

Solving Einstein's Equations through Computational Science

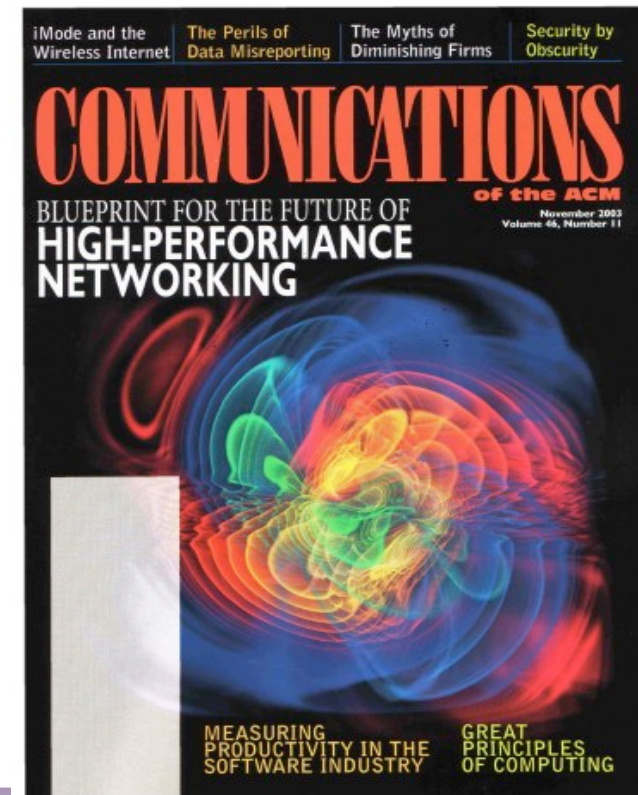
Advancing Computational Science through Gravity

Edward Seidel

Director, Center for Computation &
Technology, LSU

FPS/Cray Professor of Physics and
Computer Science, LSU

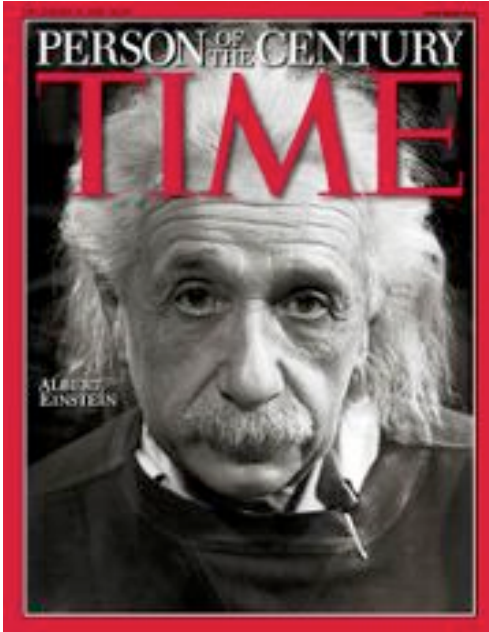
Albert-Einstein-Institut, Potsdam,
Germany



AT LOUISIANA STATE UNIVERSITY



Powerful Beyond Imagination

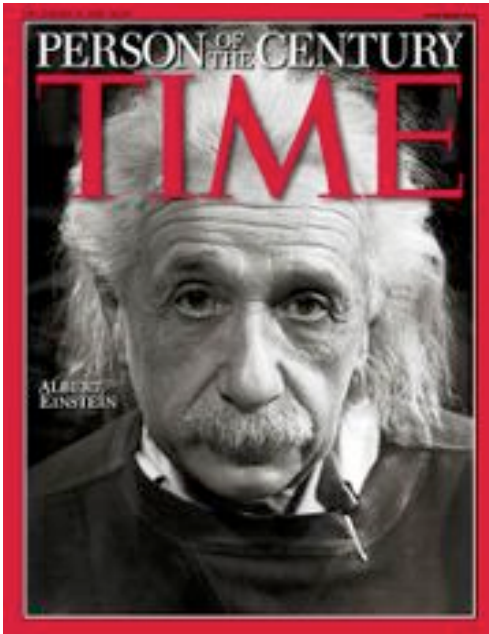


“Computers are incredibly fast, accurate, and stupid. Human beings are incredibly slow, inaccurate, and brilliant. Together they are powerful beyond imagination.”

SC06 Tag Line



Powerful Beyond Imagination

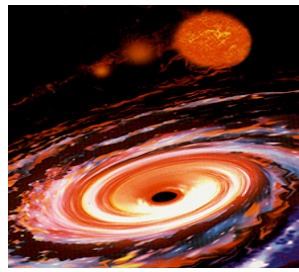


“Computers are incredibly fast, accurate, and stupid. Human beings are incredibly slow, inaccurate, and brilliant. Together they are powerful beyond imagination.” *SC06 Tag Line*

50 years later: Computers are $\sim 2^{35}$ times faster now! Extending human intelligence (a la Kurzweil) to allow us to solve equations Einstein could not! He would be very pleased with progress!



Einstein's Equations and Gravitational Waves

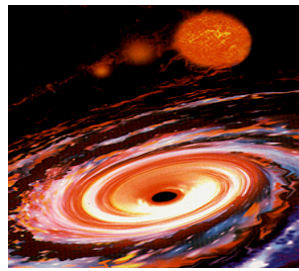


Two major motivations/directions for numerical relativity

- Exploring Einstein's General Relativity
- Developing theoretical lab to probe this fundamental theory
 - Fundamental theory of Physics
 - Among most complex equations of physics
 - Dozens of coupled, nonlinear hyperbolic-elliptic eqs: 1000's of terms
 - Barely have capability to solve after a century
 - Predict black holes, gravitational waves, etc, but want much more

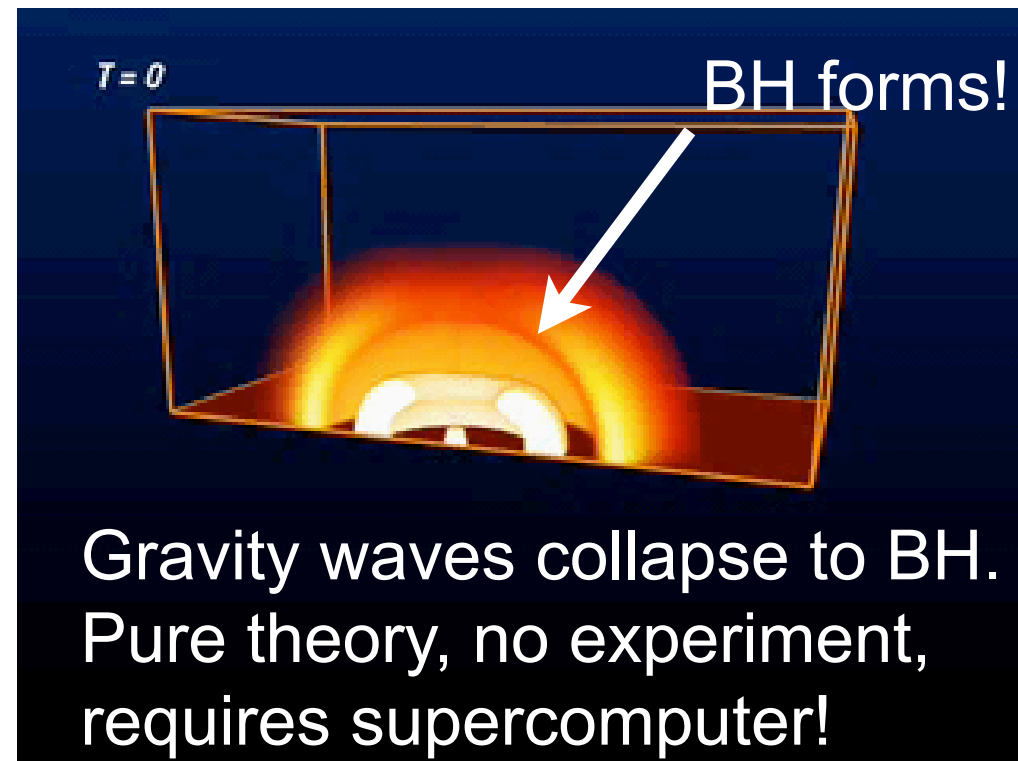


Einstein's Equations and Gravitational Waves



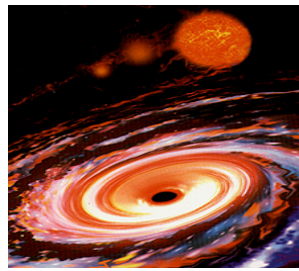
Two major motivations/directions for numerical relativity

