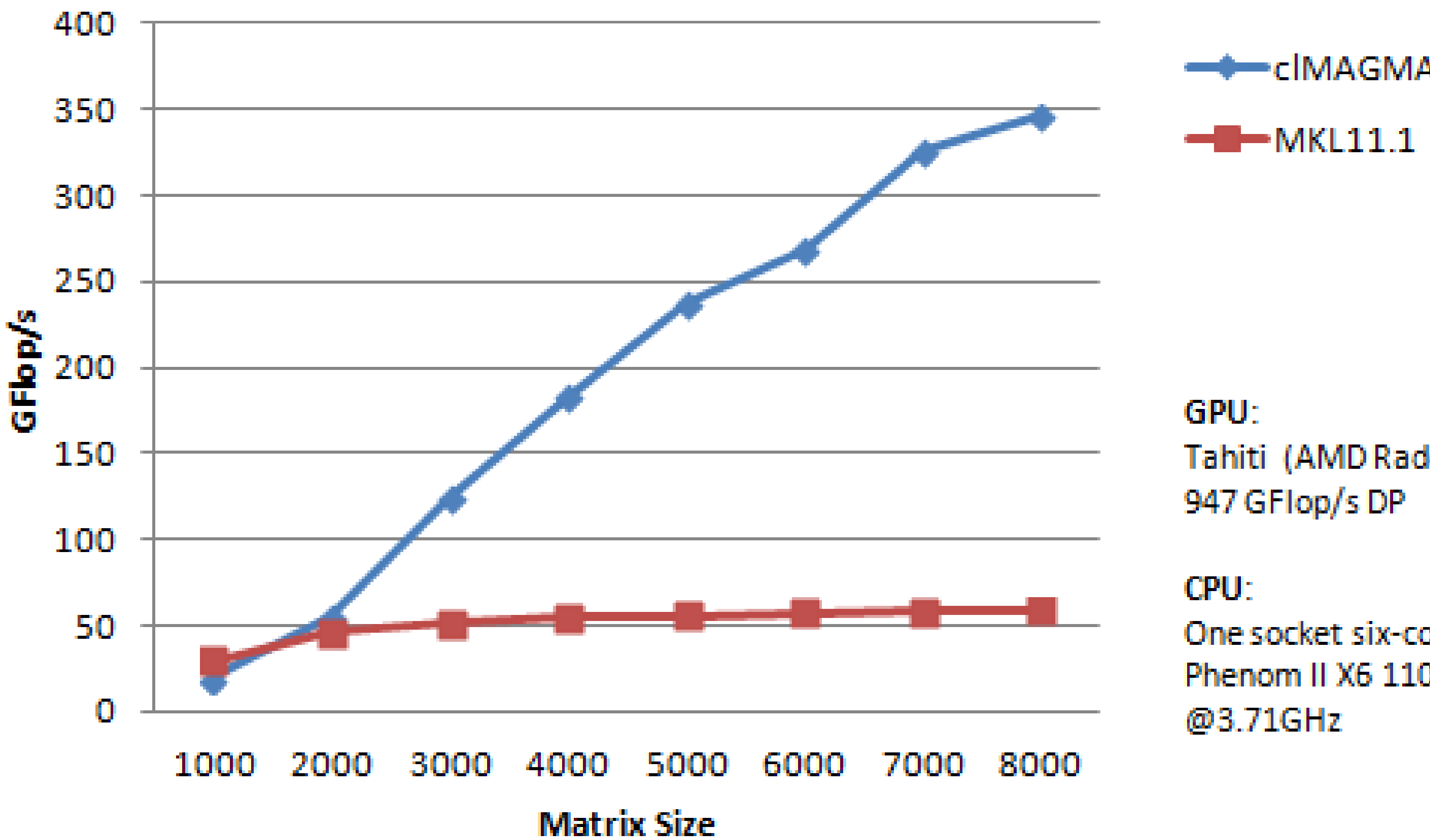
Performance of clMAGMA LU Factorization in double precision



