

Scalable Resource Management in Cloud Computing, Grid Computing and Supercomputing

Ioan Raicu

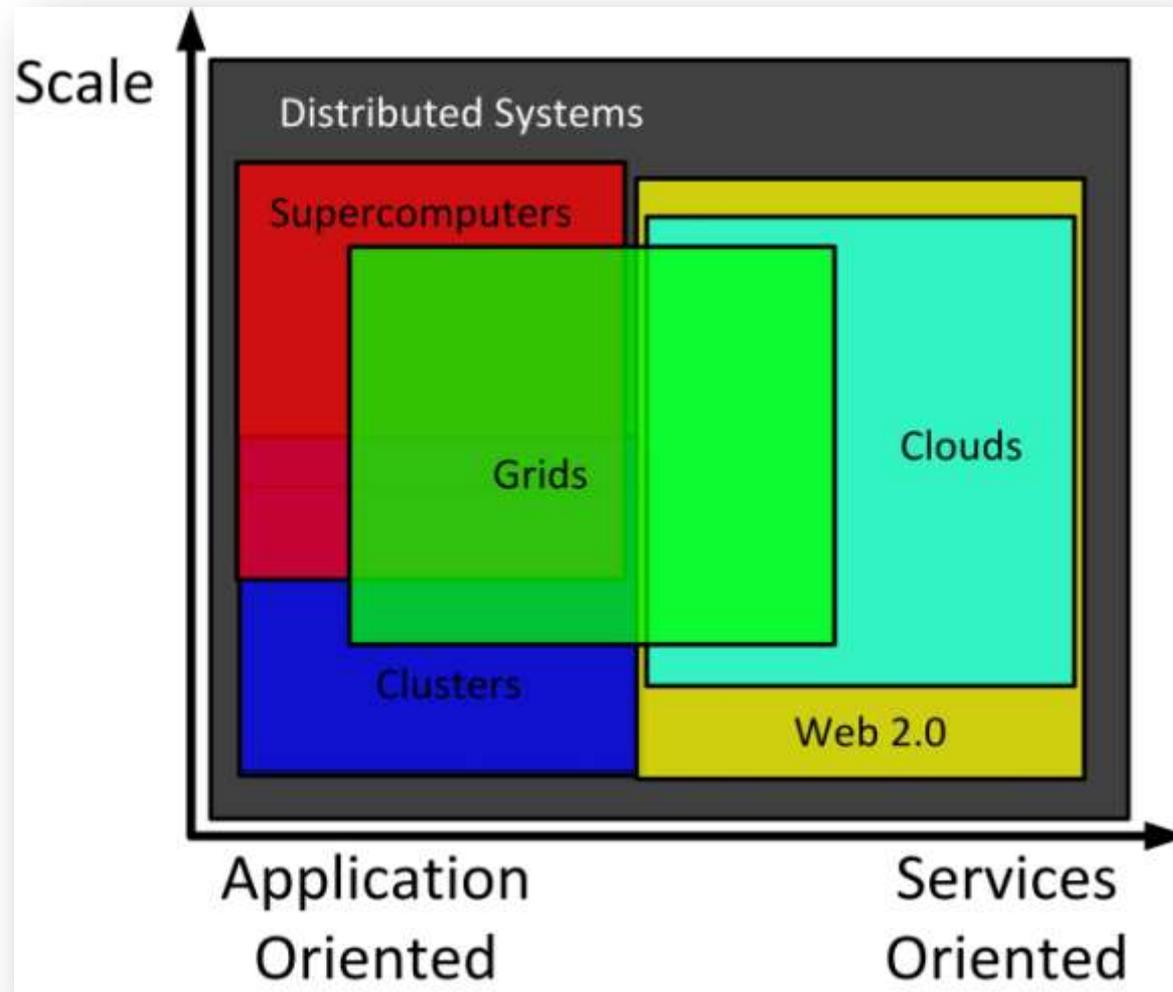
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Department of Electrical Engineering & Computer Science
Northwestern University

College of Computing and Digital Media, DePaul University
January 20th, 2010

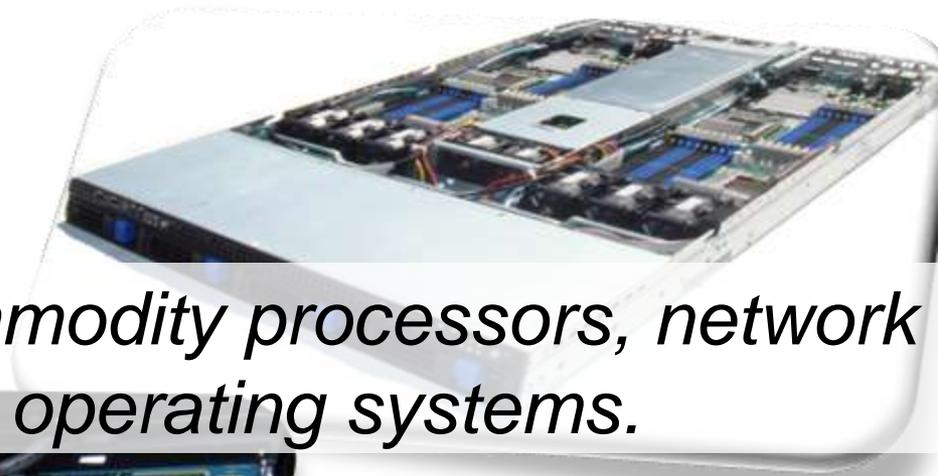
Outline

- **Overview**
- **Contributions**
- **Applications**
- **Conclusions**

Clusters, Grids, Clouds, and Supercomputers



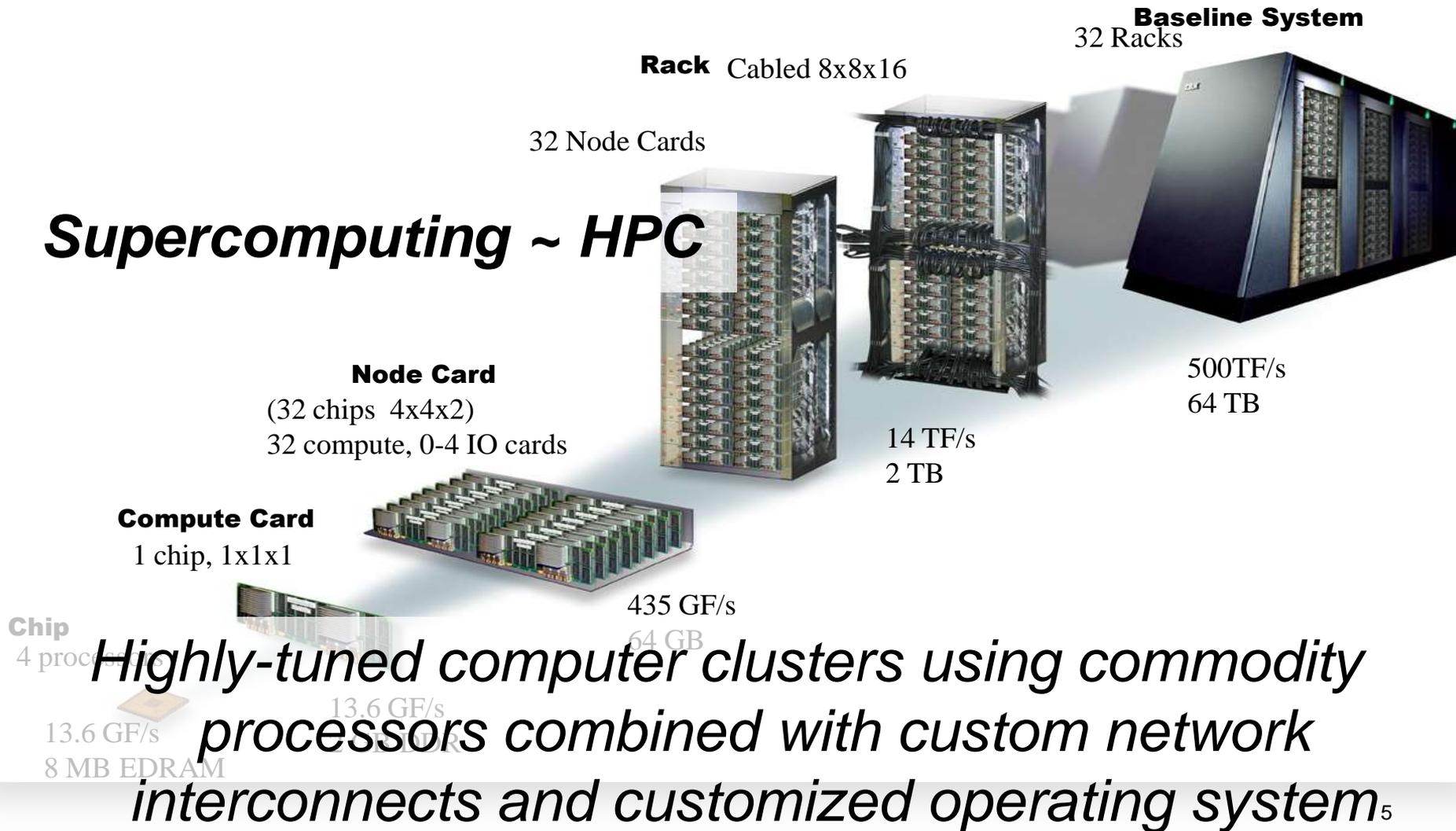
Cluster Computing



Computer clusters using commodity processors, network interconnects, and operating systems.

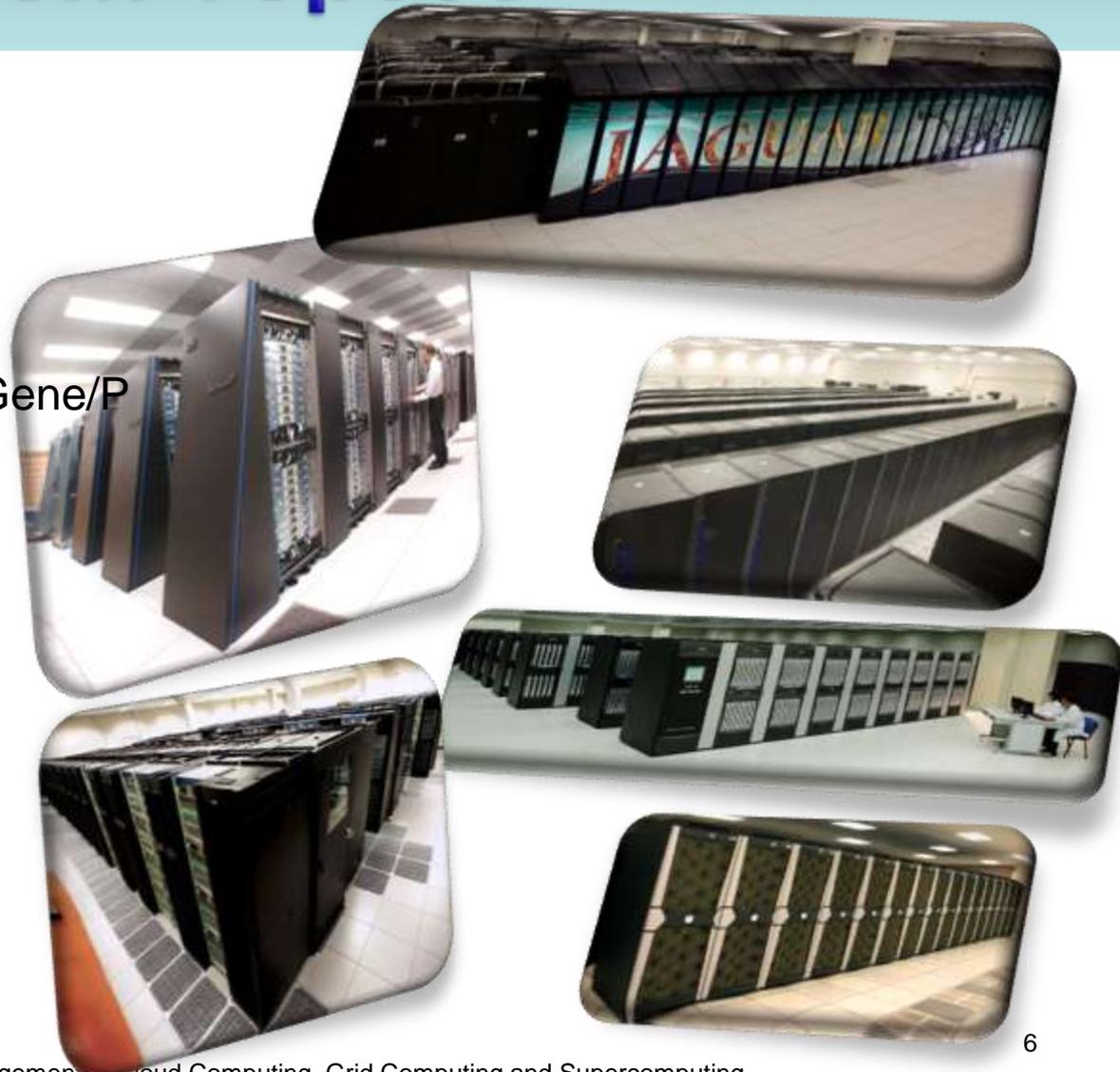
Supercomputing

Supercomputing ~ HPC



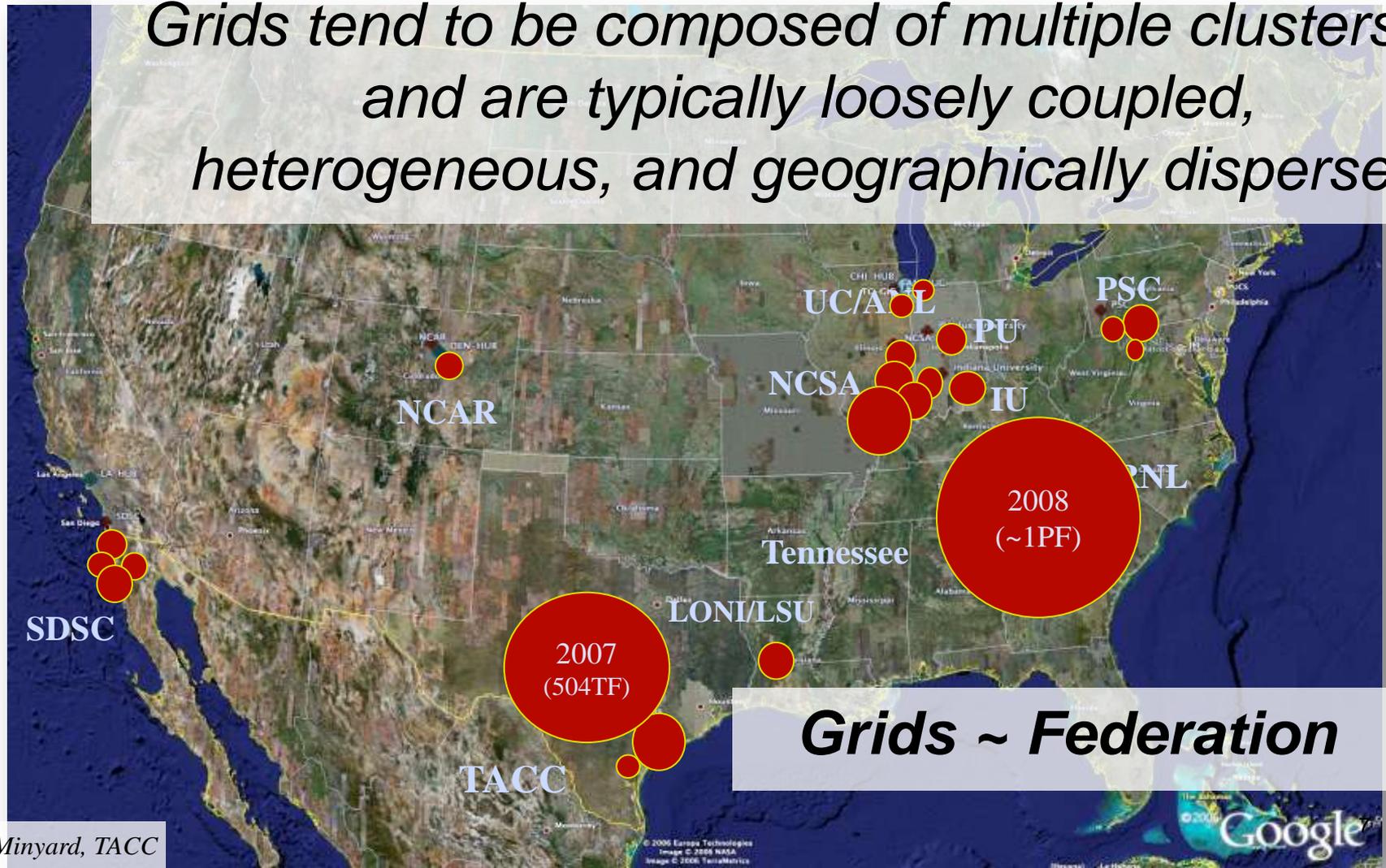
Top 10 Supercomputers from Top500

- Cray XT4 & XT5
 - Jaguar #1
 - Kraken #3
- IBM BladeCenter Hybrid
 - Roadrunner #2
- IBM BlueGene/L & BlueGene/P
 - Jugene #4
 - Intrepid #8
 - BG/L #7
- NUDT (GPU based)
 - Tianhe-1 #5
- SGI Altix ICE
 - Plaiedas #6
- Sun Constellation
 - Ranger #9
 - Red Sky #10



Grid Computing

Grids tend to be composed of multiple clusters, and are typically loosely coupled, heterogeneous, and geographically dispersed