- Exploring Einstein's General Relativity
- Developing theoretical lab to probe this fundamental theory
 - Fundamental theory of Physics
 - Among most complex equations of physics
 - Dozens of coupled, nonlinear hyperbolic-elliptic eqs: 1000's of terms
 - Barely have capability to solve after a century
 - Predict black holes, gravitational waves, etc, but want much more





Einstein's Equations and Gravitational Waves

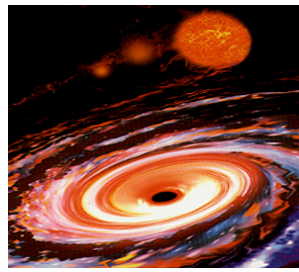


Two major motivations/directions for numerical relativity

- Exploring Einstein's General Relativity
- Developing theoretical lab to probe this fundamental theory
 - Fundamental theory of Physics
 - Among most complex equations of physics
 - Dozens of coupled, nonlinear hyperbolic-elliptic eqs: 1000's of terms
 - Barely have capability to solve after a century
 - Predict black holes, gravitational waves, etc, but want much more
- Exciting new field about to be born: Gravitational Wave Astronomy
 - LIGO, VIRGO, GEO, LISA, ... ~ \$1 Billion worldwide!
 - Fundamentally new information about Universe
 - A last major test of Einstein's theory: do they exist?
 - Eddington: "Gravitational waves propagate at the speed of thought"
 - 1993 Nobel Prize Committee: Hulse-Taylor Pulsar (indirect evidence)
 - 20xx Nobel Committee: ??? (For actual detection...)



Einstein's Equations and Gravitational Waves



Two major motivations/directions for numerical relativity

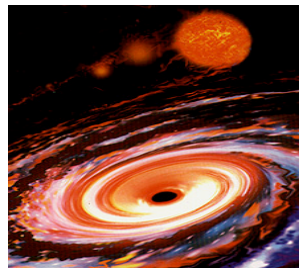
- Exciting new field about to be born: Gravitational Wave Astronomy
- LIGO, VIRGO, GEO, LISA, ... ~ \$1 Billion worldwide!
- Fundamentally new information about Universe
- A last major test of Einstein's theory: do they exist?
 - Eddington: "Gravitational waves propagate at the speed of thought"
 - 1993 Nobel Prize Committee: Hulse-Taylor Pulsar (indirect evidence)
 - 20xx Nobel Committee: ??? (For actual detection...)

Kaehler viz, ZIB, AEI

Christian Ott, et al. AEI & U Arizona. ~ First 3D GR SN...



Einstein's Equations and Gravitational Waves



Two major motivations/directions for numerical relativity

- Exciting new field about to be born: Gravitational Wave Astronomy
- LIGO, VIRGO, GEO, LISA, ... ~ \$1 Billion worldwide!
- Fundamentally new information about Universe
- A last major test of Einstein's theory: do they exist?
 - Eddington: "Gravitational waves propagate at the speed of thought"
 - 1993 Nobel Prize Committee: Hulse-Taylor Pulsar (indirect evidence)
 - 20xx Nobel Committee: ??? (For actual detection...)

Kaehler viz, ZIB, AEI

Christian Ott, et al. AEI & U Arizona. ~ First 3D GR SN...

*One century later, breakthroughs happening at the same time!
HPC + grids + algorithm + theory all essential ingredients.*

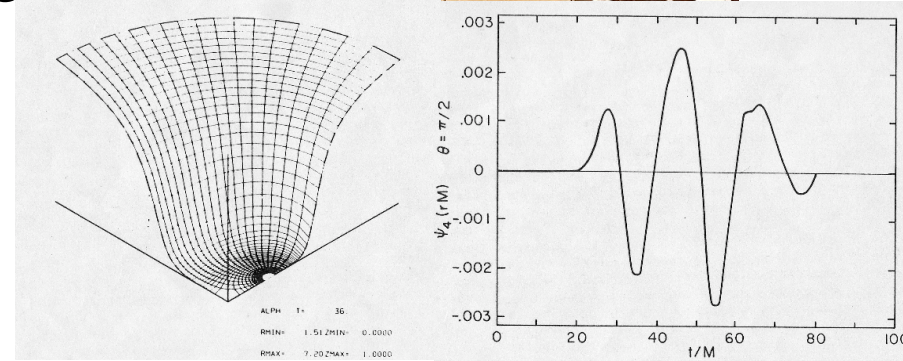


Very Early Experiments



Larry Smarr Role

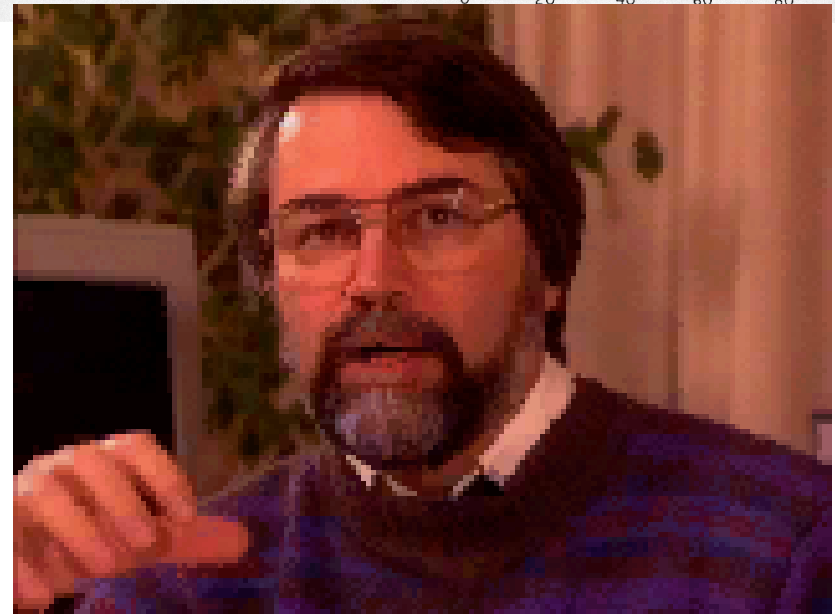
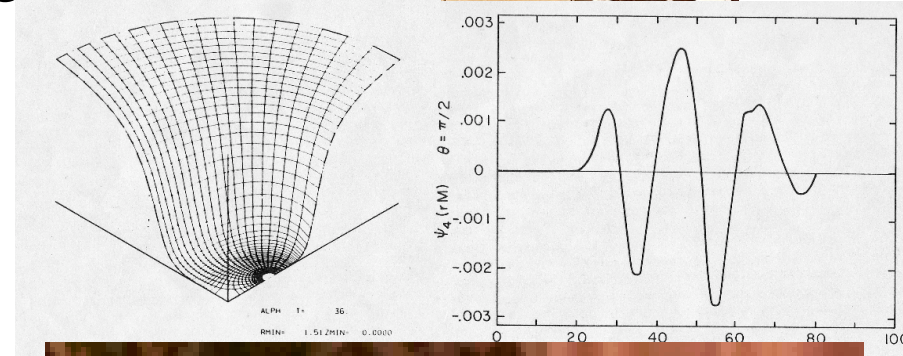
- Larry's early career: collision of two black holes
 - Foundations of modern numrel
 - “Done by X-mas!”
 - Computing on “iPod-class” supercomputer
- Max-Planck facilities
 - US Supercomputer famine
 - National centers program
- Much of modern-day HPC grew out of this; inspiration for more