GPU:
Tahiti (AMD Radeon 7970)
947 GFlop/s DP

CPU:
One socket six-core AMD
Phenom II X6 1100T
@3.71GHz

Performance of clMAGMA QR Factorization in double precision



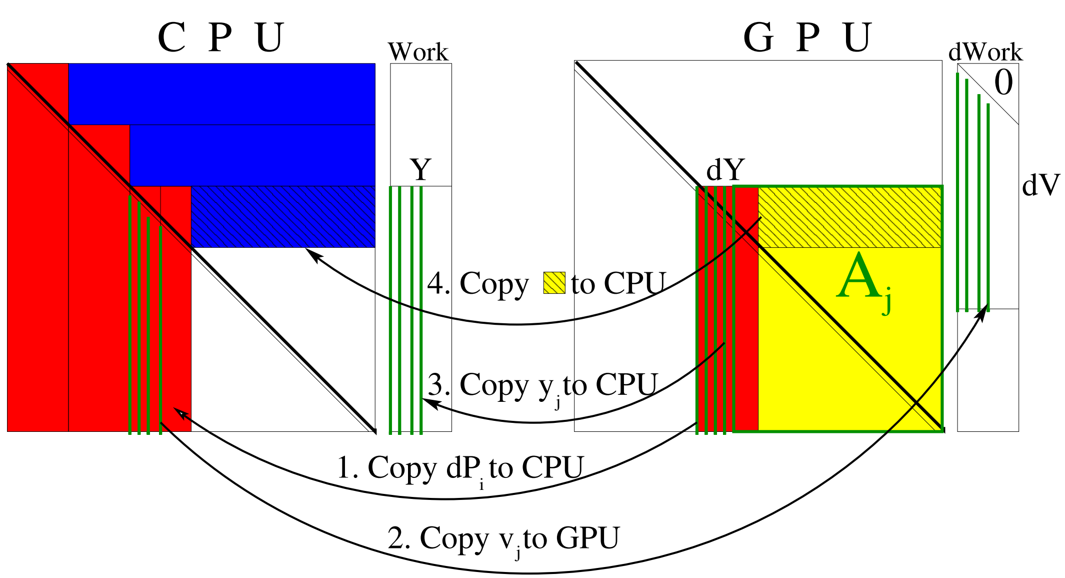
GPU:
Tahiti (AMD Radeon 7970)
947 GFlop/s DP