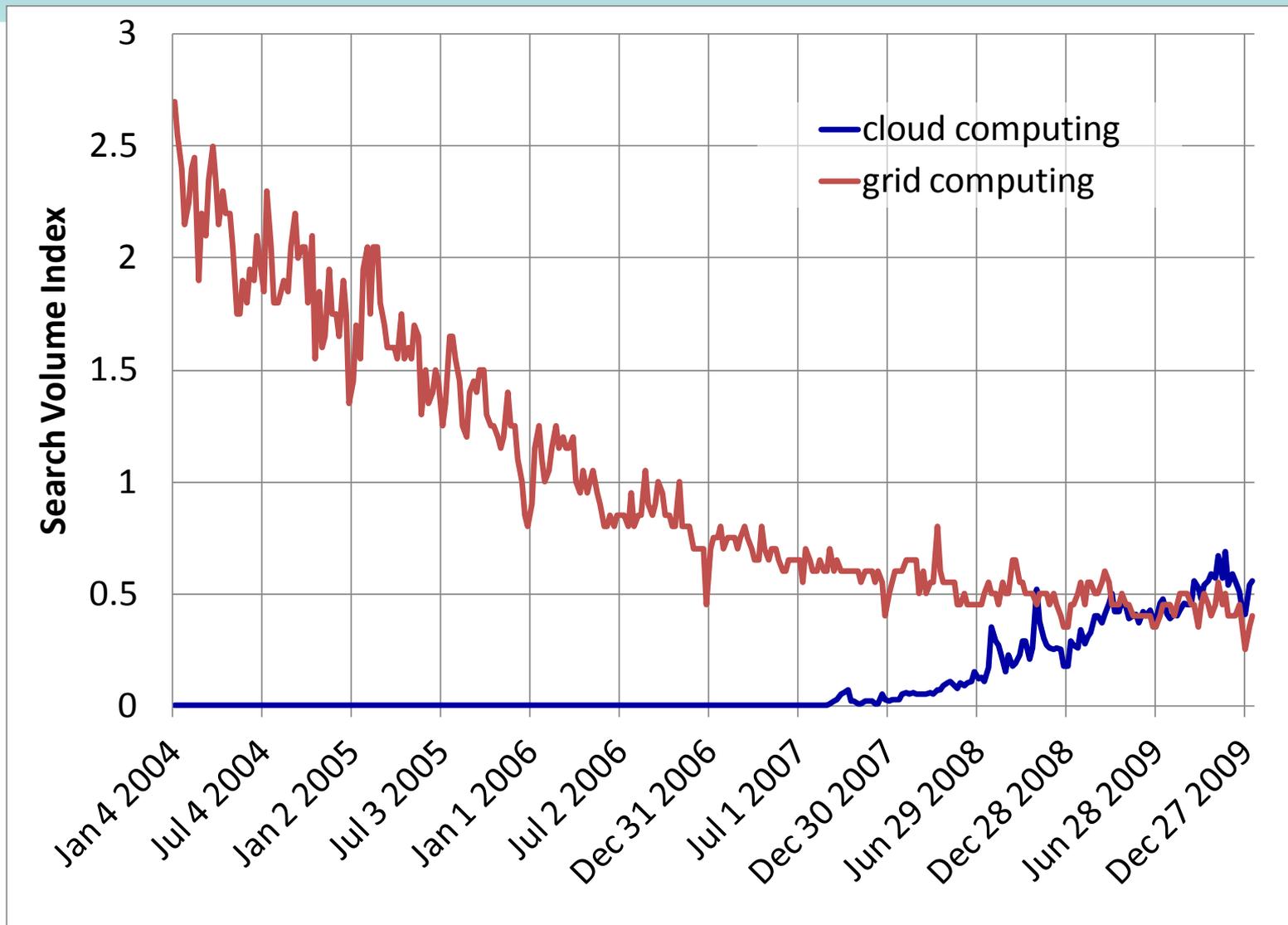


Grids ~ Federation

Major Grids

- TeraGrid (TG)
 - 200K-cores across 11 institutions and 22 systems over the US
- Open Science Grid (OSG)
 - 43K-cores across 80 institutions over the US
- Enabling Grids for E-scienceE (EGEE)
- LHC Computing Grid from CERN
- Middleware
 - Globus Toolkit
 - Unicore

Cloud Computing: An Emerging Paradigm

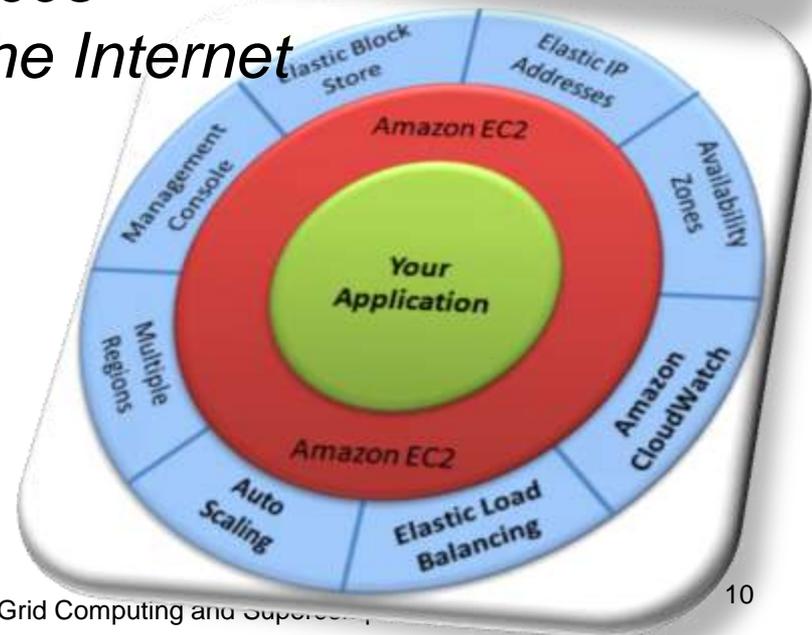


Cloud Computing

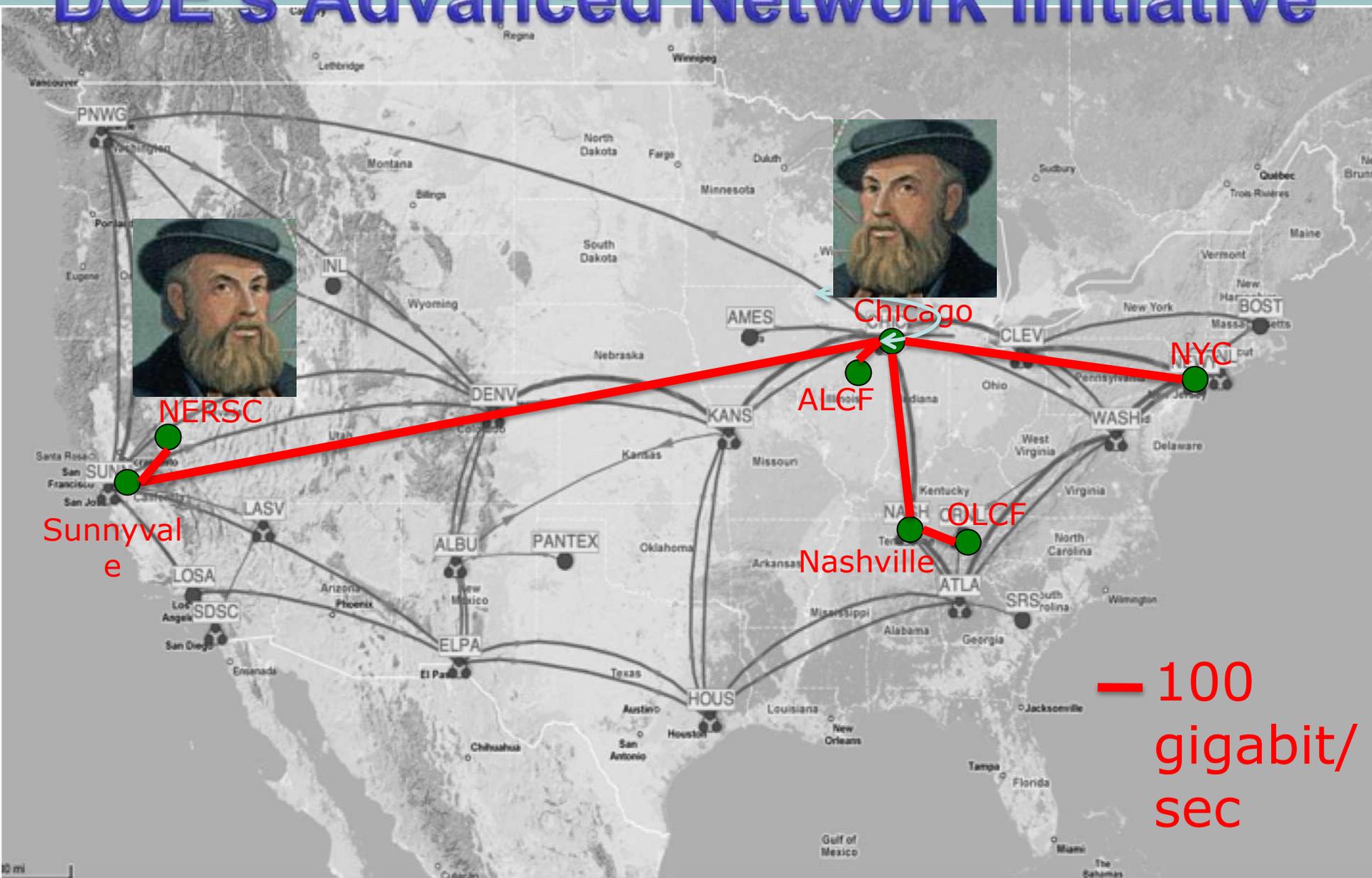
- *A large-scale distributed computing paradigm driven by:*
 1. *economies of scale*
 2. *virtualization*
 3. *dynamically-scalable resources*
 4. *delivered on demand over the Internet*



Clouds ~ hosting



Magellan + DOE's Advanced Network Initiative



NERSC
Sunnyvale

Chicago
ALCF
Nashville
OLCF
NYC

— 100 gigabit/sec

Major Clouds

- Industry
 - Google App Engine
 - Amazon
 - Windows Azure
 - Salesforce
- Academia/Government
 - Magellan
 - FutureGrid
- Opensource middleware
 - Nimbus
 - Eucalyptus
 - OpenNebula

So is “Cloud Computing” just a new name for Grid?

- IT reinvents itself every five years
- The answer is complicated...
- **YES:** the vision is the same
 - to reduce the cost of computing
 - increase reliability
 - increase flexibility by transitioning from self operation to third party

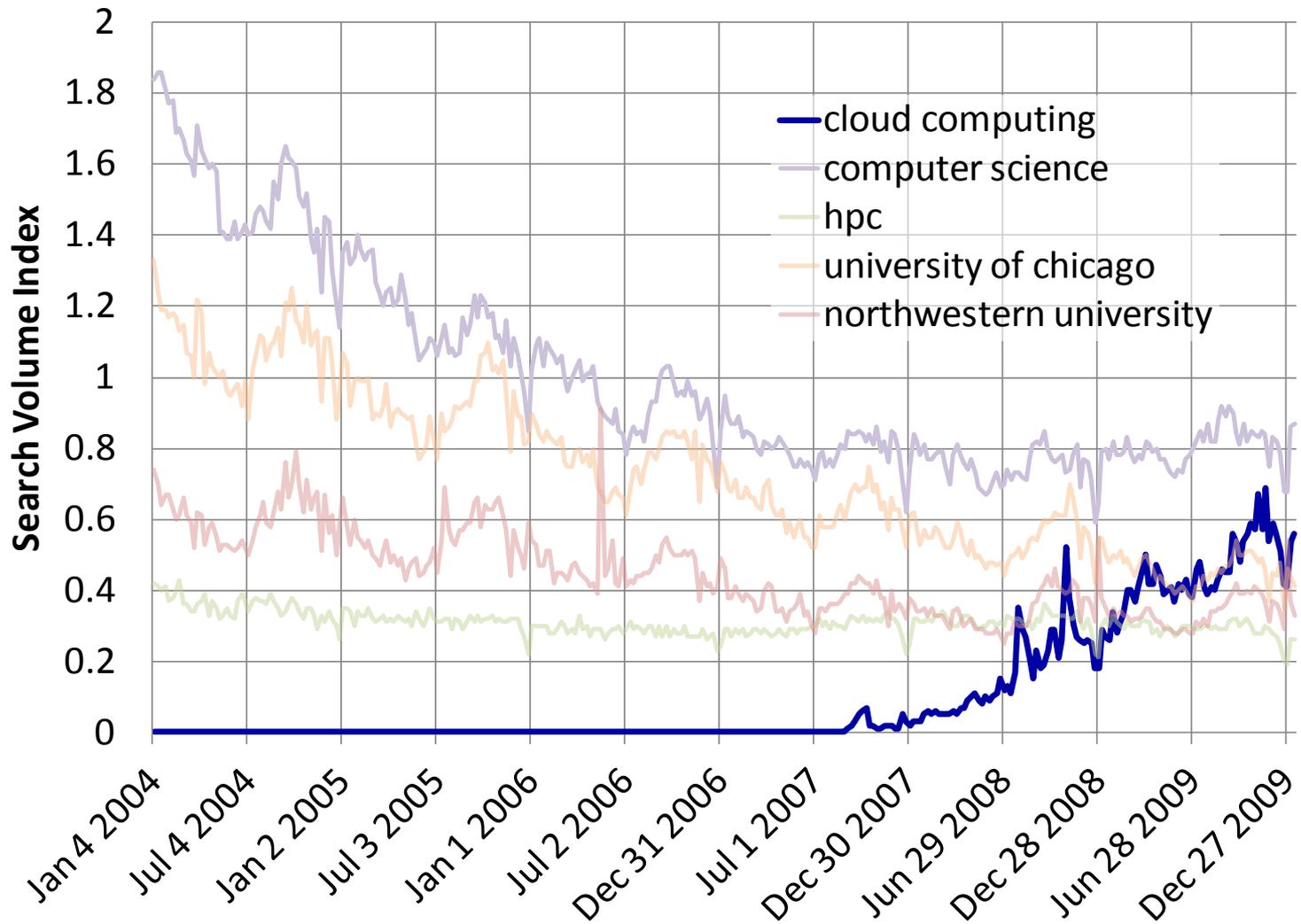
So is “Cloud Computing” just a new name for Grid?

- **NO:** things are different than they were 10 years ago
 - New needs to analyze massive data, increased demand for computing
 - Commodity clusters are expensive to operate
 - We have low-cost virtualization
 - Billions of dollars being spent by Amazon, Google, and Microsoft to create real commercial large-scale systems with hundreds of thousands of computers
 - The prospect of needing only a credit card to get on-demand access to *infinite computers is exciting; *infinite $O(1000)$

So is “Cloud Computing” just a new name for Grid?

- **YES:** the problems are mostly the same
 - How to manage large facilities
 - Define methods to discover, request, and use resources
 - How to implement and execute parallel computations
 - Details differ, but issues are similar

How does Cloud Computing Compare?



An Example of an Application in the Cloud

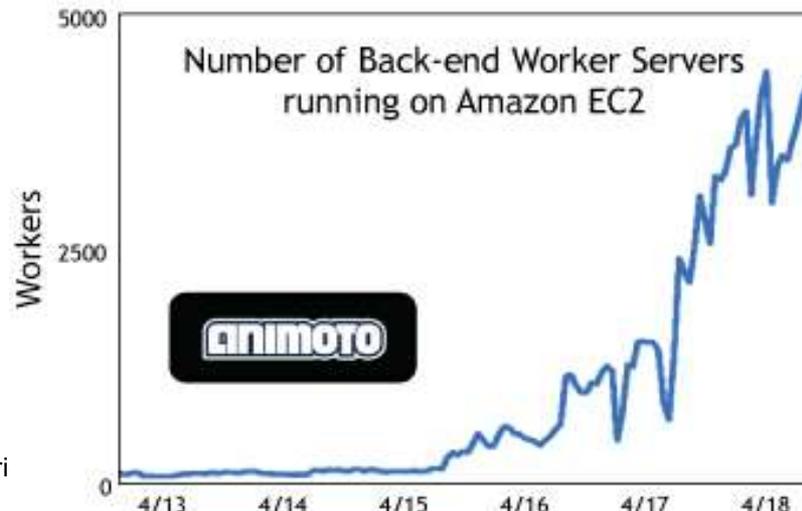
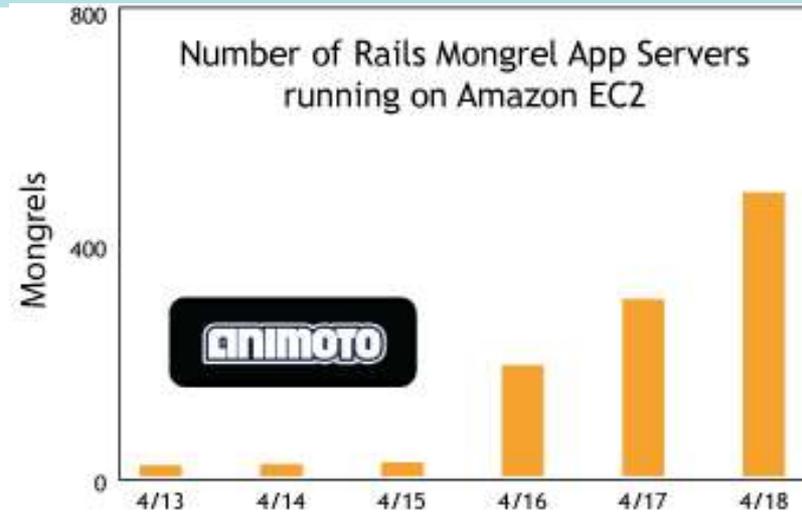
- Animoto

- Makes it **easy** to create videos with photos and videos



An Example of an Application in the Cloud

- Why is this a big deal?
 - No owned infrastructure
 - All resources rented on demand
- Critical for startups with risky business plans
- Not possible without Cloud Computing and a credit card
 - Launched in 2007/2008 timeframe