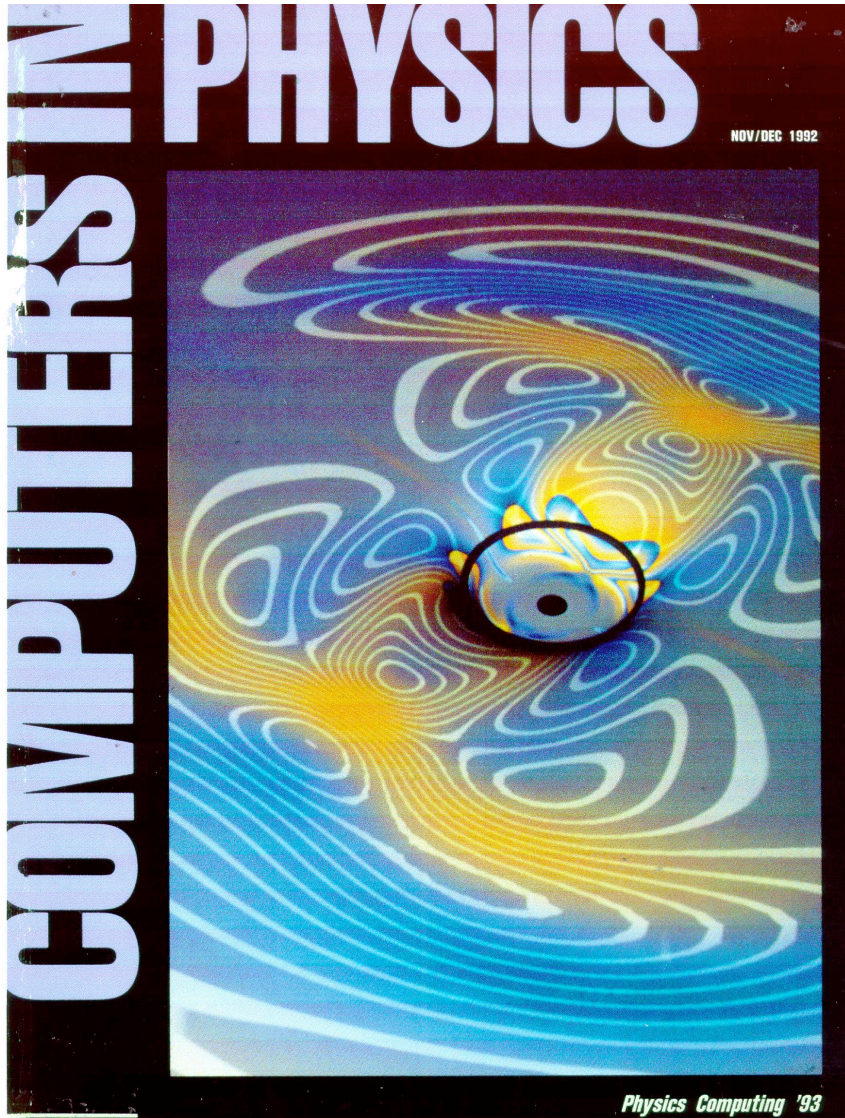
Larry Smarr Role

- Larry's early career: collision of two black holes
 - Foundations of modern numrel
 - “Done by X-mas!”
 - Computing on “iPod-class” supercomputer
- Max-Planck facilities
 - US Supercomputer famine
 - National centers program
- Much of modern-day HPC grew out of this; inspiration for more





Computational Needs for 3D Numerical Relativity



The diagram shows two 3D grid planes representing spacetime. The top plane, labeled $t=10$, shows a single black hole with red wavy lines representing gravitational waves emanating from it. The bottom plane, labeled $t=0$, shows two black holes in the process of merging, with a smaller grid area between them indicating the region of interaction.

- Get physicists + CS people together
- Initial Data: 4 coupled nonlinear elliptics
- Choose Gauge (coordinates)
- Evolution
 - Dozens of nonlin. hyperbolic eqs.
 - Coupled with elliptic eqs.
 - 100's of 3D arrays, TByte, TFlop crucial, PByte/PFlop soon needed
- Interpret Physics

Dynamic interplay between theoretical, algorithmic, technology advances!

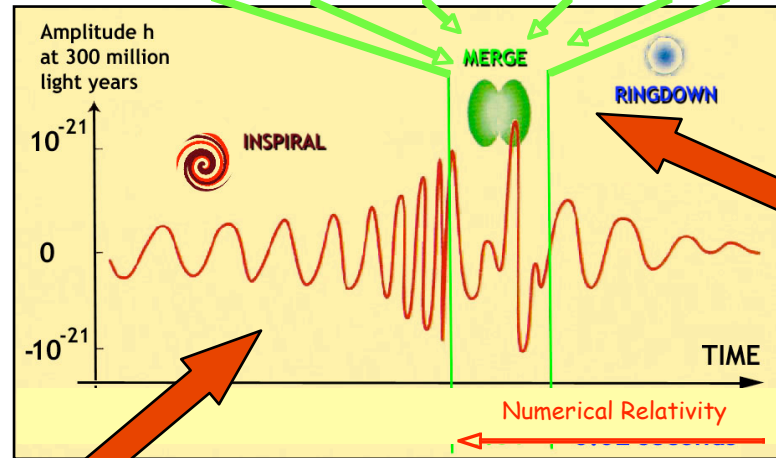


Gravitational Wave Physics

Computing Nature via HPC

Analysis & Insight

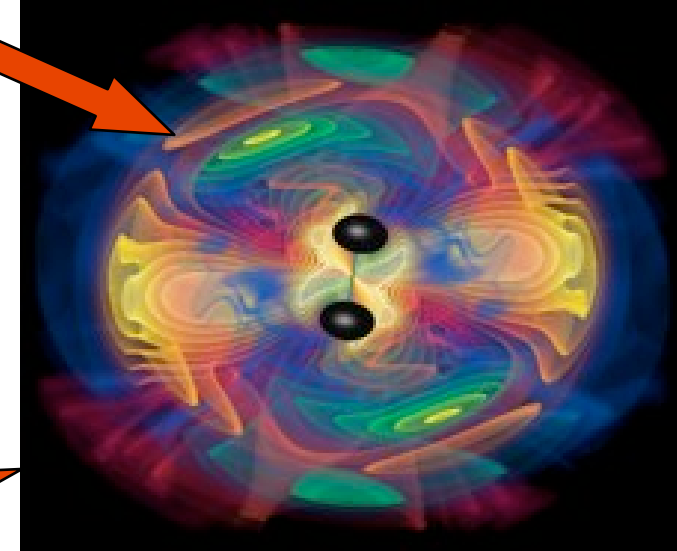
Teraflop Computation, AMR, Elliptic-Hyperbolic, ???