CPU:
One socket six-core AMD Phenom II X6 1100T @3.71GHz

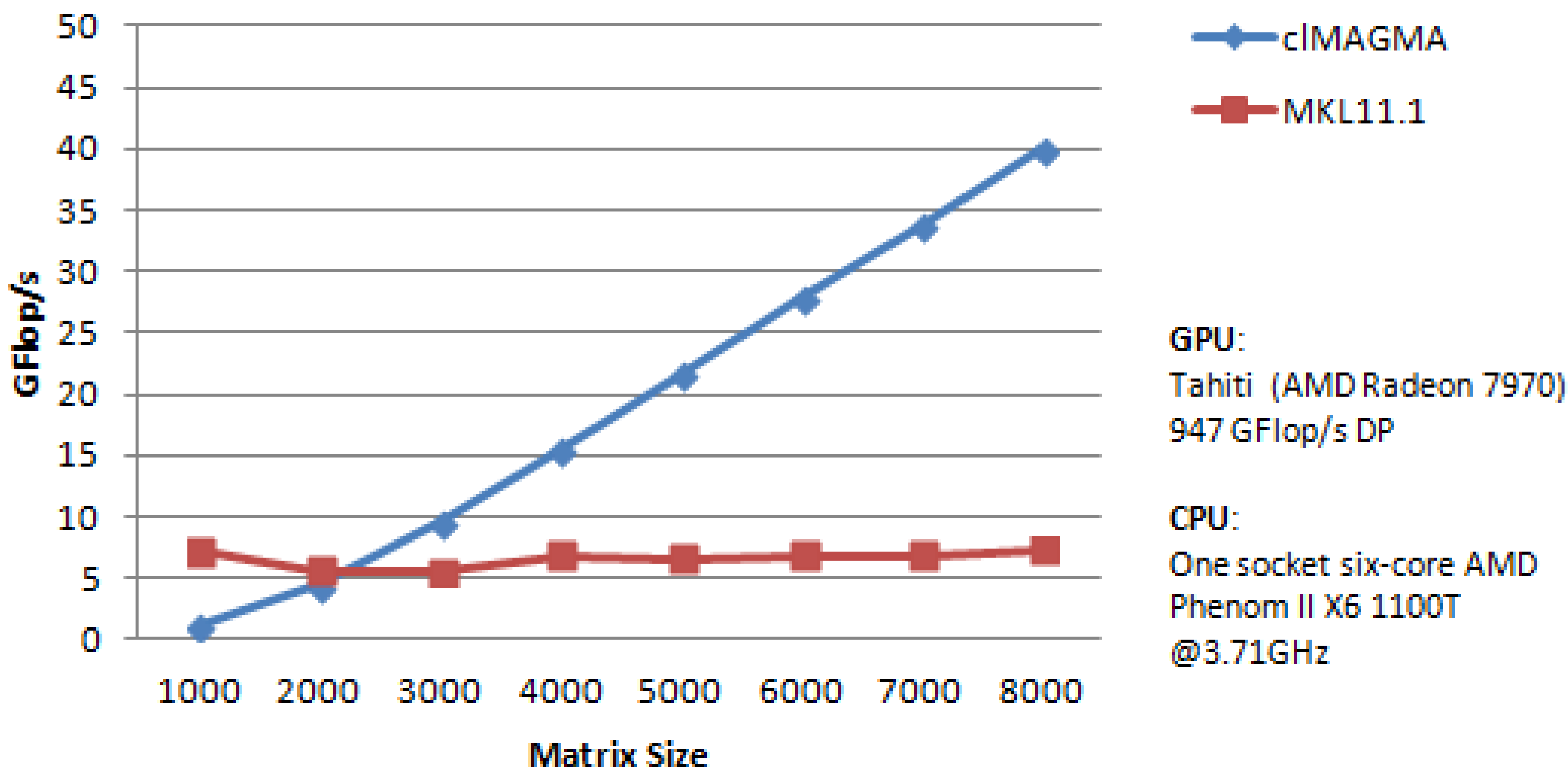
Hybrid Algorithms

Two-sided factorizations (Hessenberg, bi-, and tridiagonalization)

- **Hybridization**
  - **Panels (Level 2 BLAS) are also hybrid, using both CPU & GPU (vs. just CPU as in the one-sided factorizations)**
  - **Trailing matrix updates (Level 3 BLAS) are done on the GPU using “look-ahead”**



Performance of clMAGMA Hessenberg Factorization in double precision



Current work
Dynamic Scheduling

- **Conceptually similar to out-of-order processor scheduling because it has:**
  - Dynamic runtime DAG scheduler
  - Out-of-order execution flow of fine-grained tasks
  - Task scheduling as soon as dependencies are satisfied
  - Producer-Consumer

- **Data Flow Programming Model**
  - The DAG approach
  - Scheduling is data driven
  - Inherently parallel

Current Work
High Level of Productivity

From Sequential Nested-Loop Code to Parallel Execution:

```
for (k = 0; k < min(MT, NT); k++){
        zgeqrt(A[k;k], ...);
        for (n = k+1; n < NT; n++)
            zunmqr(A[k;k], A[k;n], ...);
        for (m = k+1; m < MT; m++){
            ztsqrt(A[k;k],,A[m;k], ...);
            for (n = k+1; n < NT; n++)
                ztsmqr(A[m;k], A[k;n], A[m;n], ...);
      }
}
```

Current Work
High Level of Productivity

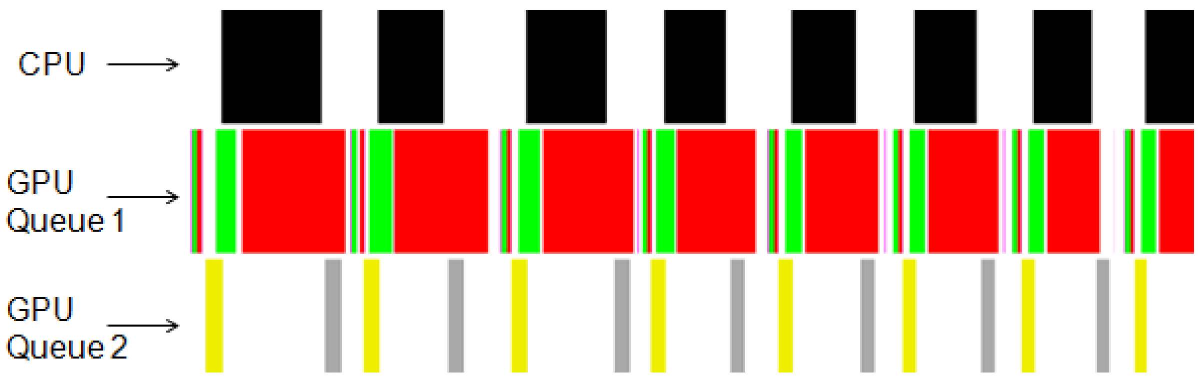
From Sequential Nested-Loop Code to Parallel Execution:

```
for (k = 0; k < min(MT, NT); k++){
        Insert_Task(&zgeqrt, k , k, ...);
        for (n = k+1; n < NT; n++)
            Insert_Task(&zunmqr, k, n, ...);
        for (m = k+1; m < MT; m++){
            Insert_Task(&ztsqrt, m, k, ...);
            for (n = k+1; n < NT; n++)
                Insert_Task(&ztsmqr, m, n, k, ...);
        }
}
```