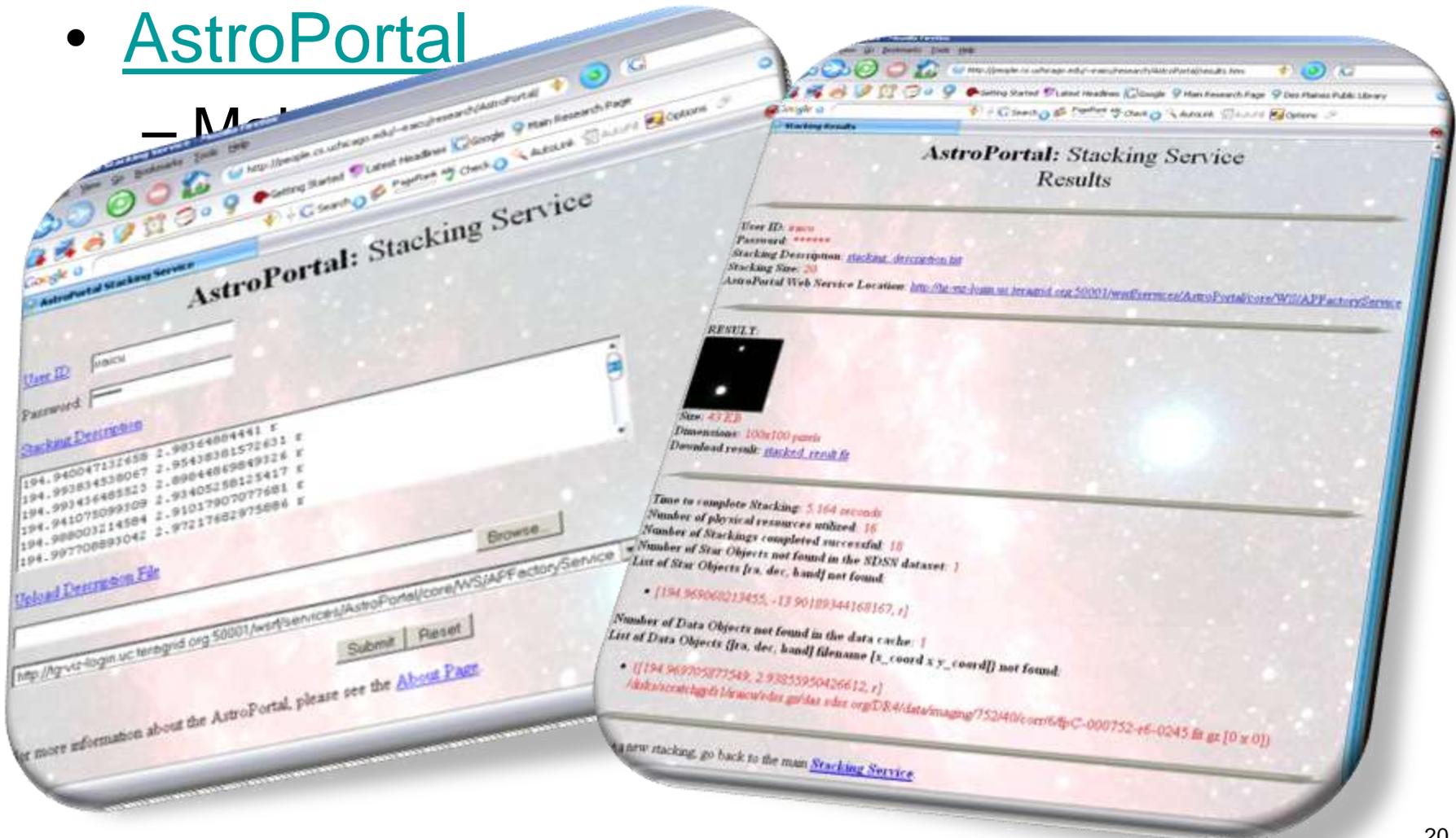
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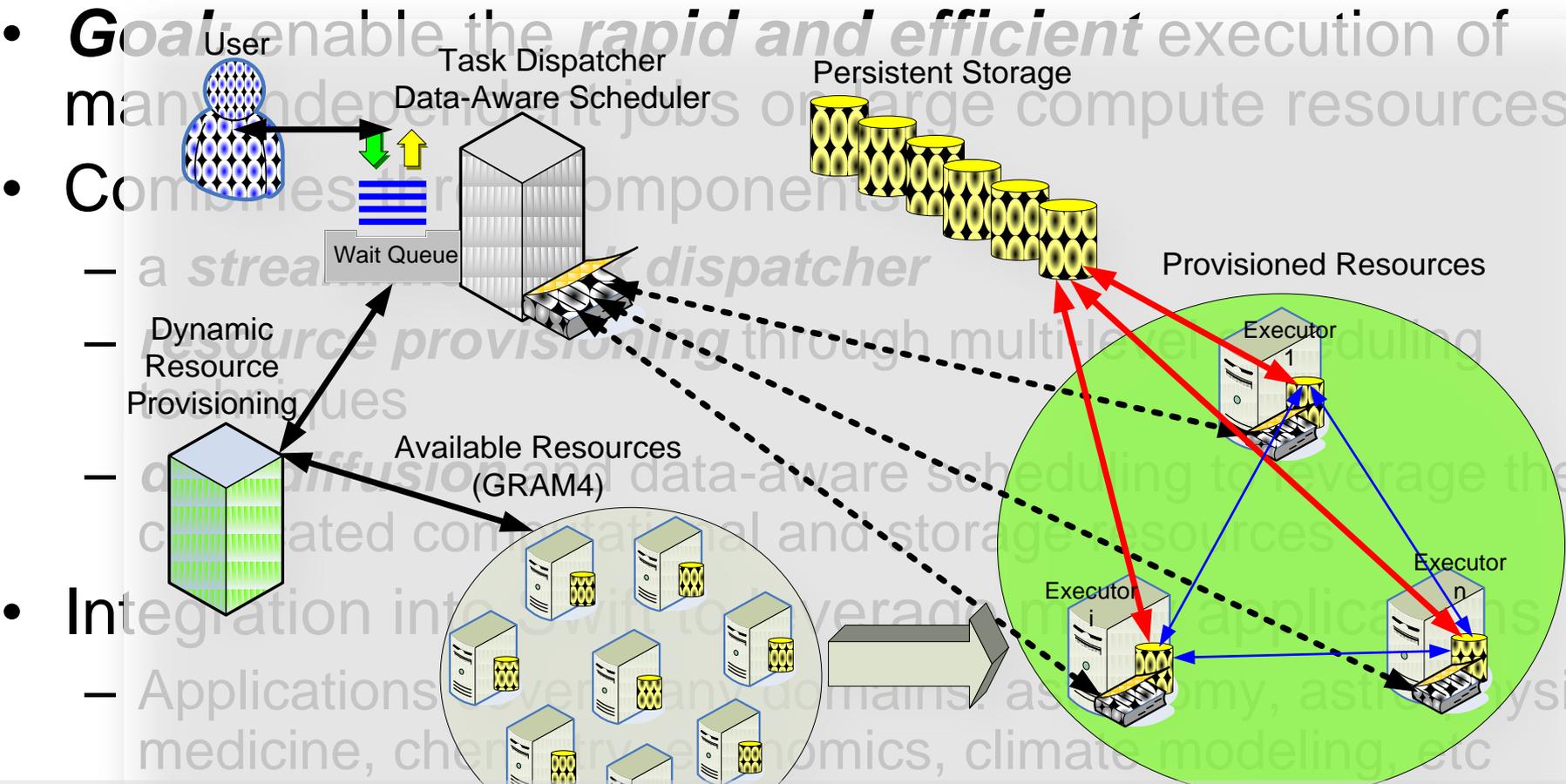
An Example of an Application in the Grid

- AstroPortal

– Main



Novel Resource Management Approach: Falkon Architecture



- **Goal** enable the *rapid and efficient* execution of many independent jobs on large compute resources
- **Component**
 - a *streamlined dispatcher*
 - *resource provisioning* through multiple scheduling techniques
 - *diffusion* and data-aware scheduling to leverage the compute capacity and storage resources
- **Integration**
 - Applications in various domains, as biology, astronomy, physics, medicine, chemistry, economics, climate modeling, etc

CS,

[SciDAC09] "Extreme-scale scripting: Opportunities for large task-parallel applications on petascale computers"

[SC08] "Towards Loosely-Coupled Programming on Petascale Systems"

[Globus07] "Falkon: A Proposal for Project Globus Incubation"

[SC07] "Falkon: a Fast and Light-weight task executiON framework"

[SWF07] "Swift: Fast, Reliable, Loosely Coupled Parallel Computation"

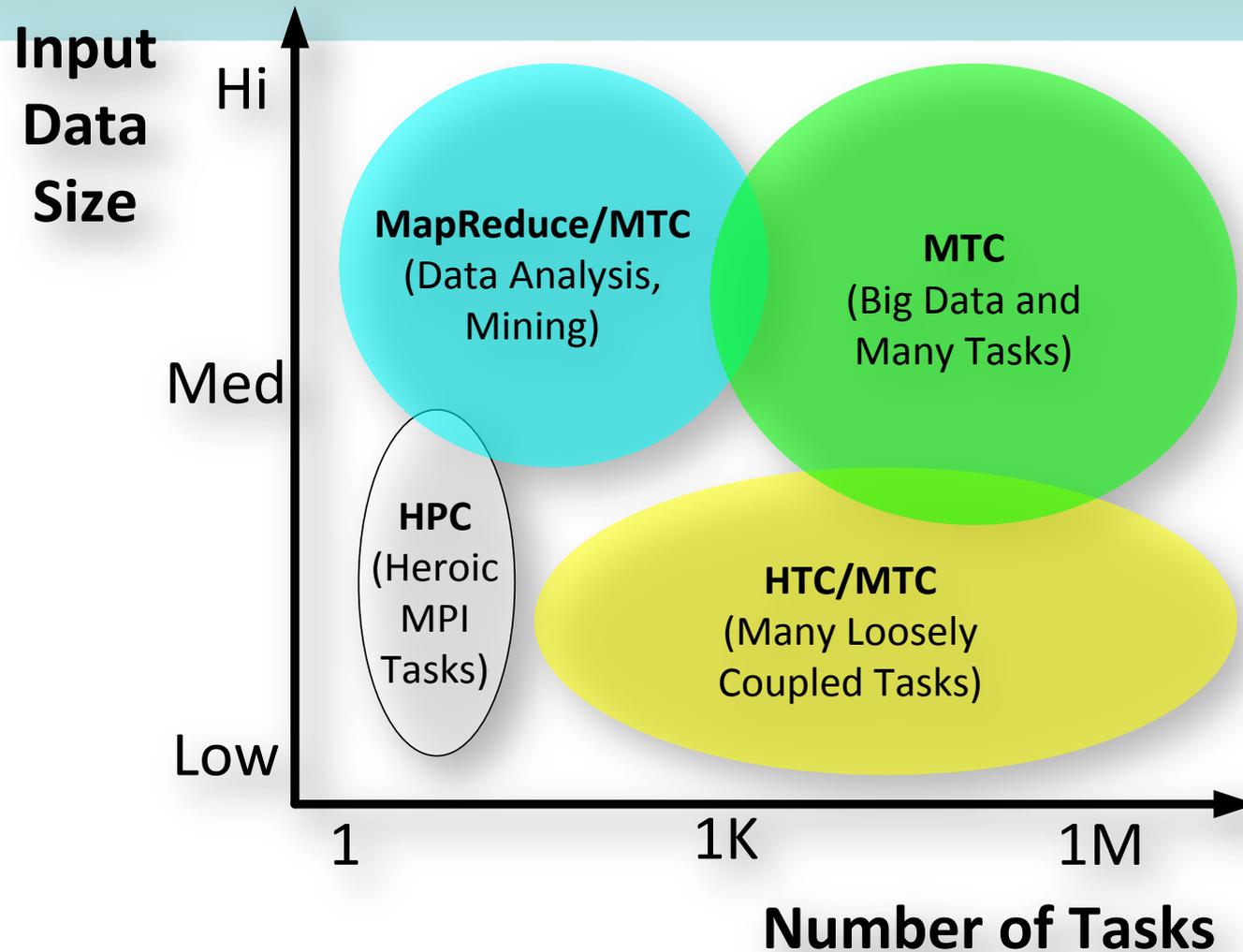
High-Throughput Computing & High-Performance Computing

- **HTC: High-Throughput Computing**
 - Typically applied in clusters and grids
 - Loosely-coupled applications with sequential jobs
 - Large amounts of computing for long periods of times
 - Measured in operations per month or years
- **HPC: High-Performance Computing**
 - Synonymous with supercomputing
 - Tightly-coupled applications
 - Implemented using Message Passing Interface (MPI)
 - Large of amounts of computing for short periods of time
 - Usually requires low latency interconnects
 - Measured in FLOPS

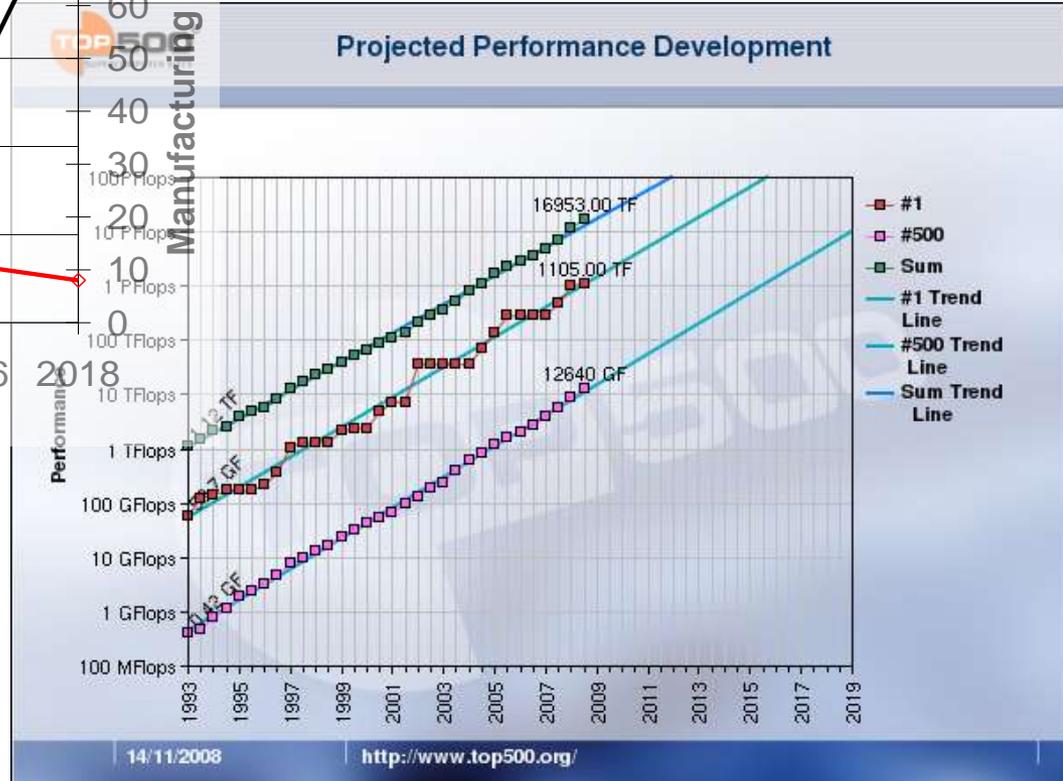
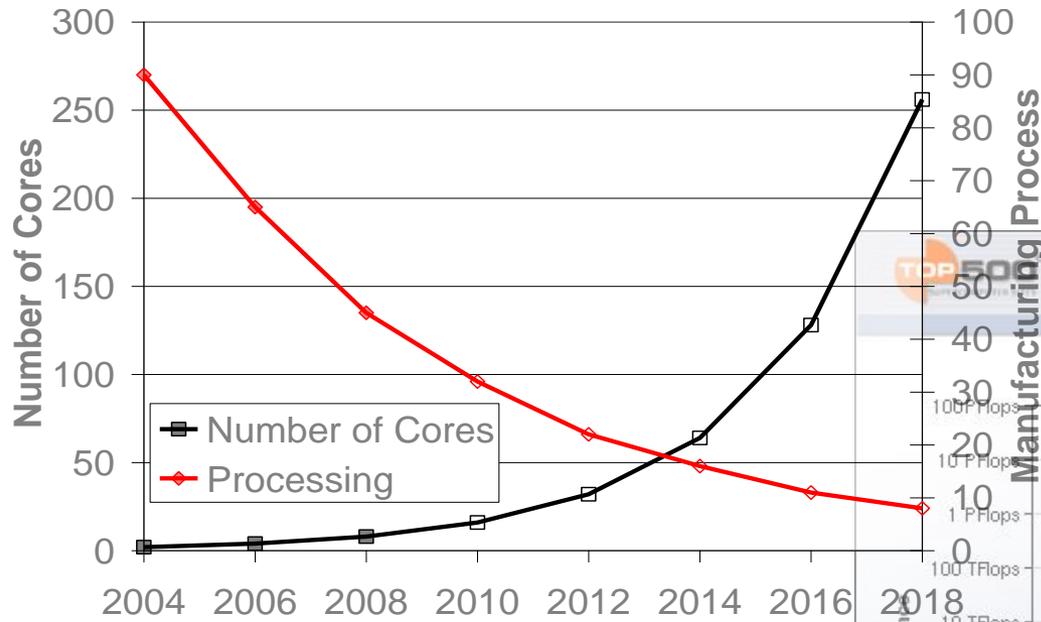
MTC: Many-Task Computing

- Bridge the gap between HPC and HTC
- Applied in clusters, grids, and supercomputers
- Loosely coupled apps with HPC orientations
- Many activities coupled by file system ops
- Many resources over short time periods
 - Large number of tasks, large quantity of computing, and large volumes of data

Problem Space



Projected Growth Trends



Pat Helland, Microsoft, The Irresistible Forces Meet the Movable Objects, November 9th, 2007

Growing Storage/Compute Gap

- Local Disk:

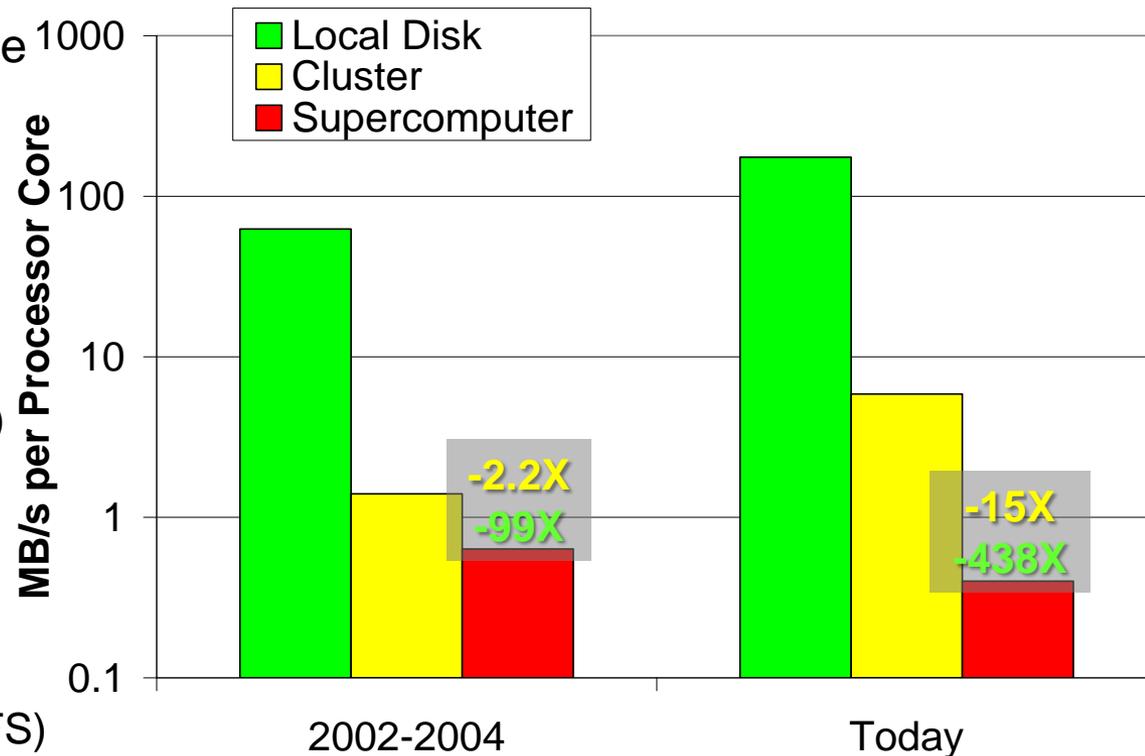
- 2002-2004: ANL/UC TG Site (70GB SCSI)
- Today: PADS (RAID-0, 6 drives 750GB SATA)