Observations



Models



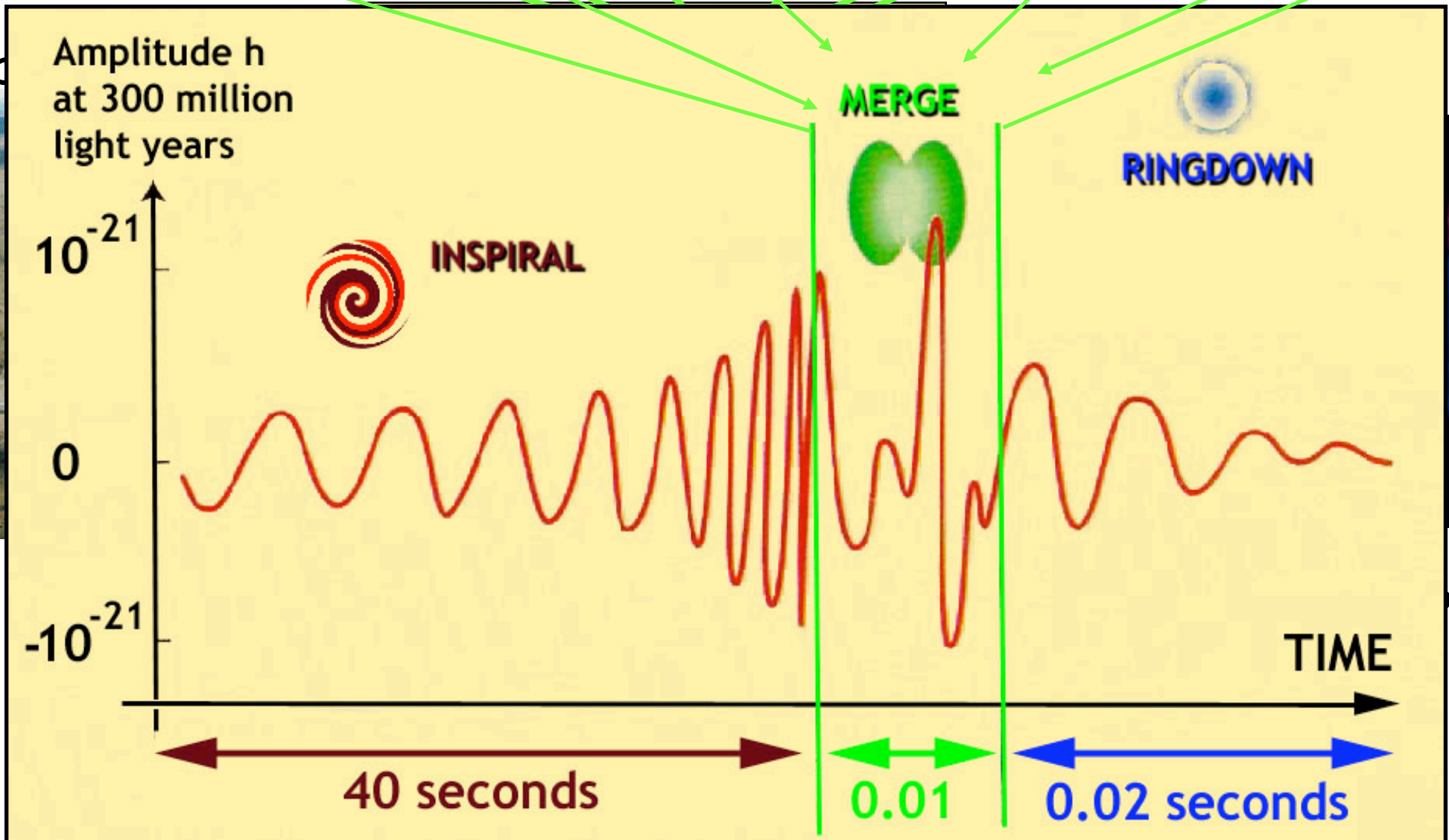
LSU/AEI Collaboration
(Seidel/Rezzolla)



Gravitational Wave Physics

Computing Nature via HPC

Teraflop Computation, AMR, Elliptic-Hyperbolic, ???

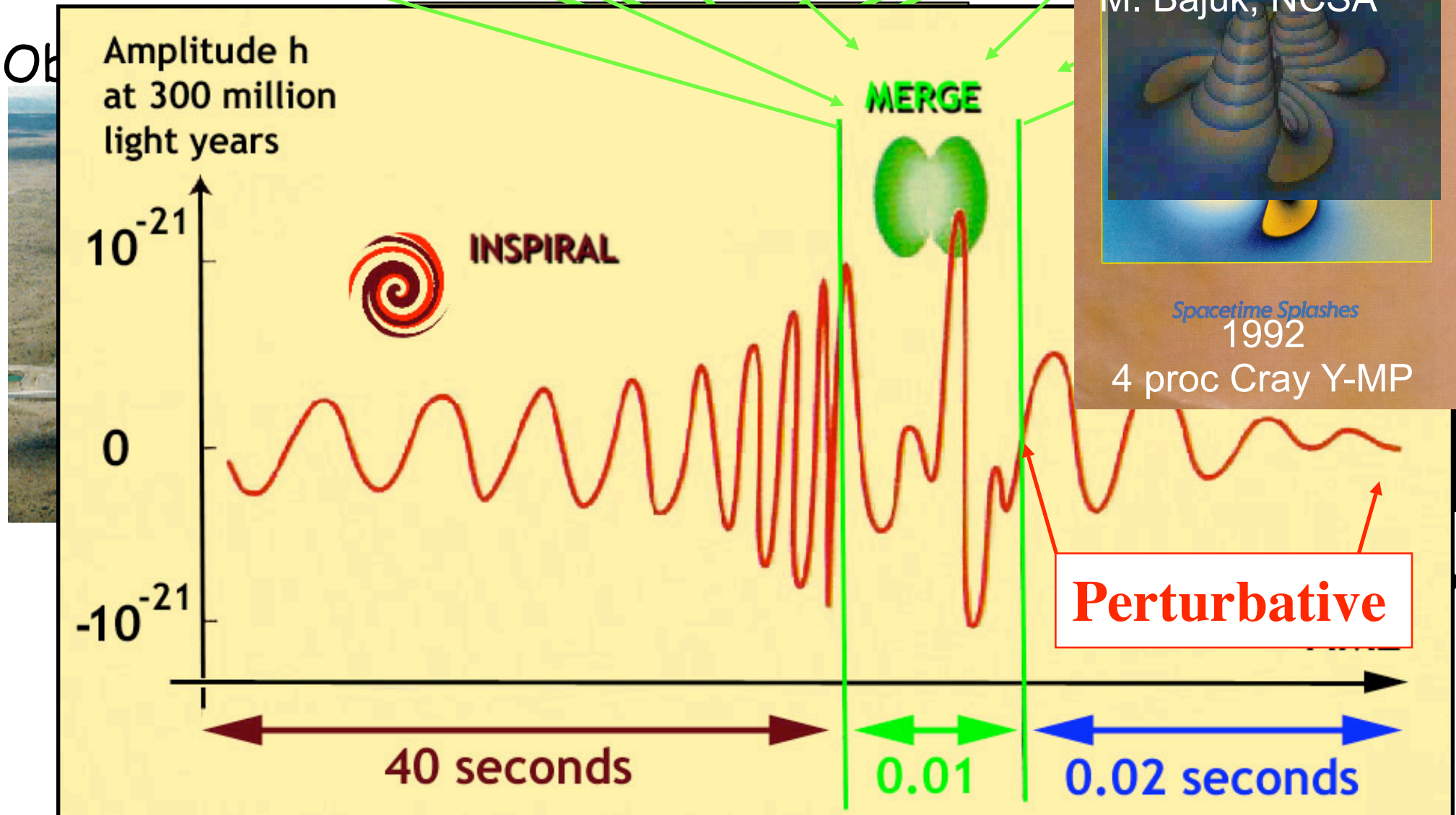
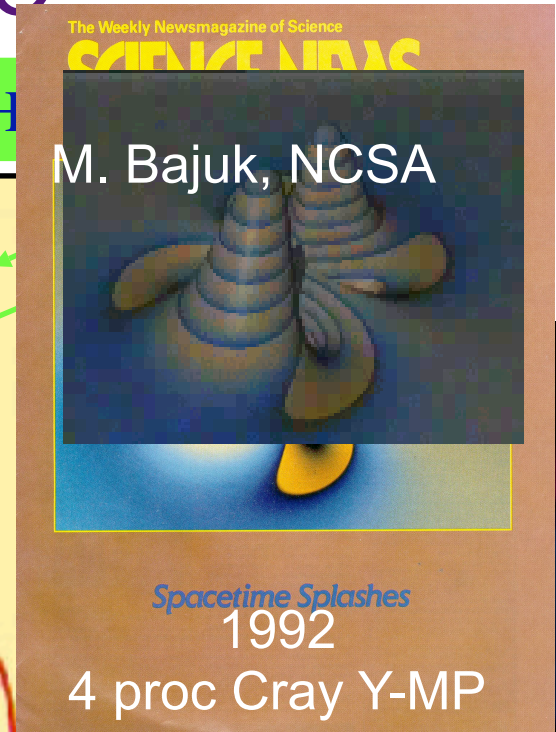