Current work
Performance optimizations

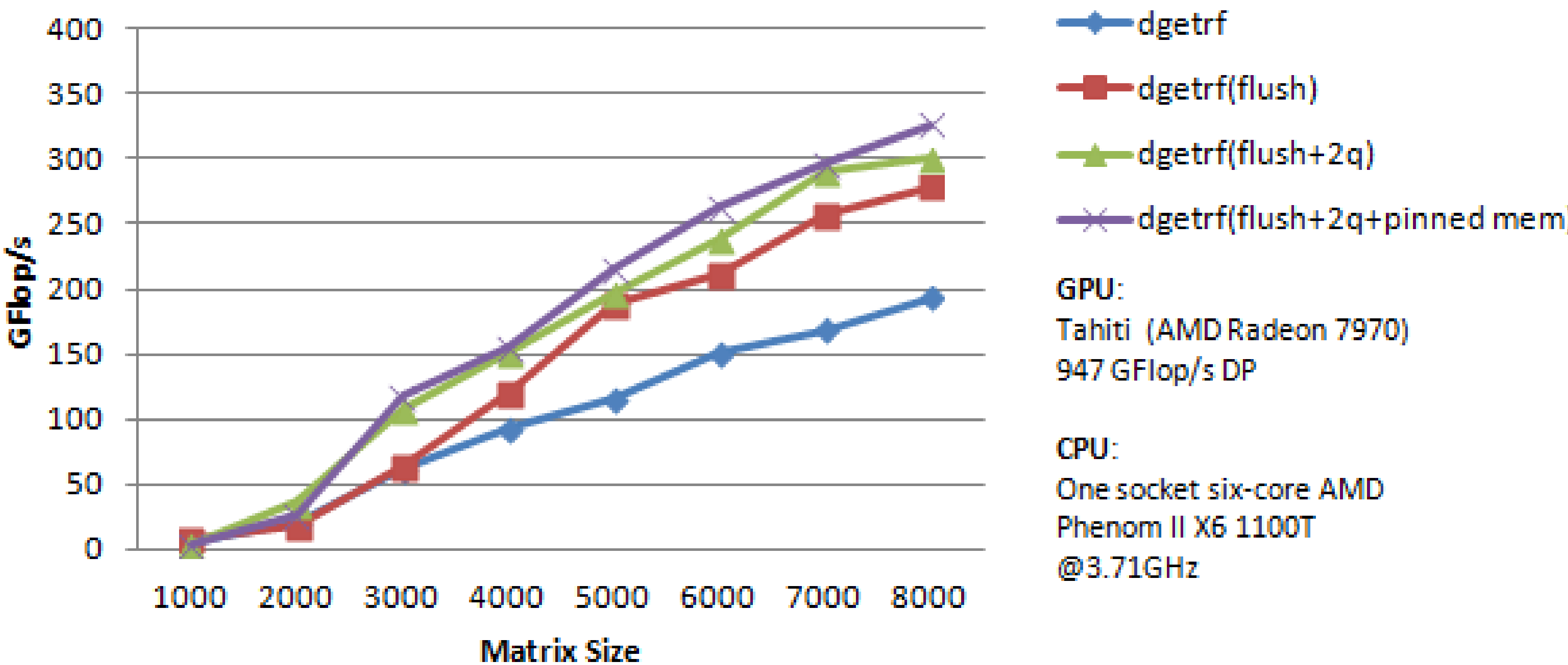
- **Overlap CPU work, GPU work, and CPU-GPU communications**