- Cluster:

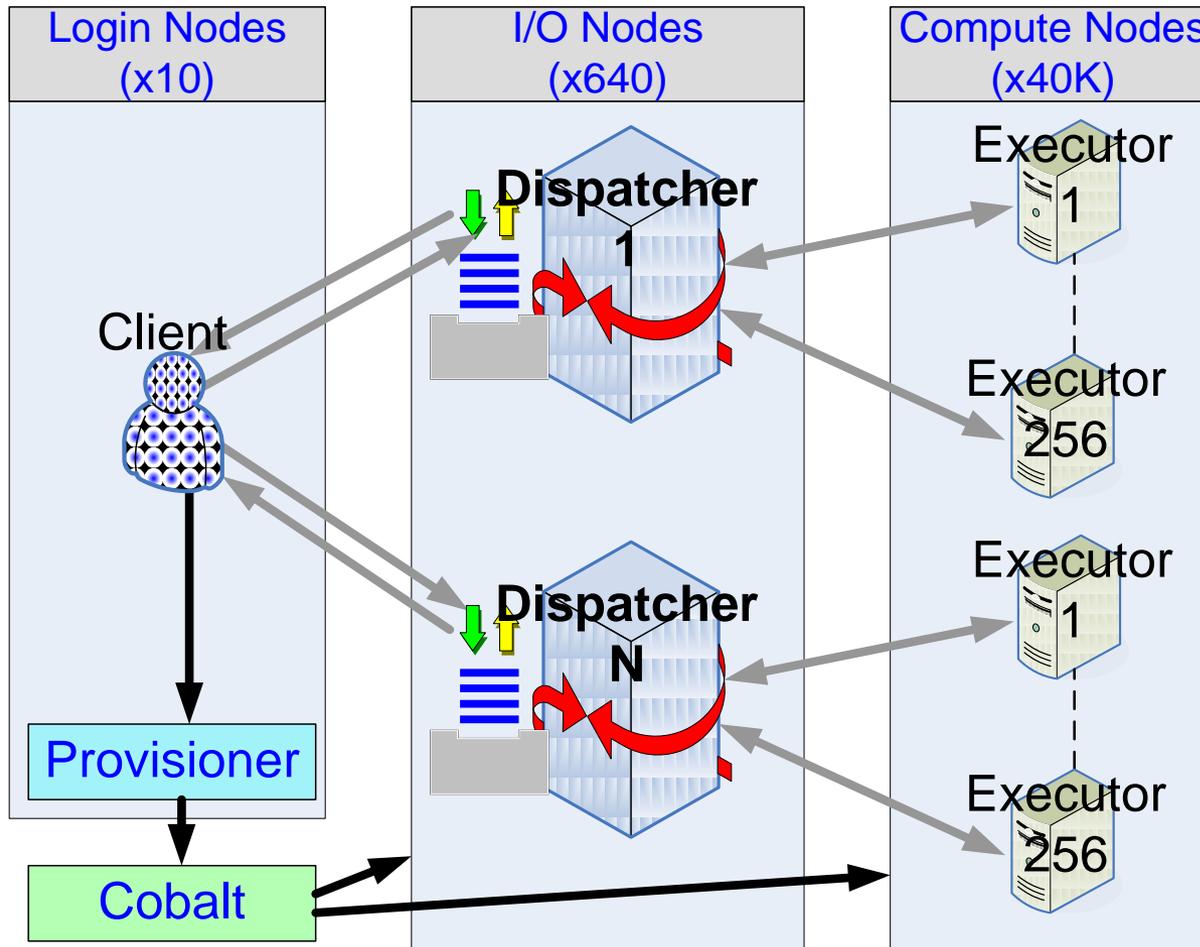
- 2002-2004: ANL/UC TG Site (GPFS, 8 servers, 1Gb/s each)
- Today: PADS (GPFS, SAN)

- Supercomputer:

- 2002-2004: IBM Blue Gene/L (GPFS)
- Today: IBM Blue Gene/P (GPFS)



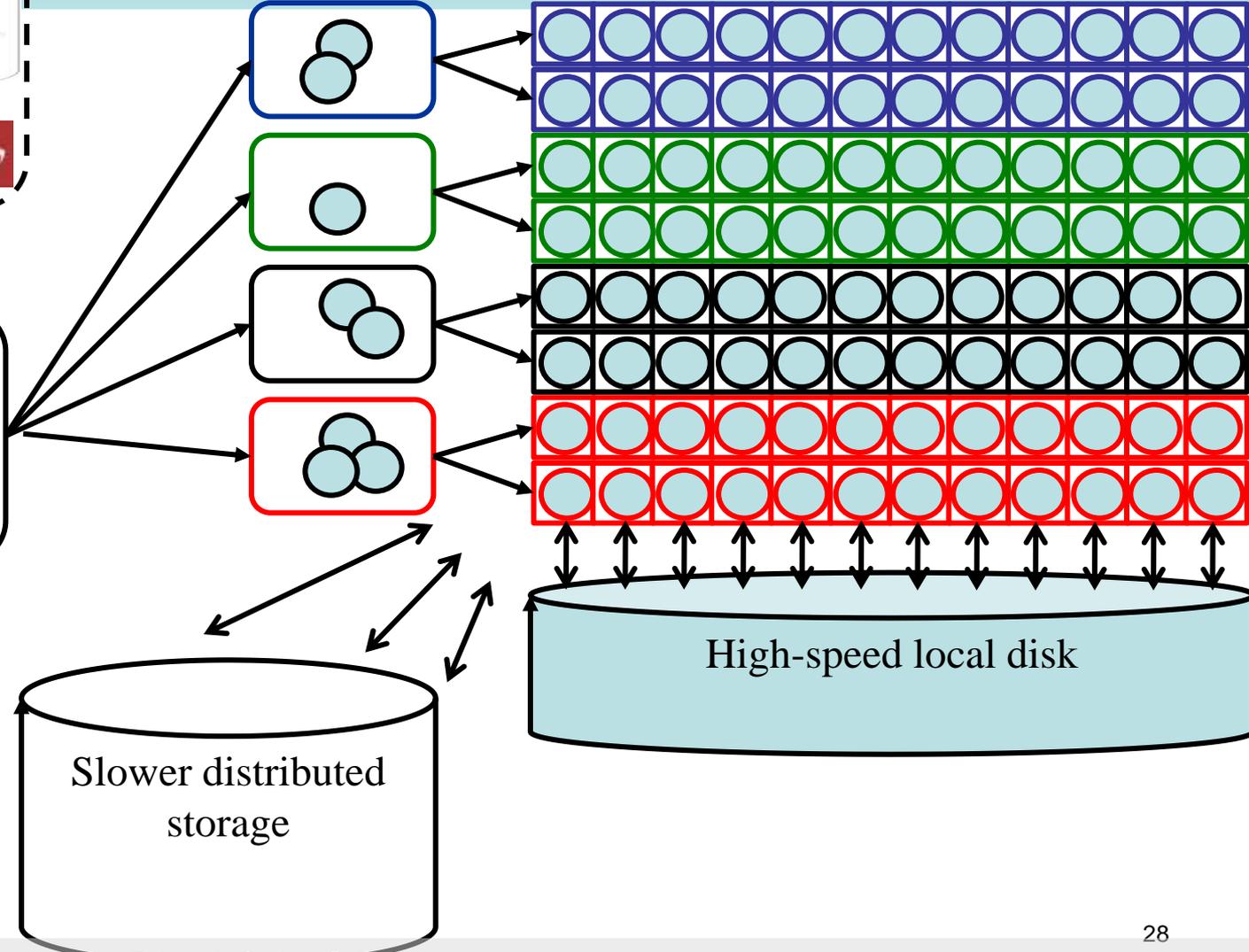
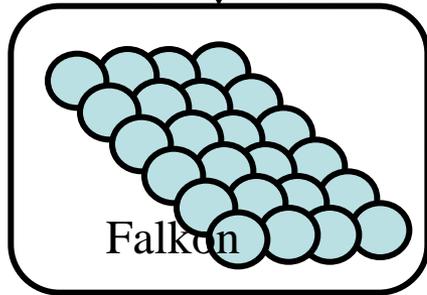
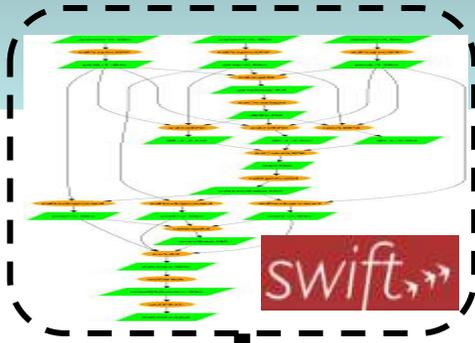
Distributed Falkon Architecture



Managing 160K CPUs

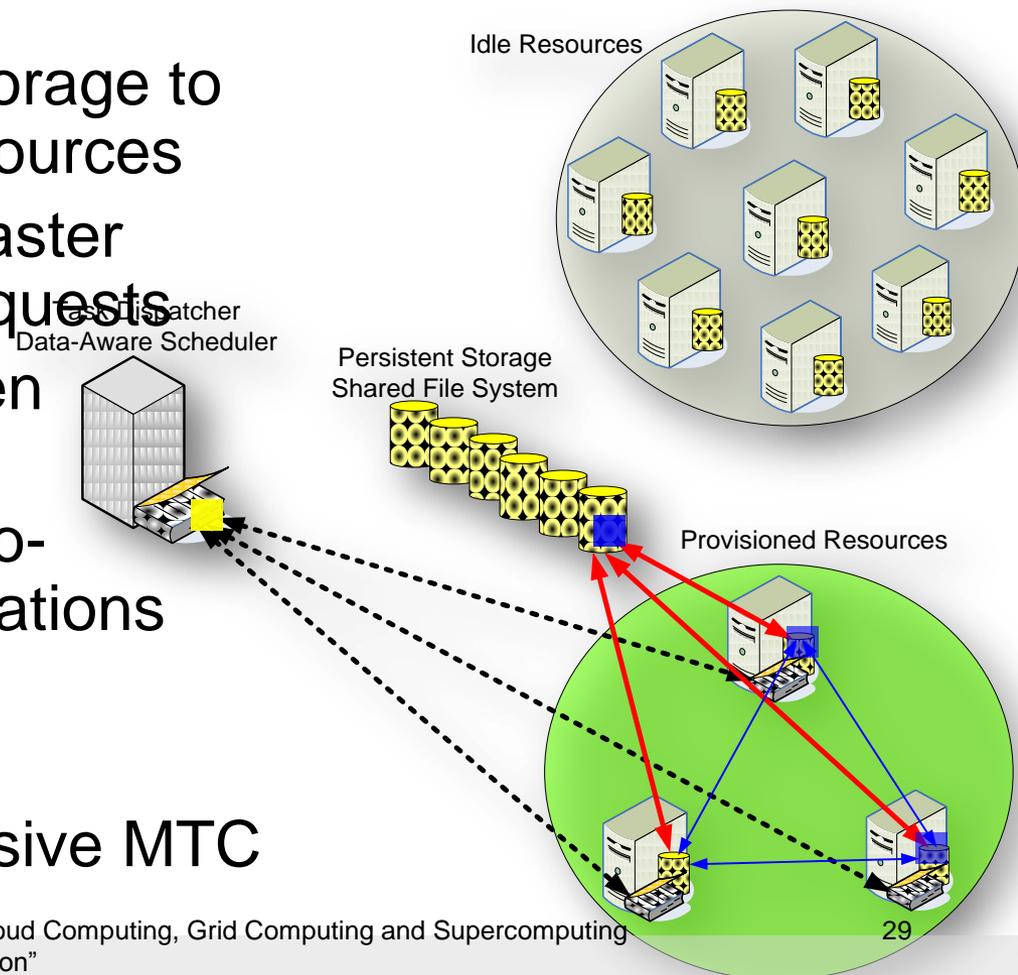
IBM Blue Gene/P

ZeptOS

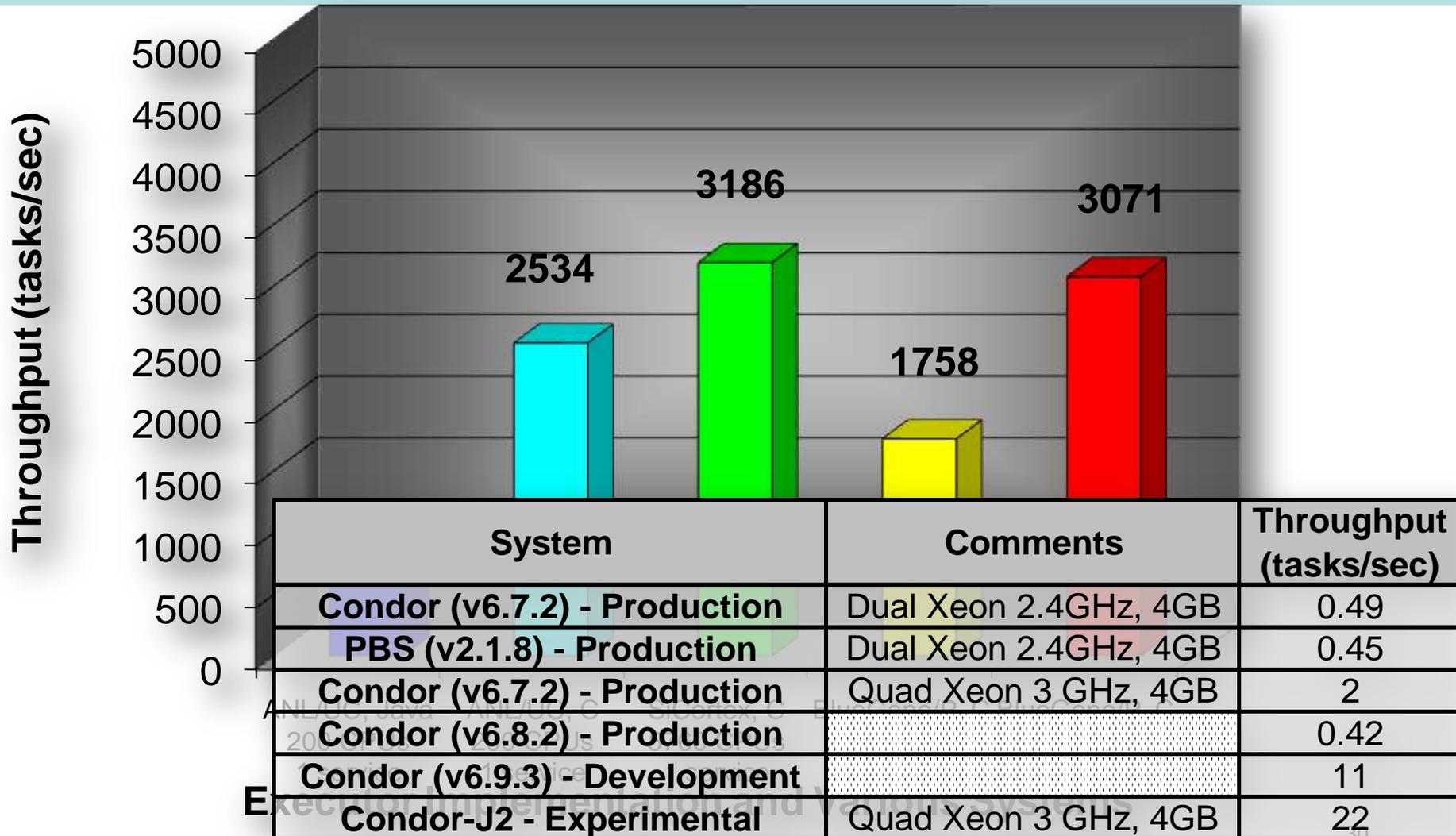


Data Diffusion

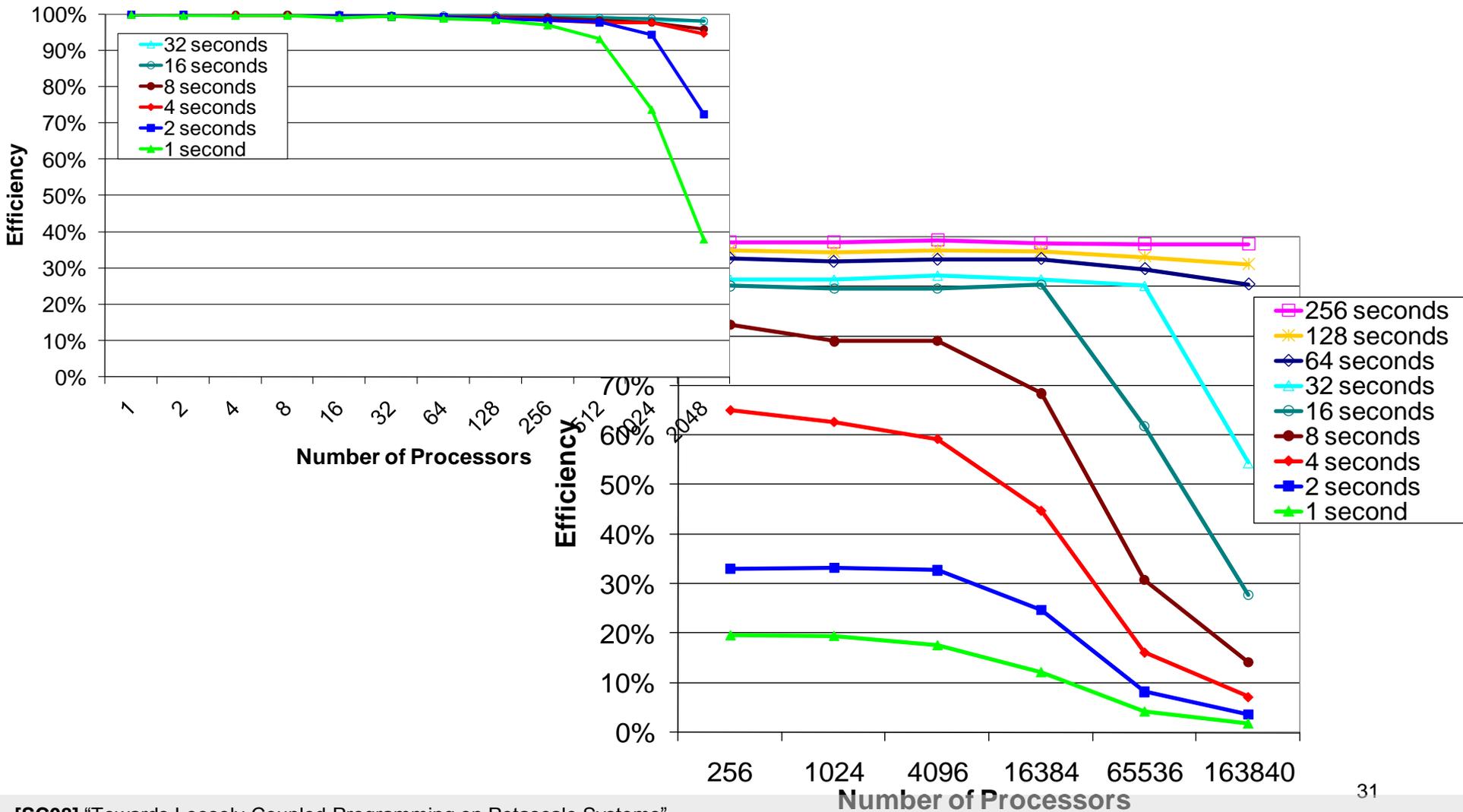
- Resource acquired in response to demand
- Data diffuse from archival storage to newly acquired transient resources
- Resource “caching” allows faster responses to subsequent requests
- Resources are released when demand drops
- Optimizes performance by co-scheduling data and computations
- Decrease dependency of a shared/parallel file systems
- Critical to support data intensive MTC