Gravitational Wave Physics

Computing Nature via HPC

Teraflop Computation, AMR, Elliptic-H

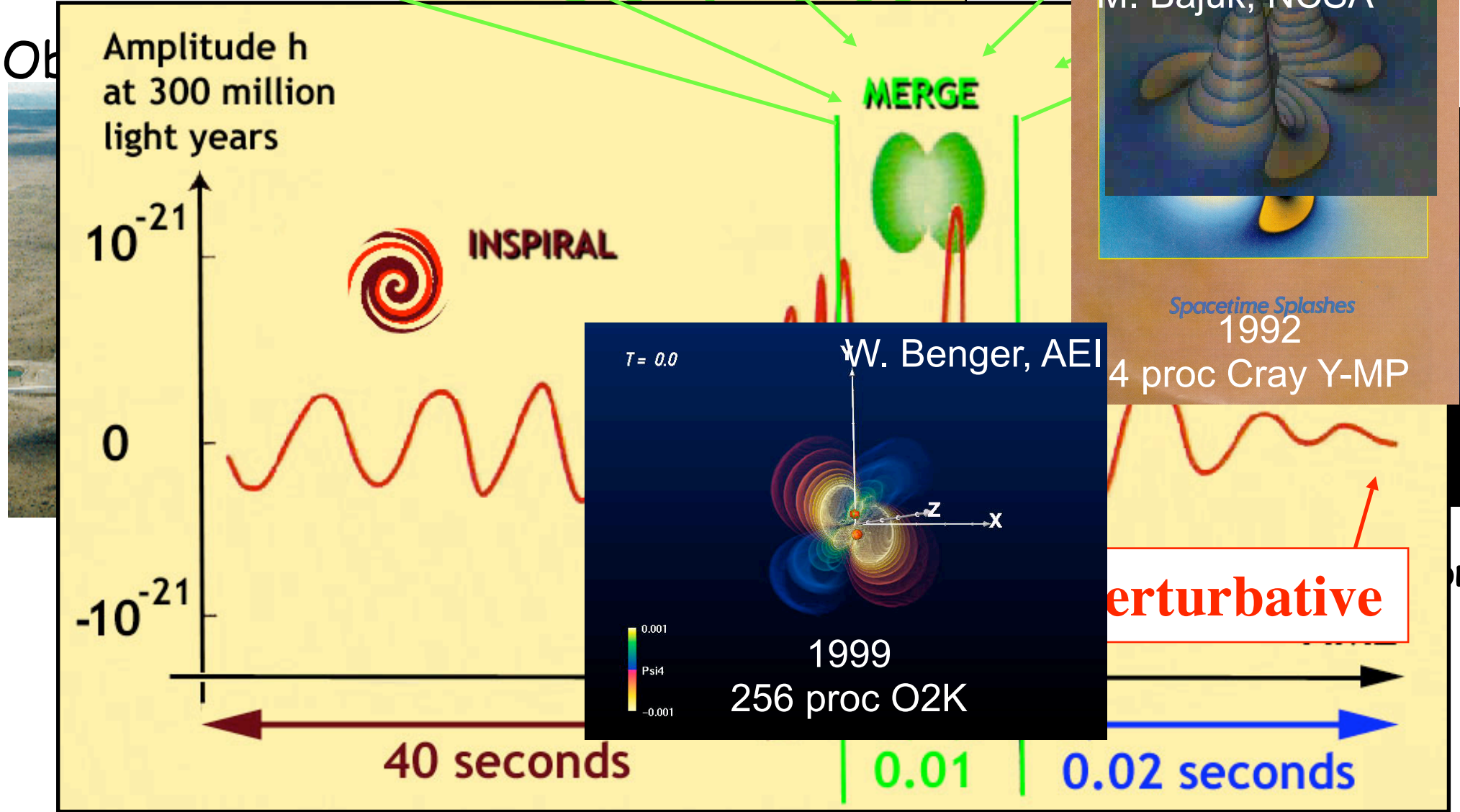




Gravitational Wave Physics

Computing Nature via HPC

Teraflop Computation, AMR, Elliptic-H

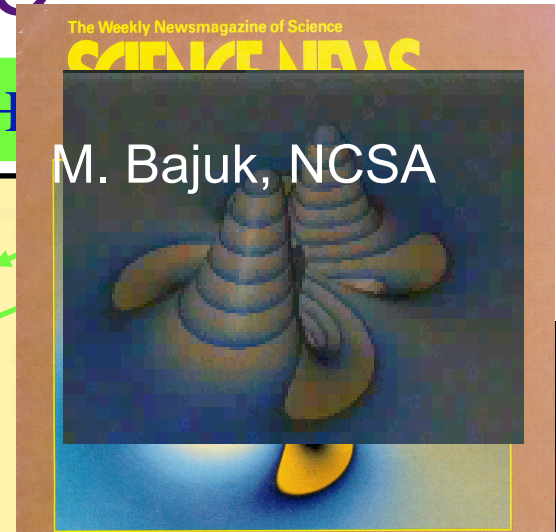




Gravitational Wave Physics

Computing Nature via HPC

Teraflop Computation, AMR, Elliptic-H

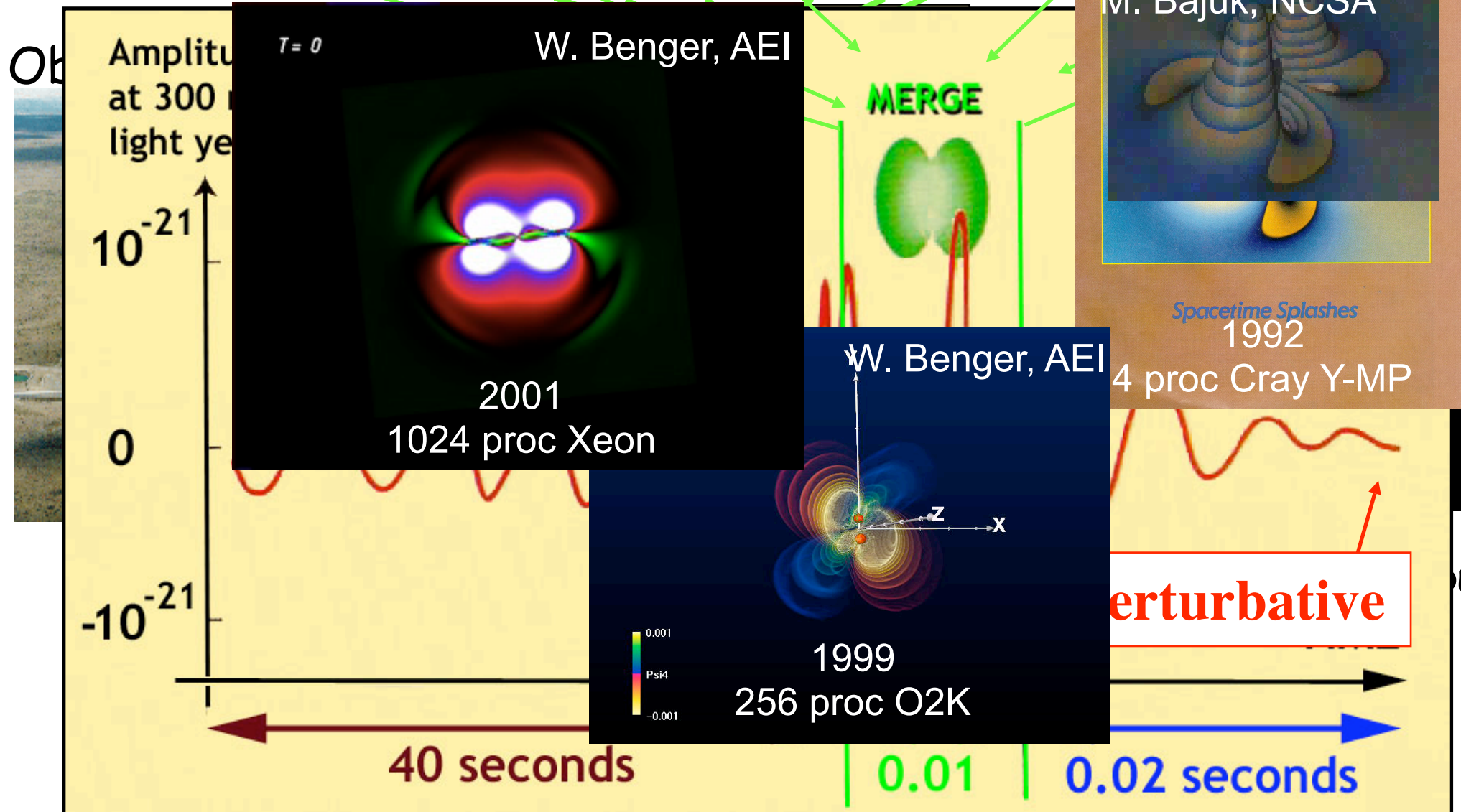


M. Bajuk, NCSA

Spacetime Splashes
1992

4 proc Cray Y-MP

erturbative

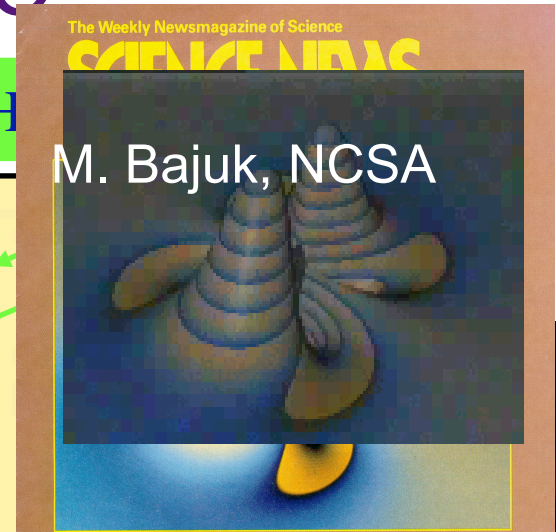




Gravitational Wave Physics

Computing Nature via HPC

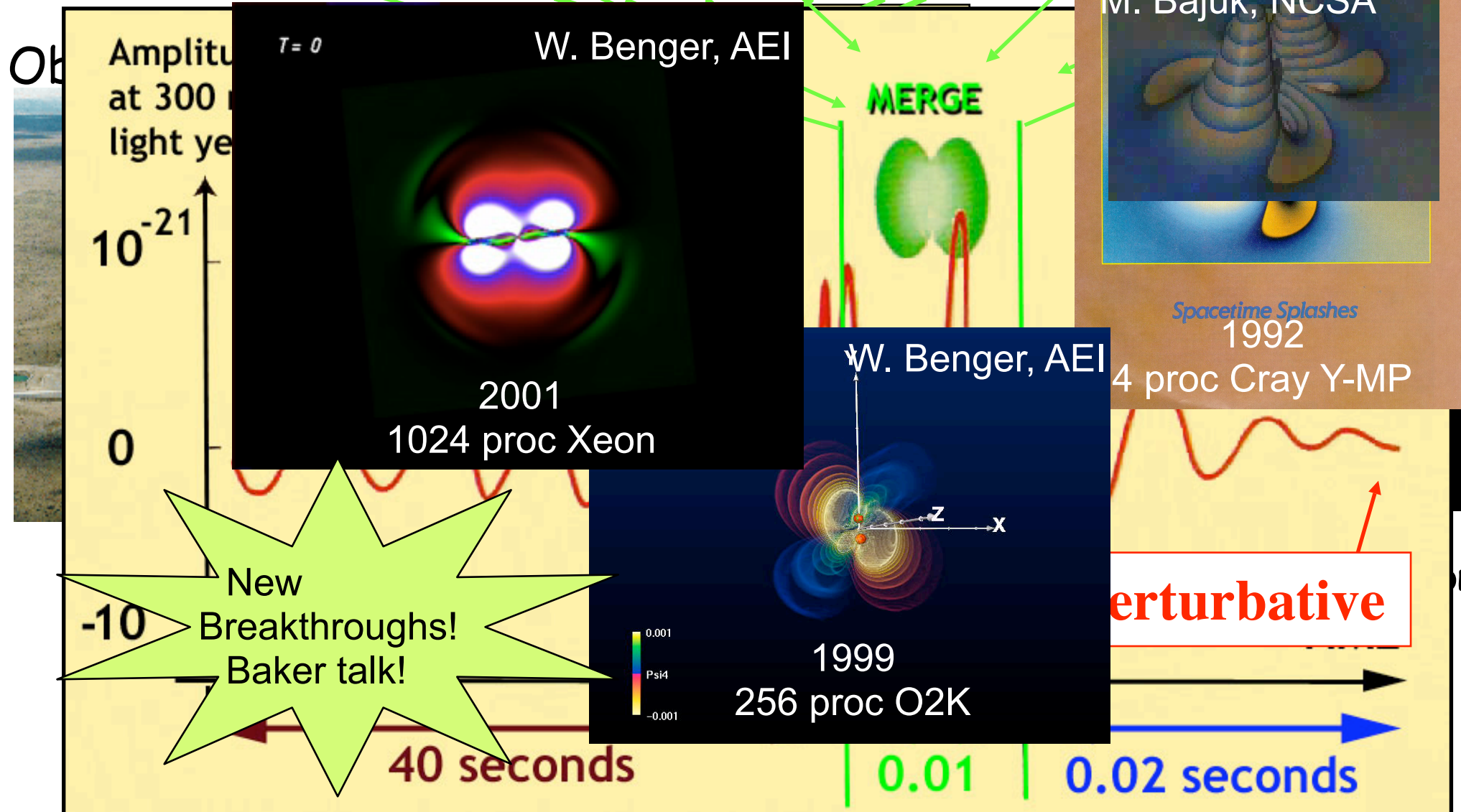
Teraflop Computation, AMR, Elliptic-H



Spacetime Splashes
1992

4 proc Cray Y-MP

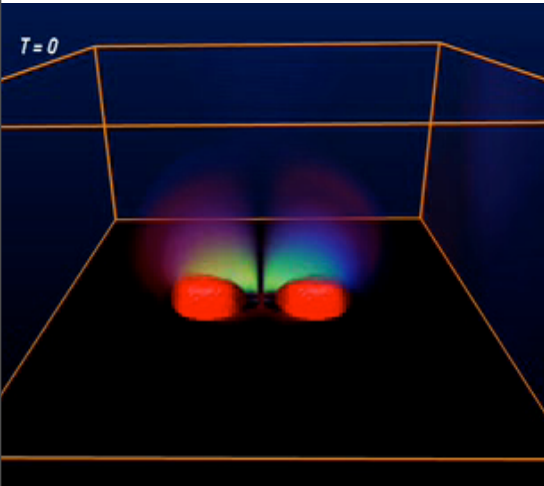