A dgetrf trace example



Black – panel	Red – dgemm	Green – dtrsm	Gray / Yellow – dset / dget

Performance optimizations in LU

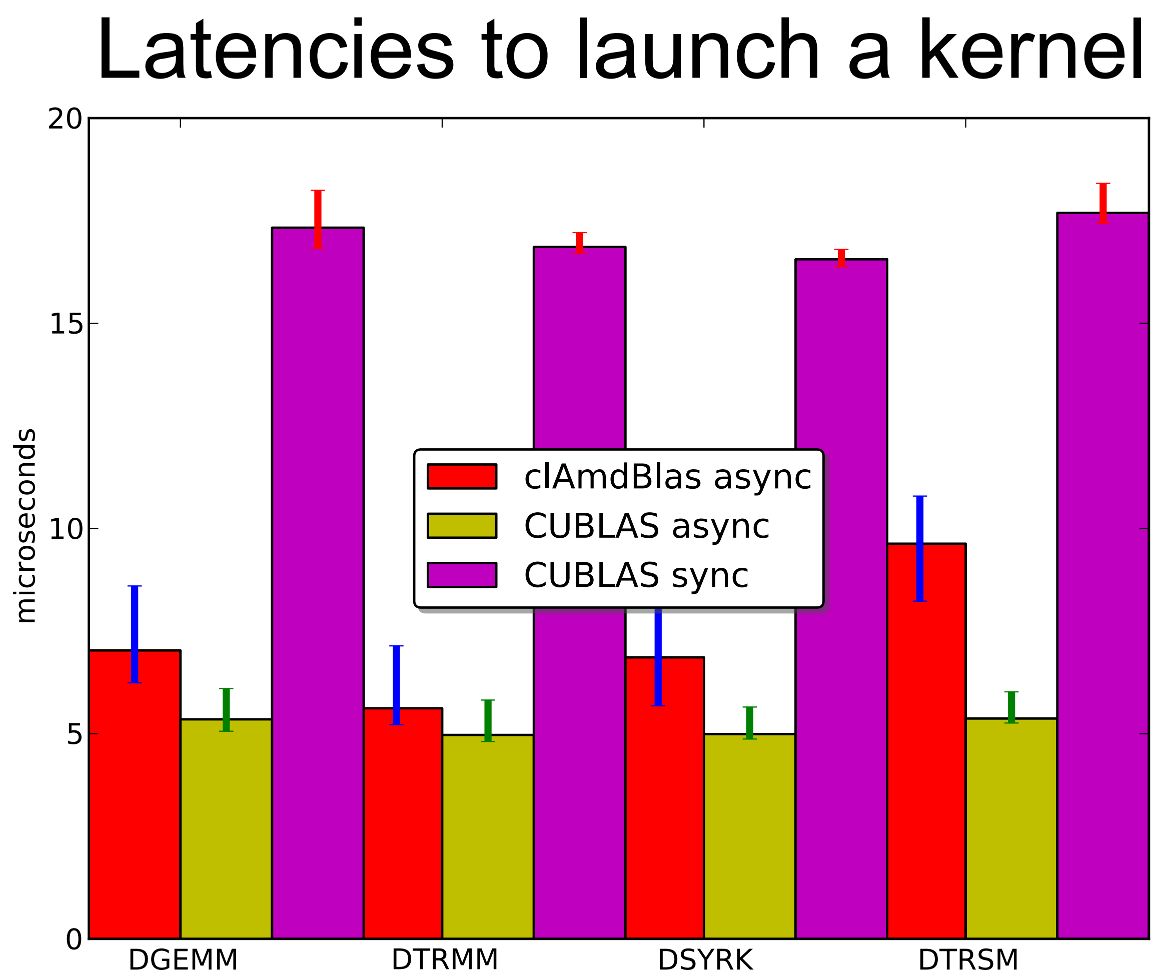


GPU:
Tahiti (AMD Radeon 7970)
947 GFlop/s DP

CPU:
One socket six-core AMD
Phenom II X6 1100T
@3.71GHz

OpenCL-specific optimizations

- **Benchmarks to discover OpenCL specifics**



Panels entirely on GPU?

- **Important to have for both dense and certain sparse linear system and eigen-problem solvers**
- **Can we factor panels faster on GPU as panels are memory bound?**
- **Latencies may be a bottleneck**
  - e.g., 64 columns panel would require the invocation of ~400 kernels

Performance of QR panels in double precision
on Kepler (in CUDA), Tahiti (in OpenCL), and 16 Intel Sandy Bridge cores

M	N	CUDA Time (ms)	OpenCL Time (ms)	16 Sandy Bridge (ms)
1,000	64	5	94	9
10,000	64	7	104	17
100,000	64	36	131	89
1,000,000	64	365	528	1,431

Difference is due to latencies (in our software/hardware configuration) as shown by increasing the problem size.

Summary and Future Directions

- **A hybrid methodology and its application to DLA using OpenCL**
- **clMAGMA: LAPACK for heterogeneous computing**
  - Achieving high-performance linear algebra using OpenCL
  - clMAGMA 1.0 includes the main
    - one- and two-sided factorizations
    - orthogonal transformation routines
    - linear and eigen-problem solvers
- **What is next?**
  - Further performance/efficiency improvements
  - MultiGPU and distributed environments

Collaborators / Support

- **MAGMA [Matrix Algebra on GPU and Multicore Architectures] team**
  http://icl.cs.utk.edu/magma/

- **PLASMA [Parallel Linear Algebra for Scalable Multicore Architectures] team**
  http://icl.cs.utk.edu/plasma

- **Collaborating Partners**
  University of Tennessee, Knoxville
  University of California, Berkeley
  University of Colorado, Denver

  INRIA, France
  KAUST, Saudi Arabia