Dispatch Throughput

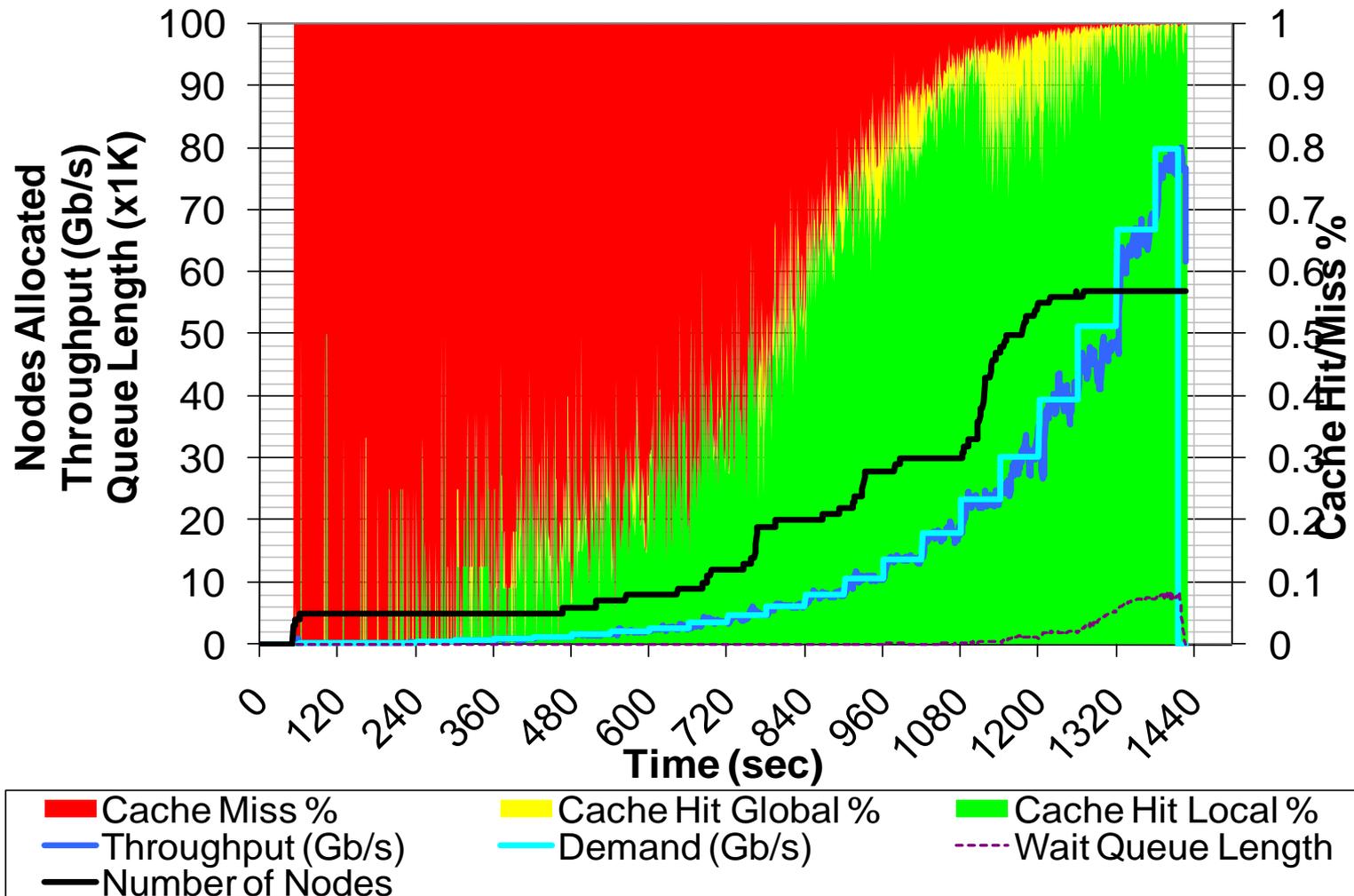


Execution Efficiency



Data Diffusion

Monotonically Increasing Workload

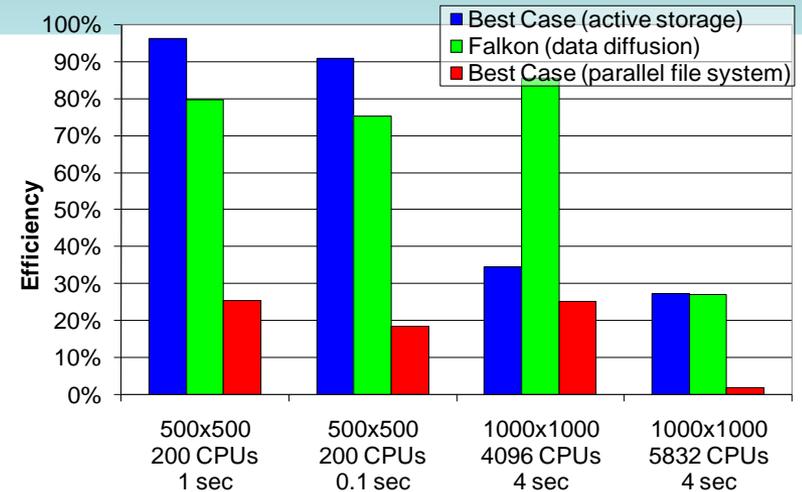


Data Diffusion vs. Active Storage

All-Pairs Workload

- Pull vs. Push
 - Data Diffusion
 - Pulls *task* working set
 - Incremental spanning forest
 - Active Storage:
 - Pushes *workload* working set to all nodes
 - Static spanning tree

**Christopher Moretti, Douglas Thain,
University of Notre Dame**



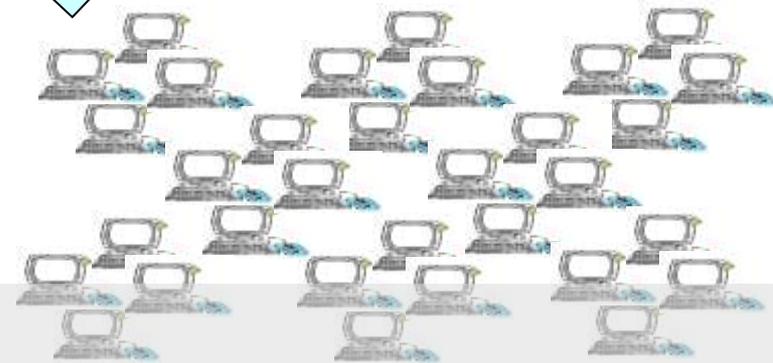
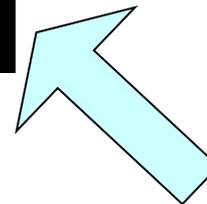
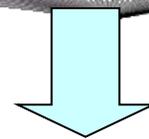
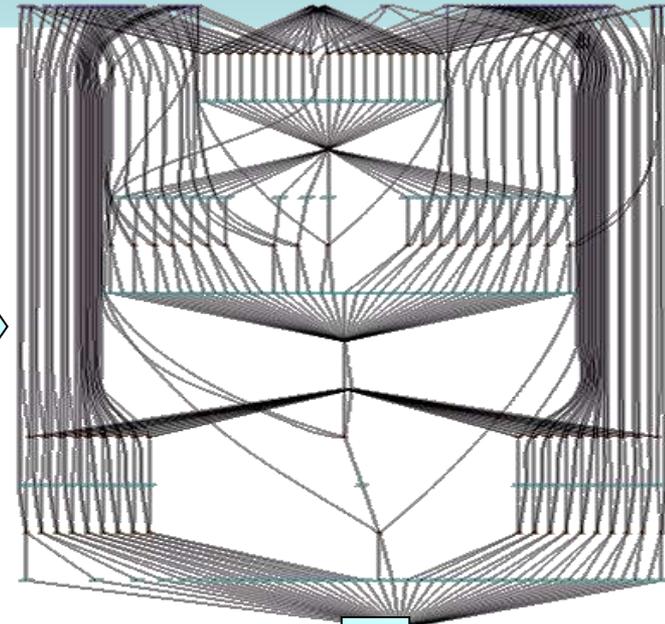
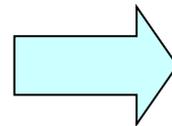
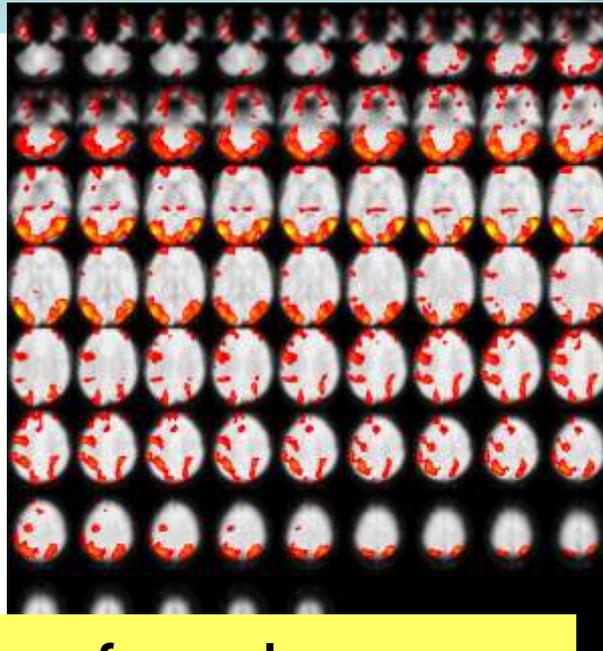
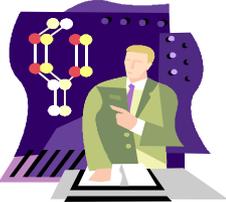
Experiment	Approach	Experiment		
		Local Disk/Memory (GB)	Network (node-to-node) (GB)	Shared File System (GB)
500x500 200 CPUs 1 sec	Best Case (active storage)	6000	1536	12
	Falkon (data diffusion)	6000	1698	34
500x500 200 CPUs 0.1 sec	Best Case (active storage)	6000	1536	12
	Falkon (data diffusion)	6000	1528	62
1000x1000 4096 CPUs 4 sec	Best Case (active storage)	24000	12288	24
	Falkon (data diffusion)	24000	4676	384
1000x1000 5832 CPUs 4 sec	Best Case (active storage)	24000	12288	24
	Falkon (data diffusion)	24000	3867	906

Outline

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- **Applications**
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Applications

Medical Imaging: fMRI



- Wide range of analyses
 - Testing, interactive analysis, production runs
 - Data mining
 - Parameter studies

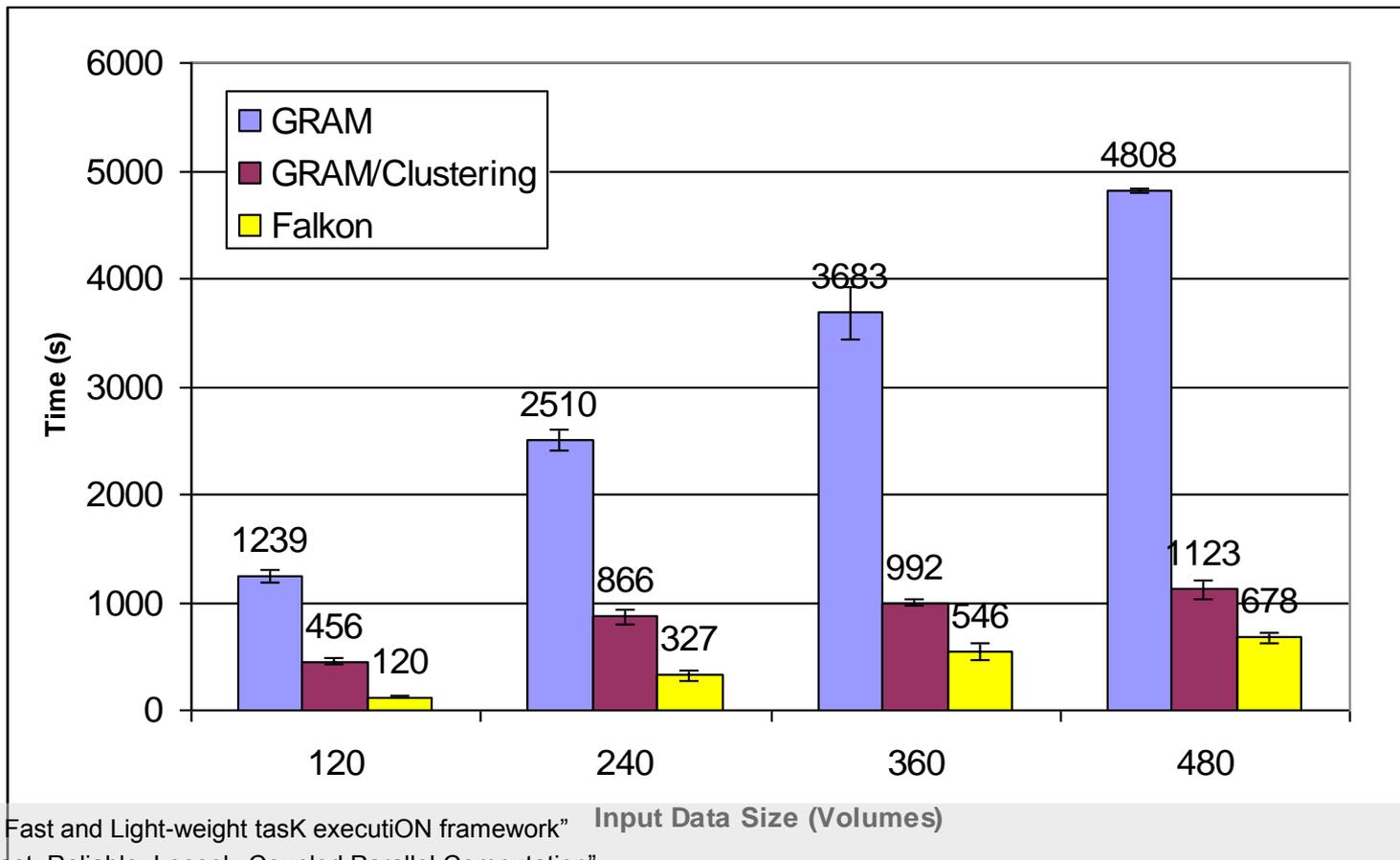
[SC07] "Falkon: a Fast and Light-weight task executiON framework"

[SWF07] "Swift: Fast, Reliable, Loosely Coupled Parallel Computation"

Applications

Medical Imaging: fMRI

- GRAM vs. Falcon: 85%~90% lower run time
- GRAM/Clustering vs. Falcon: 40%~74% lower run time

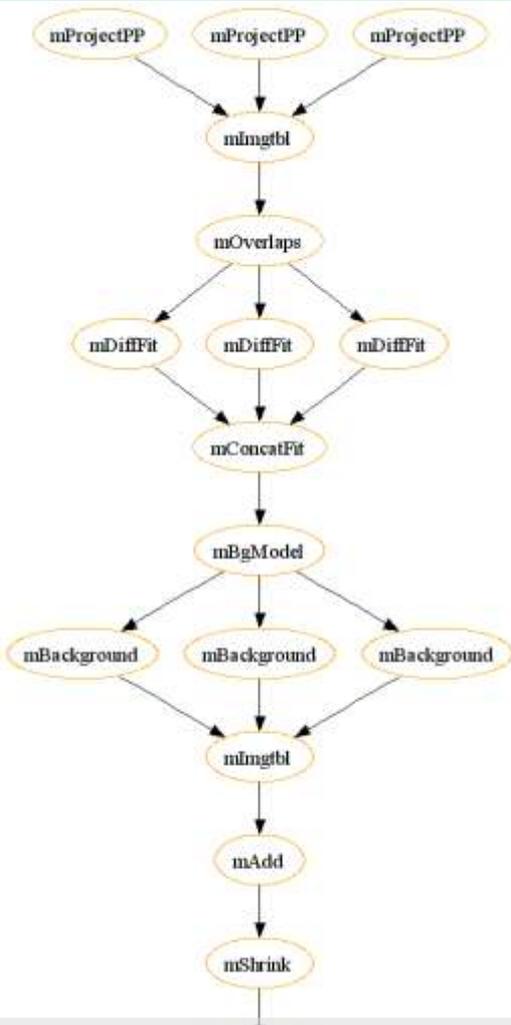


[SC07] "Falcon: a Fast and Light-weight task executiON framework"