erturbative





Grand Challenge Collaborations

Science and Eng. Go Large Scale: Needs Dwarf Capabilities



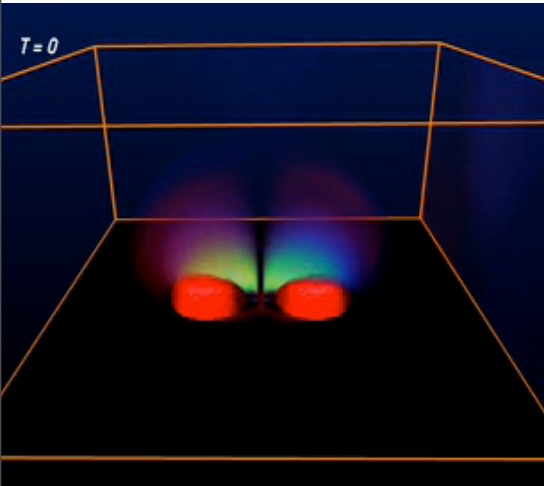
NASA Neutron Star Grand Challenge

- 5 US Institutions,
3years, \$1.4M
- Solve problem of
colliding neutron
stars (try...)



Grand Challenge Collaborations

Science and Eng. Go Large Scale: Needs Dwarf Capabilities



NASA Neutron Star Grand Challenge

- 5 US Institutions, 3 years, \$1.4M
- Solve problem of colliding neutron stars (try...)



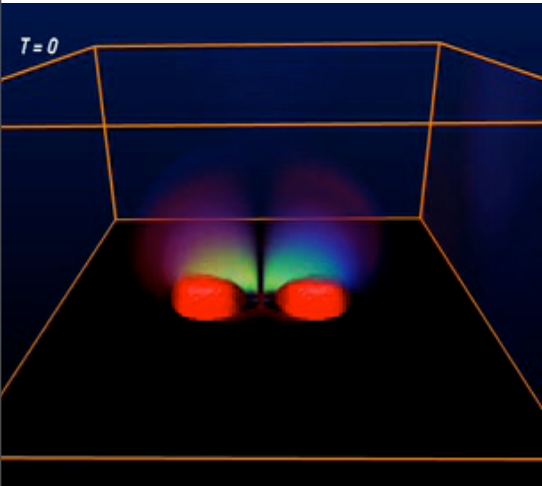
NSF Black Hole Grand Challenge

- 8 US Institutions, 5 years, \$4M
- Solve problem of colliding black holes (try...)



Grand Challenge Collaborations

Science and Eng. Go Large Scale: Needs Dwarf Capabilities