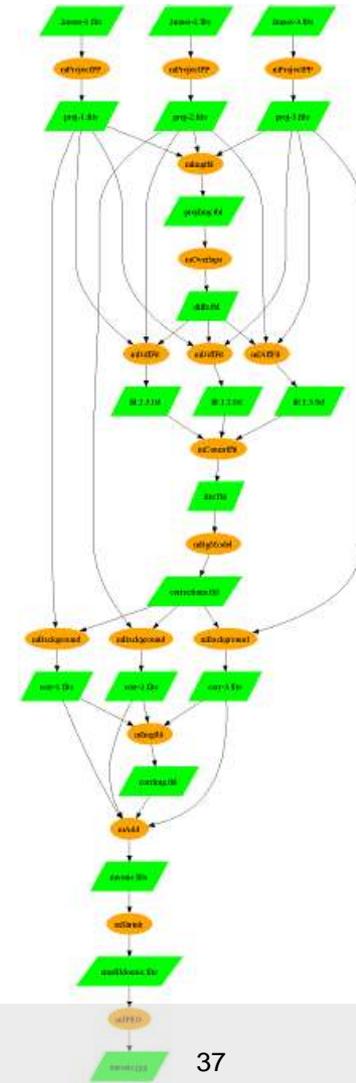
[SWF07] "Swift: Fast, Reliable, Loosely Coupled Parallel Computation"

Applications

Astronomy: Montage



B. Berriman, J. Good (Caltech)
 J. Jacob, D. Katz (JPL)



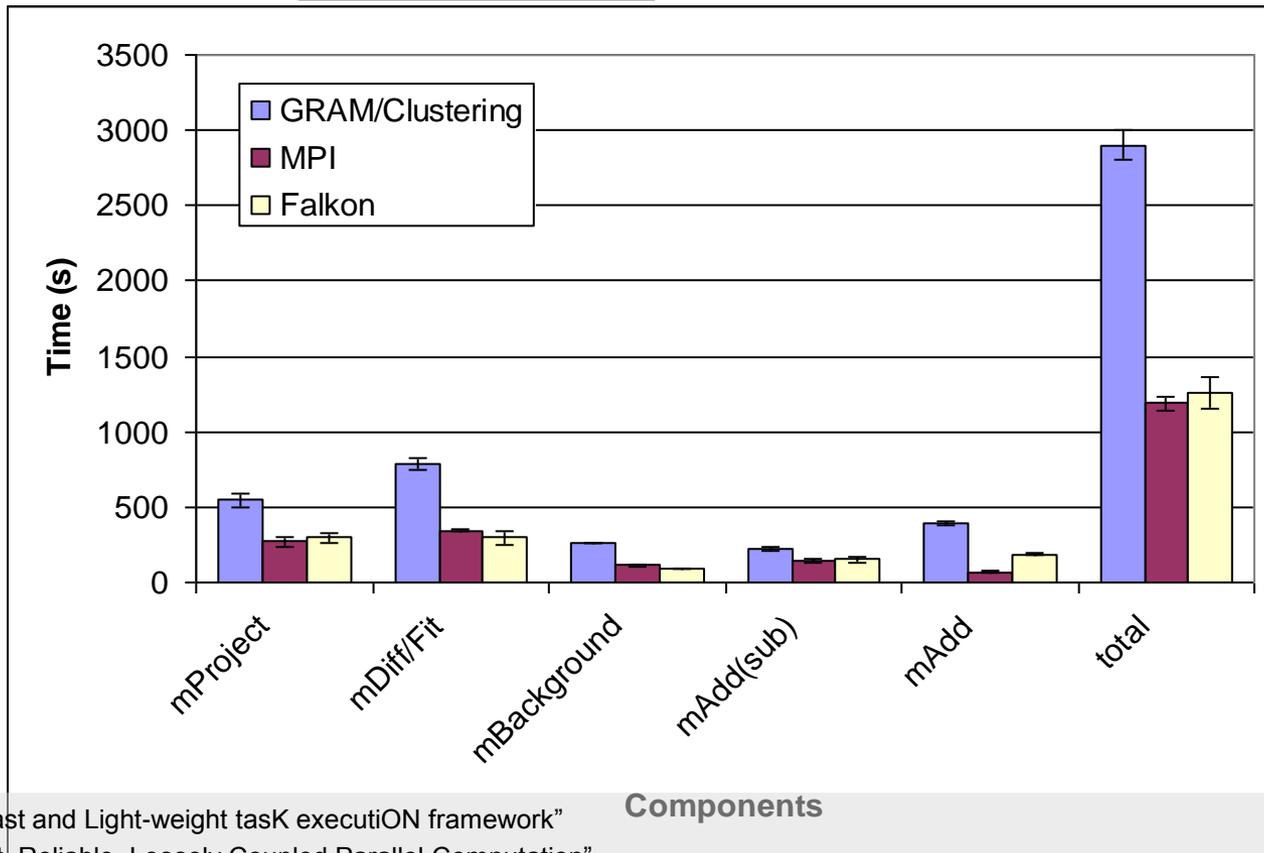
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Applications

Astronomy: Montage

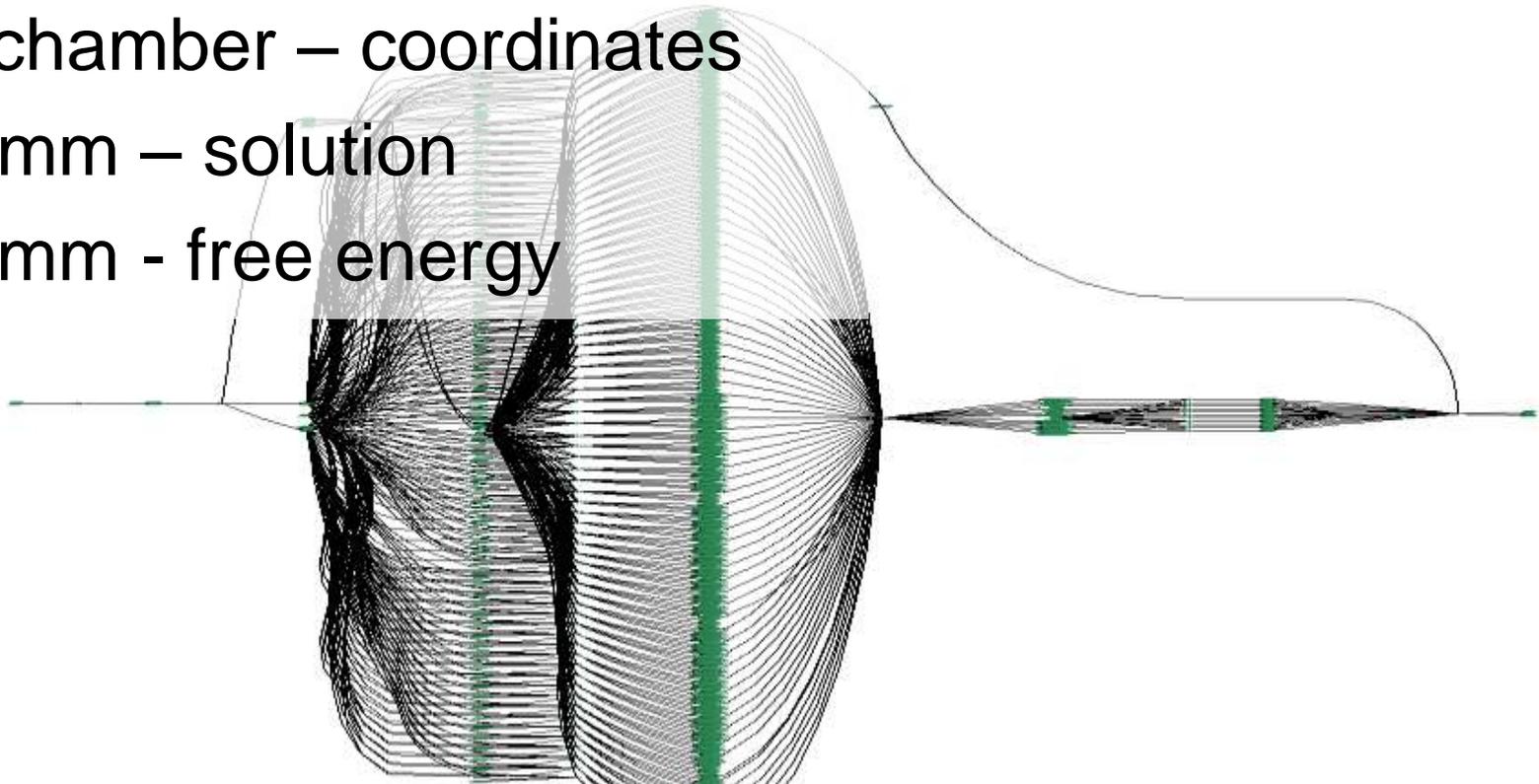
- GRAM/Clustering vs. Falcon: **57%** lower application run time
- MPI* vs. Falcon: **4%** higher application run time
- * MPI should be **lower bound**



Applications

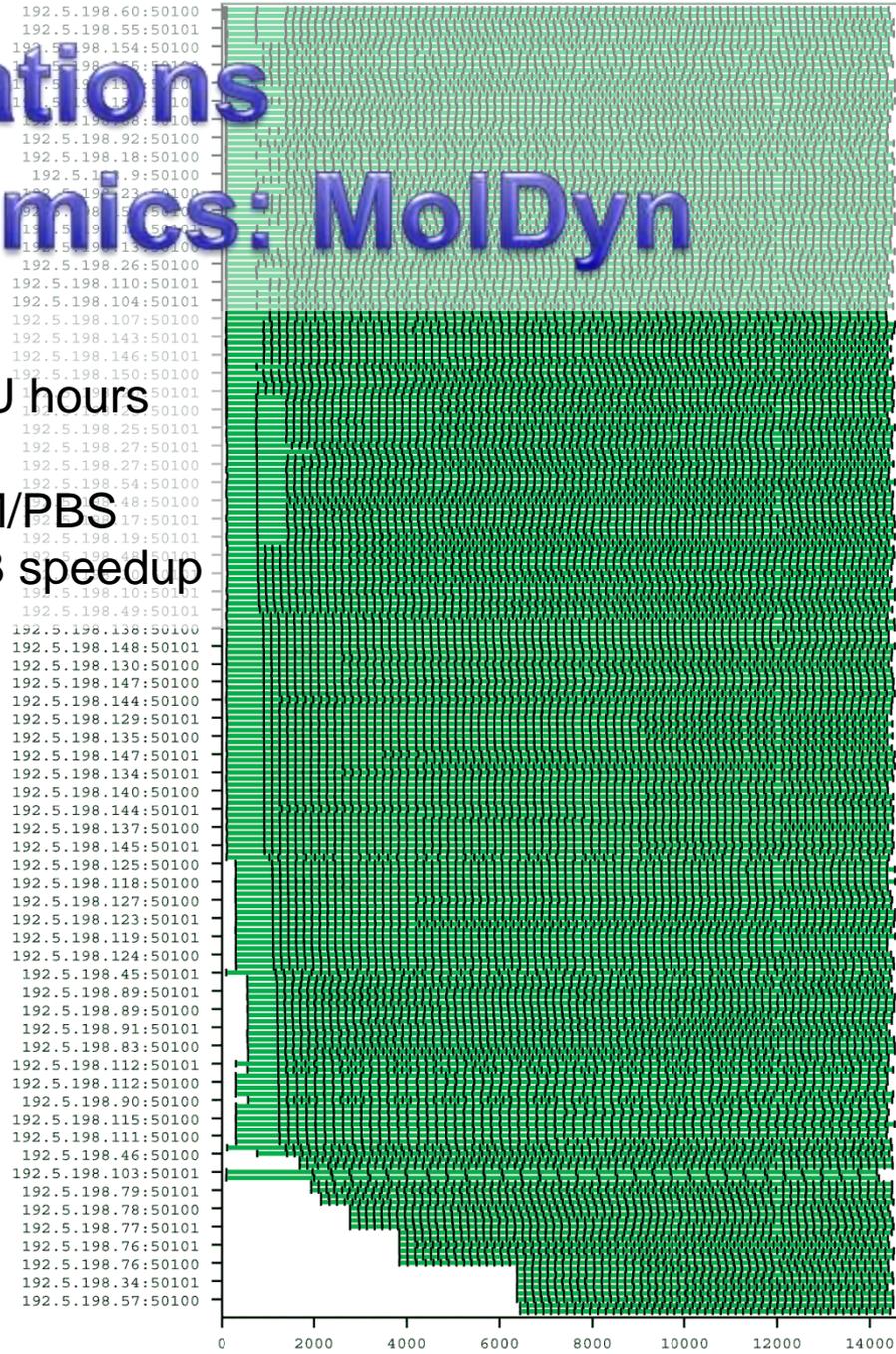
Molecular Dynamics: MolDyn

- Determination of free energies in aqueous solution
 - Antechamber – coordinates
 - Charmm – solution
 - Charmm - free energy

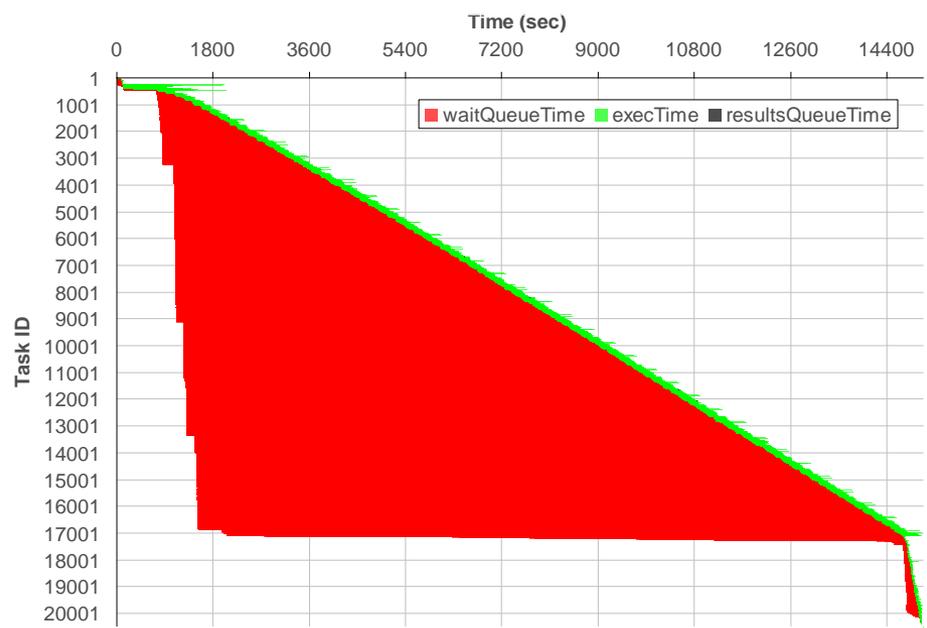


Applications

Molecular Dynamics: MolDyn



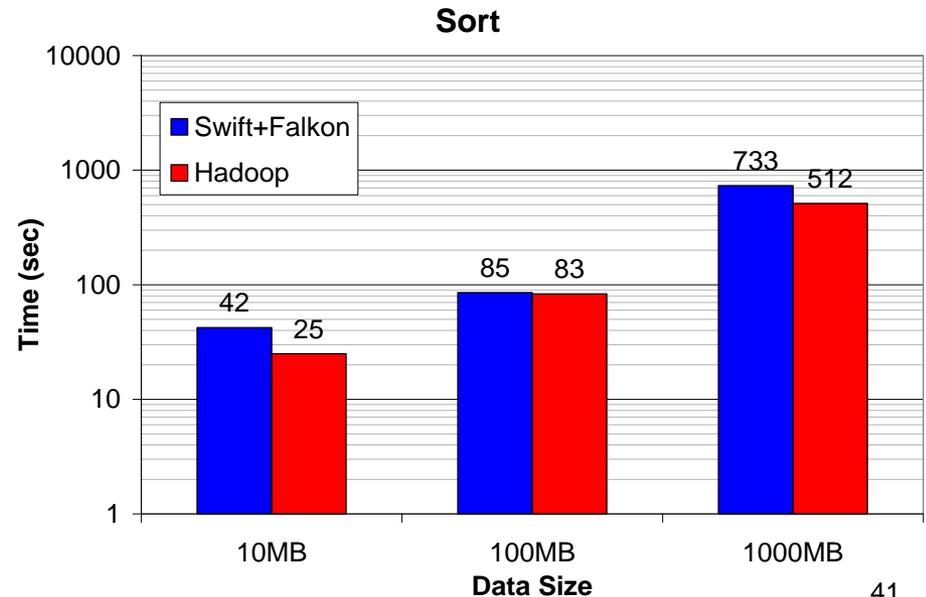
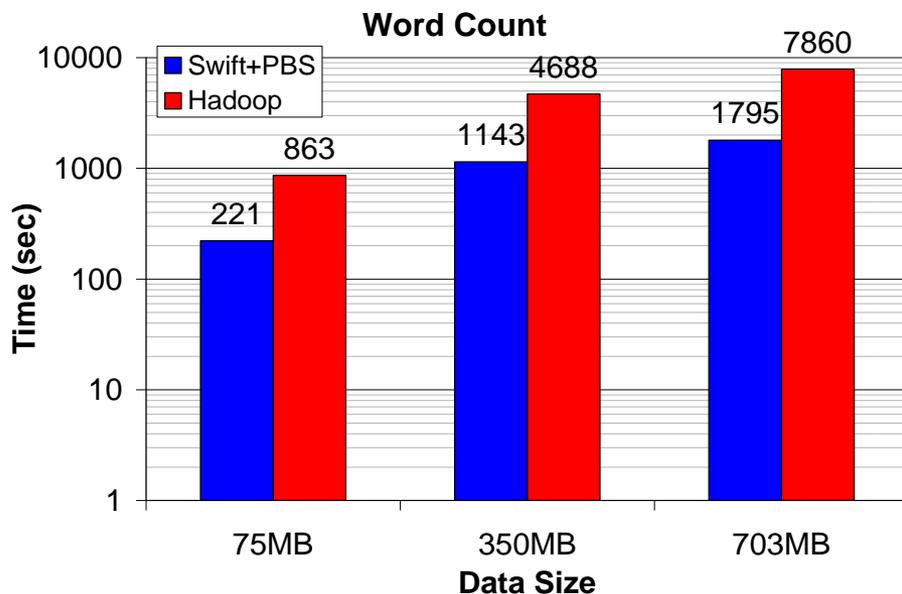
- 244 molecules → 20497 jobs
- 15091 seconds on 216 CPUs → 867.1 CPU hours
- Efficiency: **99.8%**
- Speedup: 206.9x → 8.2x faster than GRAM/PBS
- 50 molecules w/ GRAM (4201 jobs) → 25.3 speedup



Applications

Word Count and Sort

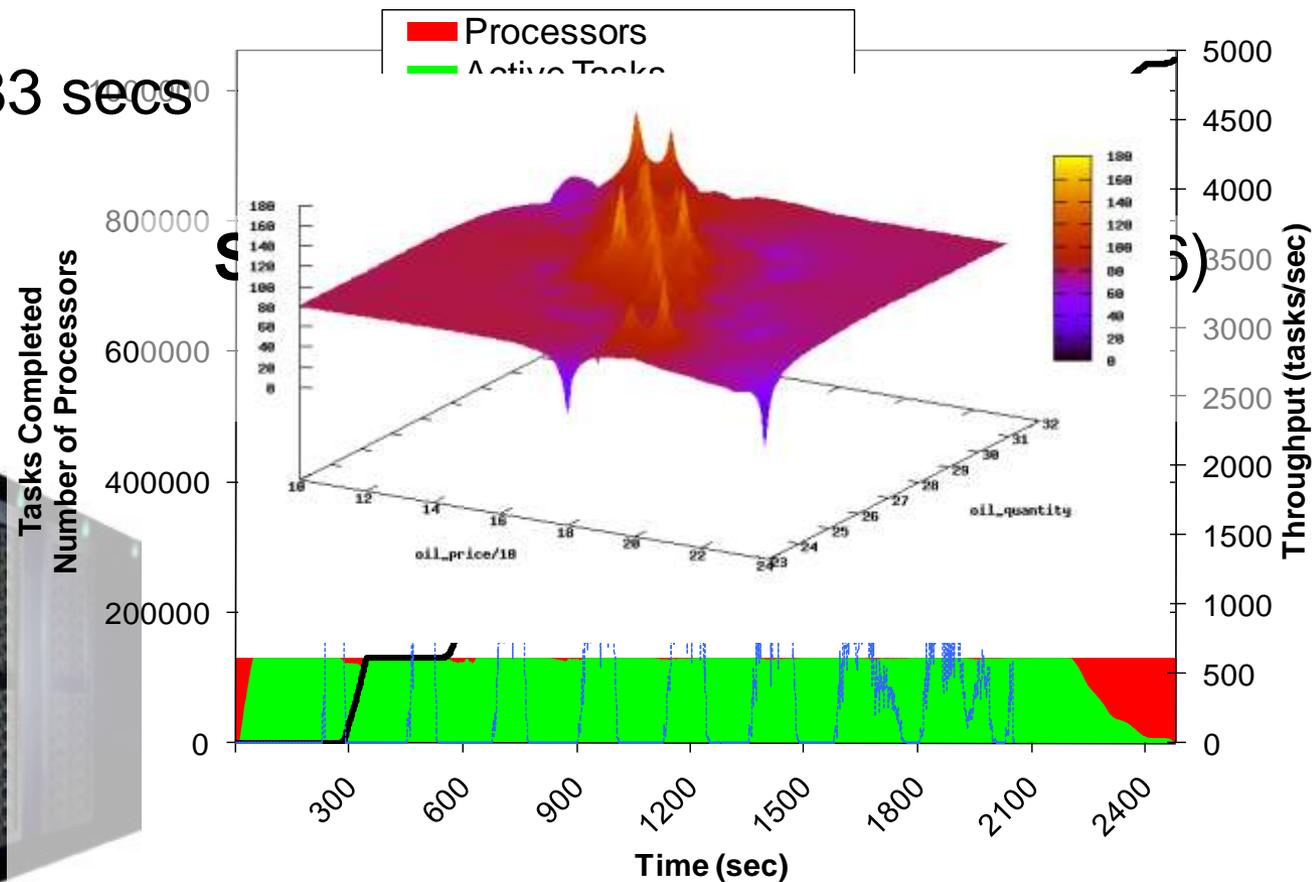
- Classic benchmarks for MapReduce
 - Word Count
 - Sort
- Swift and Falcon performs similar or better than Hadoop (on 32 processors)



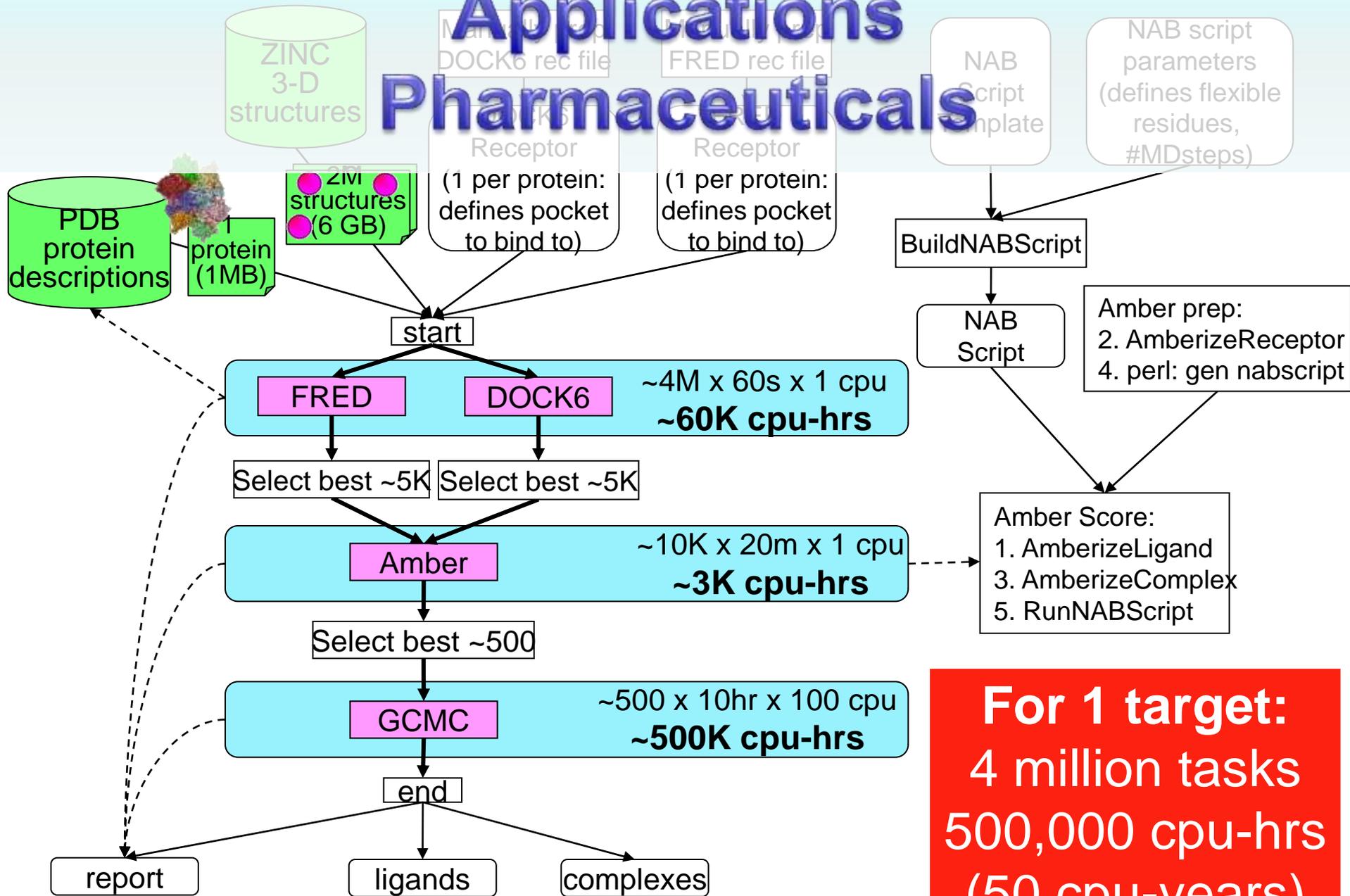
Applications

Economic Modeling: MARS

- CPU Cores: 130816
- Tasks: 1048576
- Elapsed time: 2483 secs
- CPU Years: 9.3



Applications Pharmaceuticals



**For 1 target:
4 million tasks
500,000 cpu-hrs
(50 cpu-years)**

Applications

Pharmaceuticals: DOCK

CPU cores: 118784

Tasks: 934803

Elapsed time: 2.01 hours

Compute time: 21.43 CPU years

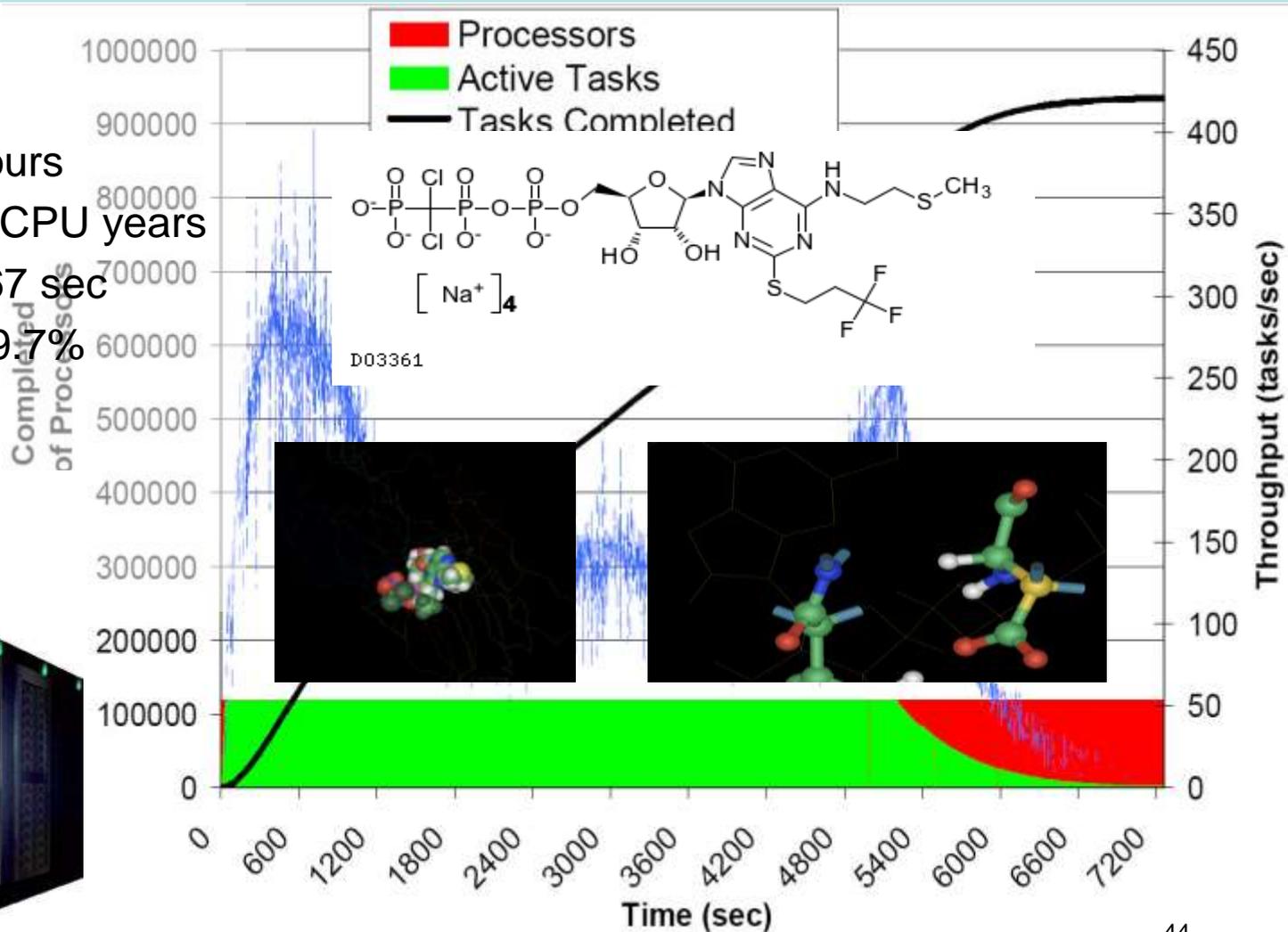
Average task time: 667 sec

Relative Efficiency: 99.7%

(from 16 to 32 racks)

Utilization:

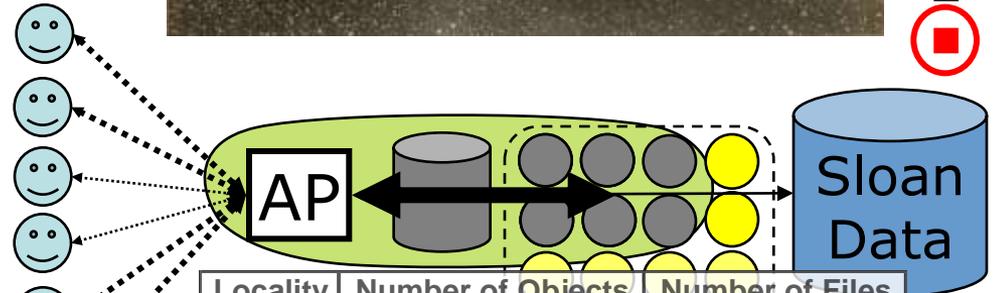
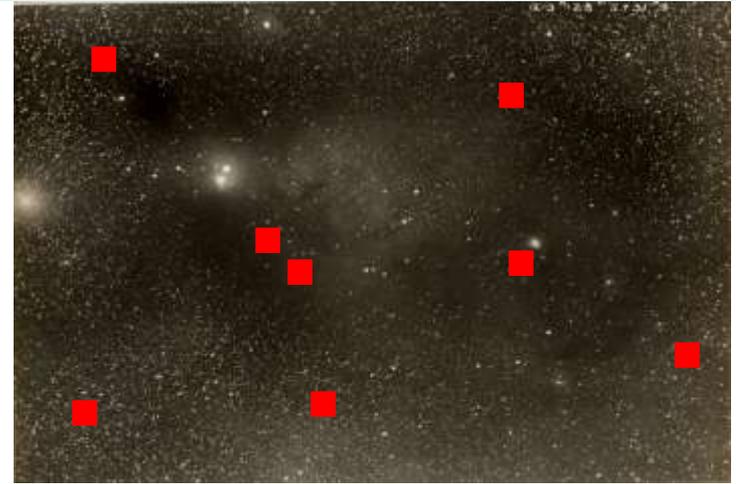
- Sustained: 99.6%
- Overall: 78.3%



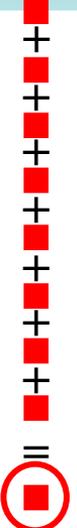
Applications

Astronomy: AstroPortal

- Purpose
 - On-demand “stacks” of random locations within ~10TB dataset
- Challenge
 - Processing Costs:
 - O(100ms) per object
 - Data Intensive:
 - 40MB:1sec
 - Rapid access to 10-10K “random” files
 - Time-varying load



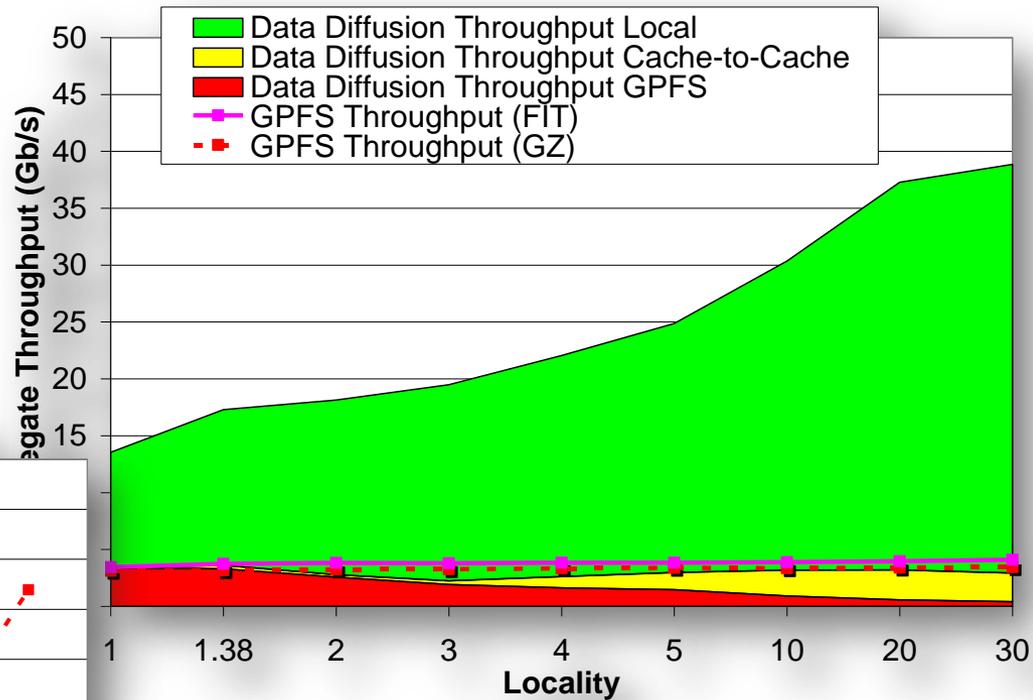
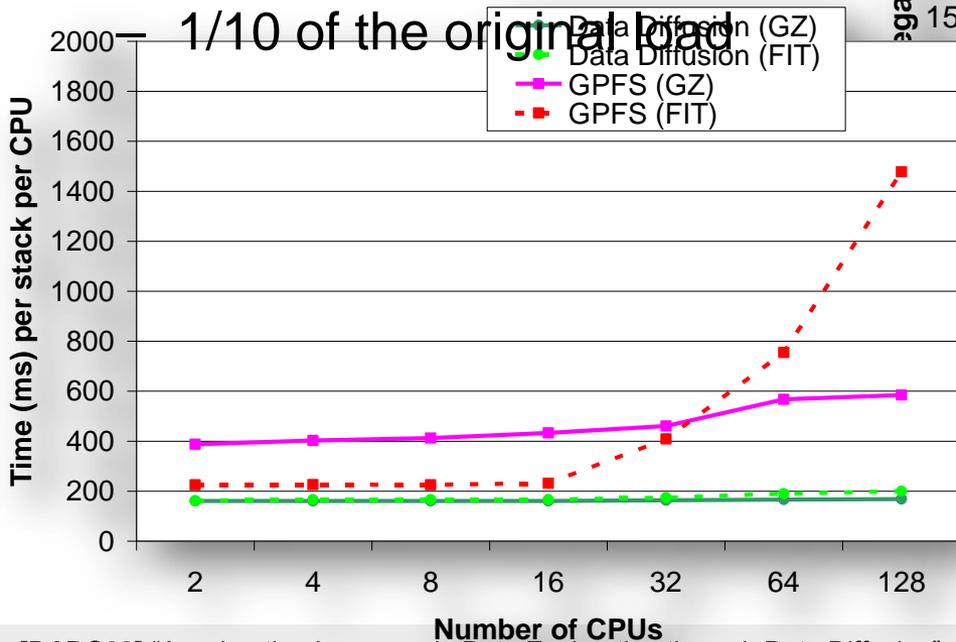
Locality	Number of Objects	Number of Files
1	111700	111700
1.38	154345	111699
2	97999	49000
3	88857	29620
4	76575	19145
5	60590	12120
10	46480	4650
20	40460	2025
30	23695	790