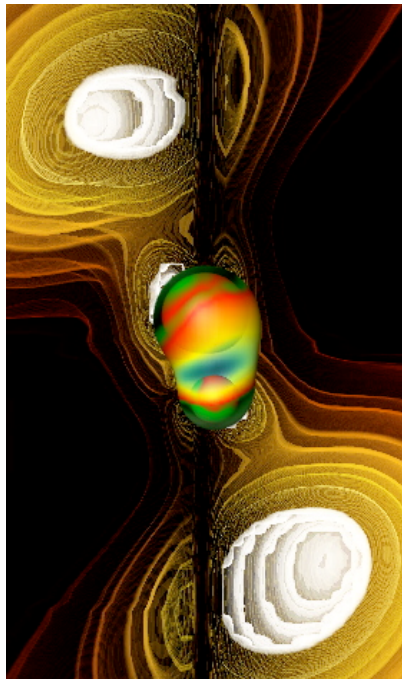
NASA Neutron Star Grand Challenge

- 5 US Institutions, 3 years, \$1.4M
- Solve problem of colliding neutron stars (try...)



NSF Black Hole Grand Challenge

- 8 US Institutions, 5 years, \$4M
- Solve problem of colliding black holes (try...)



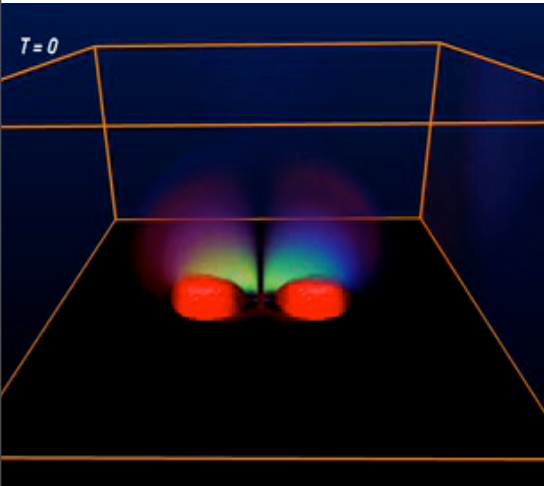
EU Network Astrophysics

- 10 EU Institutions, 3 years, €1.5M
- Continue these problems
- *Entire Community becoming Grid enabled*



Grand Challenge Collaborations

Science and Eng. Go Large Scale: Needs Dwarf Capabilities



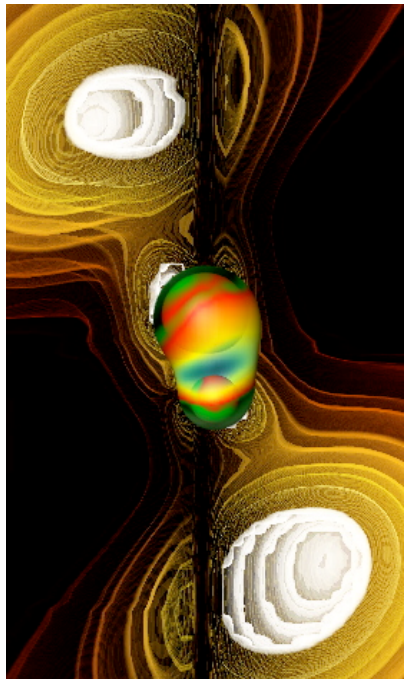
NASA Neutron Star Grand Challenge

- 5 US Institutions, 3 years, \$1.4M
- Solve problem of colliding neutron stars (try...)