Applications

Astronomy: AstroPortal

- Aggregate throughput:
 - 39Gb/s
 - 10X higher than GPFS
- Reduced load on GPFS
 - 0.49Gb/s
 - 1/10 of the original load



← High data locality
– Near perfect scalability

Outline

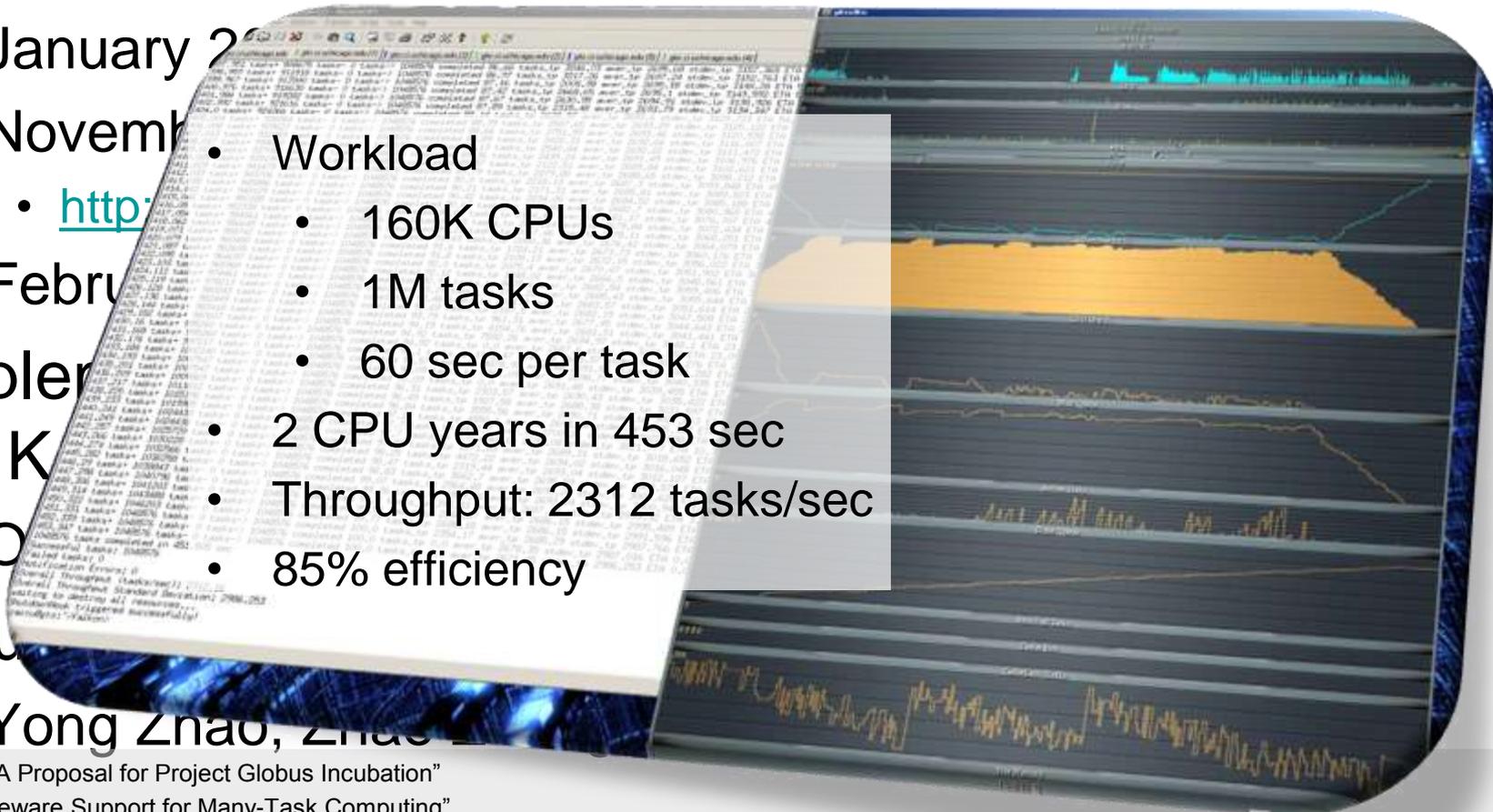
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Conclusions

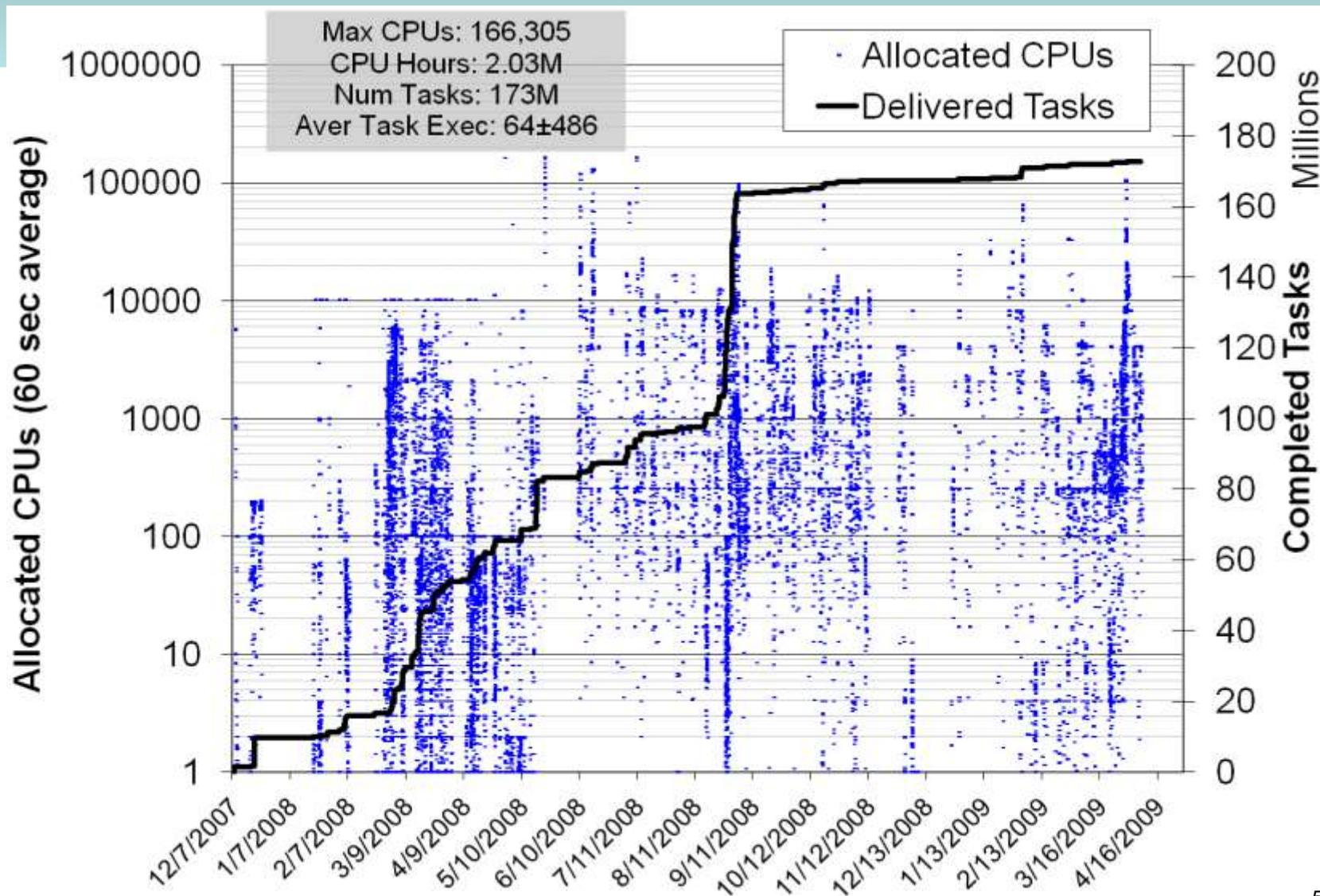
- There is more to HPC than tightly coupled MPI, and more to HTC than embarrassingly parallel long jobs
 - MTC: Many-Task Computing
 - Addressed real challenges in resource management in large scale distributed systems to enable MTC
 - Covered many domains (via Swift and Falcon): astronomy, medicine, chemistry, molecular dynamics, economic modelling, and data analytics
- Identified that data locality is crucial to the efficient use of large scale distributed systems for data-intensive applications →
Data Diffusion
 - Data aware scheduling policies
 - Heuristics to maximize real world performance
 - Suitable for varying, data-intensive workloads
 - Proof of $O(NM)$ Competitive Caching

Falkon Project

- Falkon is a real system
 - Late 2005: Initial prototype, AstroPortal
 - January 2006: Initial release
 - November 2006: Initial release
 - Workload
 - 160K CPUs
 - 1M tasks
 - 60 sec per task
 - February 2007: Initial release
 - 2 CPU years in 453 sec
 - Throughput: 2312 tasks/sec
 - 85% efficiency
- Implementation
 - (~1K lines of code)
 - Open source
- Source code
 - Yong Zhao, Zhaohui



Falkon Activity History (16 months)



Mythbusting

- ~~Embarrassingly~~ Happily parallel apps are trivial to run
 - Logistical problems can be tremendous
- Loosely coupled apps do not require “supercomputers”
 - Total computational requirements can be enormous
 - Individual tasks may be tightly coupled
 - Workloads frequently involve large amounts of I/O
 - Make use of idle resources from “supercomputers” via byproducting
 - Costs to run “supercomputers” per FLOP is among the best
- Loosely coupled apps do not require specialized system software
 - Their requirements on the job submission and storage systems can be extremely large
- Shared/parallel file systems are good for all applications
 - They don’t scale proportionally with the compute resources
 - Data intensive applications don’t perform and scale well
 - Growing compute/storage gap

“Impossible only means that you haven't found the solution yet.”

Anonymous

Where can you learn more about Distributed Systems?

- Hot Topics in Distributed Systems: Data-Intensive Computing
 - Northwestern University (EECS495), Instructor
 - <http://www.eecs.northwestern.edu/~iraicu/teaching/EECS495-DIC/index.html>
- Big Data: Data-intensive Computing Methods, Tools, and Apps
 - University of Chicago (CMSC 34900), Dr. Ian Foster
 - <http://dsl-wiki.cs.uchicago.edu/index.php/BigData09>
- Networks and Distributed Systems (2006)
 - University of Chicago (CMSC 33300), TA
 - <http://dsl.cs.uchicago.edu/Courses/CMSC33300/index.html>
- Grid Computing (2005)
 - University of Chicago (CMSC 33340), TA
 - <http://www.mcs.anl.gov/~itf/CMSC23340/>



ScienceCloud

1st Workshop on Scientific Cloud Computing

co-located with [ACM HPDC 2010 \(High Performance Distributed Computing\)](#)
Chicago, Illinois -- June 21st, 2010

ACM ScienceCloud Workshop @ HPDC2010

Chicago, IL

June 21st, 2010

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[Workshop](#)
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Program Committee

Workshop Chairs

- Pete Beckman, University of Chicago & Argonne National Laboratory
- Ian Foster, University of Chicago & Argonne National Laboratory
- Ioan Raicu, Northwestern University



[Dr. Peter Beckman](#) is the director of the Leadership Computing Facility at the U.S. Department of Energy's National Energy Research Computing Facility (ALCF), which is home to one of the world's fastest computers for open science, the Blue Gene/L. He is also a Senior Scientist in the Department of Engineering at the University of Chicago, where he provides leadership to the open science community. Beckman also leads Argonne's exascale computing strategic initiative and has previously served as the ALCF's chief architect and project director. He has worked on high-performance systems and Grid computing for 20 years. After receiving a Ph.D. degree in computer science from Indiana University in 1993, he helped create the Extreme Computing Laboratory (ACL) at Los Alamos National Laboratory, where he founded the ACL's Linux cluster team and organized the Extreme Linux series of workshops. Beckman has also worked in industry, founding a research laboratory in 2000 in Santa Fe sponsored by Turbolinux, Inc. Beckman was also the vice president of Turbolinux's worldwide engineering efforts, managing development offices in the Argonne in 2002. As Director of Engineering for the TeraGrid, he designed and deployed the world's most advanced Grid system for linking production HPC computing for the first time. After becoming fully operational, he started research teams focusing on petascale high-performance operating systems, fault tolerance, system software and the SPRUCE urgent computing high-performance applications at many of the nation's supercomputer centers.



[Dr. Ian Foster](#) is the Associate Division Director and a Senior Scientist in the Mathematics and Computer Science Division at Argonne National Laboratory, where he leads the Holly Compton Professor in the Department of Computer Science at the University of Chicago. He is also involved with both the Open Grid Forum and with the Globus Alliance. He was appointed director of the Computation Institute, a joint project between the University of Chicago, and Argonne. An earlier project, Strand, received the British Computer Society award for the development of techniques, tools and algorithms for high-performance distributed computing and parallel computing. As a result he is denoted as "the father of the Grid". He was also the principal investigator of the I-WAY wide-area distributed computing experiment, which connected supercomputers, databases and other high-end resources at 17 sites across North America in 1995. He is also the principal investigator of the multi-institute Globus Project, a research and development effort that encourages collaborative computing by providing advances necessary for engineering, but also addresses many of the most challenging computational and communications problems facing Grid implementations today. In 2004, he founded Univa Corporation, which now operates under the name Univa UD. Foster's honors include the Lovelace Medal of the British Computer Society, the Gordon Bell Prize for high-performance computing (2001), the American Association for the Advancement of Science in 2003. Dr. Foster also serves as PI or Co-PI on projects connected to the DOE global change program, the National Energy Research Computing Power Grid project, the NSF Grid Physics Network, GRIDS Center, and International Virtual Data Grid Laboratory projects, and other DOE and NSF programs. His research is



[Dr. Ioan Raicu](#) is a NSF/CRA Computation Innovation Fellow at Northwestern University, in the Department of Electrical Engineering and Computer Science. Ioan holds a Ph.D. in Computer Science under the guidance of Dr. Ian Foster. His research work focuses on resource management in distributed systems to support large scale loosely coupled and data intensive applications. He is also the principal investigator of the MTC (Multi-Task Computing), as well as architected and implemented the middleware, Falkon, a fast and light-weight task execution framework, necessary to support MTC across a wide range of supercomputers. The impact of his research can be measured through his 50+ peer-reviewed publications and proposals that received over 800 citations summing to an H-Index of 15. He has been involved in over 50 events (workshops, conferences, journals, book chapters) in various capacities such as reviewer, program committee, organizing committee, chair and the ACM Workshop on Many-Task Computing on Grids and Supercomputers (MTAGS08, MTAGS09) co-located with the ACM Workshop on Scientific Cloud Computing (ScienceCloud2010) co-located with the ACM HPDC conference. He is also the guest editor for the special issue on Parallel and Distributed Systems (TPDS) to appear in November 2010.

Where can you learn more about Distributed Systems?

- ScienceCloud: [ACM Workshop on Scientific Cloud Computing, 2010](#)
- TPDS: [IEEE Transactions on Parallel and Distributed Systems, Special Issue on Many-Task Computing, 2010](#)
- HPDC: [ACM International Symposium on High Performance Distributed Computing, 2010](#)
- SWF: [IEEE International Workshop on Scientific Workflows, 2010](#)
- TG: [TeraGrid Conference, 2010](#)
- SC: [IEEE/ACM Supercomputing Conference, 2010](#)
- MTAGS: [ACM Workshop on Many-Task Computing on Grids and Supercomputers, 2009](#)
- MTAGS : [IEEE Workshop on Many-Task Computing on Grids and Supercomputers, 2008](#)
- BegaJob: [Bird of Feather Session – “How to Run One Million Jobs”, at IEEE/ACM SC08, 2008](#)

More Information

- More information: <http://www.eecs.northwestern.edu/~iraicu/>
- Related Projects:
 - Falkon: <http://dev.globus.org/wiki/Incubator/Falkon>
 - Swift: <http://www.ci.uchicago.edu/swift/index.php>
- People contributing ideas, slides, source code, applications, results, etc
 - Ian Foster, Alex Szalay, Rick Stevens, Mike Wilde, Jim Gray, Catalin Dumitrescu, Yong Zhao, Zhao Zhang, Gabriela Turcu, Ben Clifford, Mihael Hategan, Allan Espinosa, Kamil Iskra, Pete Beckman, Philip Little, Christopher Moretti, Amitabh Chaudhary, Douglas Thain, Quan Pham, Atilla Balkir, Jing Tie, Veronika Nefedova, Sarah Kenny, Gregor von Laszewski, Tiberiu Stef-Praun, Julian Bunn, Andrew Binkowski, Glen Hocky, Donald Hanson, Matthew Cohoon, Fangfang Xia, Mike Kubal, Alok Choudhary...
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 - **NASA**: Ames Research Center, Graduate Student Research Program
 - **DOE**: Office of Advanced Scientific Computing Research
 - **NSF**: TeragGrid and Computing Research Innovation Fellow Program