NSF Black Hole Grand Challenge

- 8 US Institutions, 5 years, \$4M
- Solve problem of colliding black holes (try...)



EU Network Astrophysics

- 10 EU Institutions, 3 years, €1.5M
- Continue these problems
- *Entire Community becoming Grid enabled*

Examples of Future of Science & Engineering

- Require large scale simulations, and collaborations
- Bring together cross disciplinary teams
- Demands on software engineering
- Solving problems simply beyond reach until now...

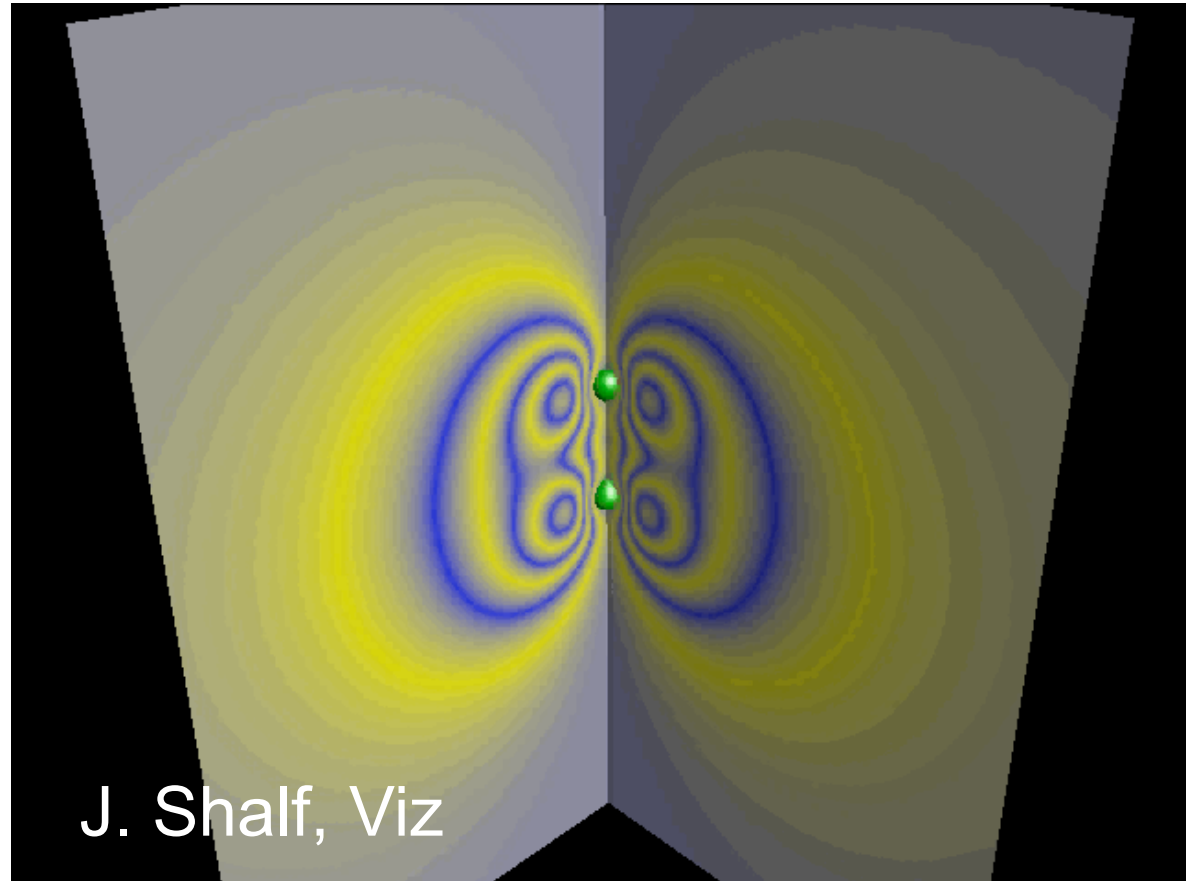
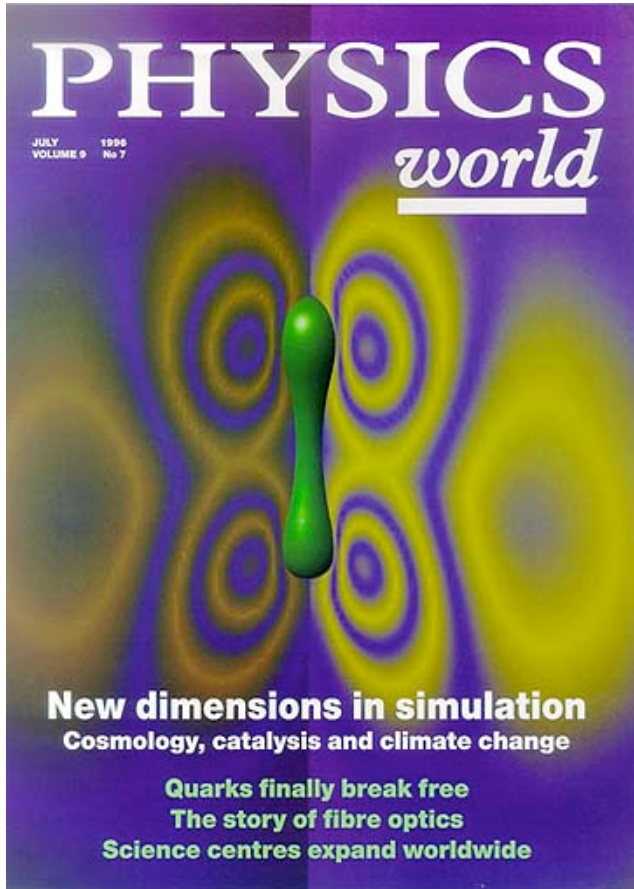


Early Experiments



First 3D Black Hole Collisions, 1994

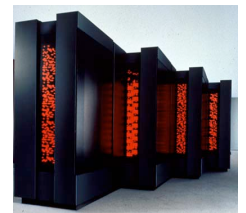
NSF Black Hole Grand Challenge Era



J. Shalf, Viz

Event Horizon in green Ψ_4 (gravitational waves) in blue-yellow

- Smarr thesis now a “test problem” for 3D
- Possible due to 2D studies, 512 node CM-5





Relativity Workbench (1992)

Inspired by Mike Norman

- Above work very tedious! Want workflow, resource selection, live viz, etc
- Choose resources, compute initial data, visualize
- Evolve, visualize
- Archive, store results
- Early grid, portal ideas!

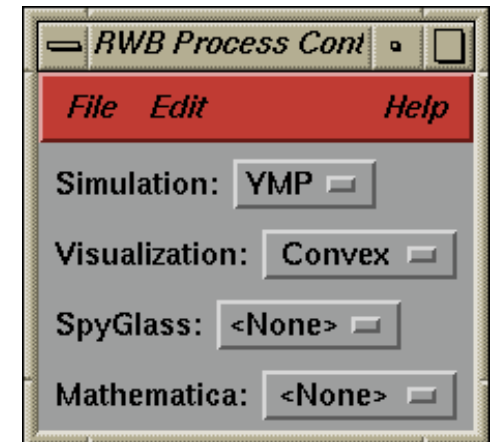


Relativity Workbench (1992)

Inspired by Mike Norman

- Above work very tedious! Want workflow, resource selection, live viz, etc
- Choose resources, compute initial data, visualize
- Evolve, visualize
- Archive, store results
- Early grid, portal ideas!

G. Heinz



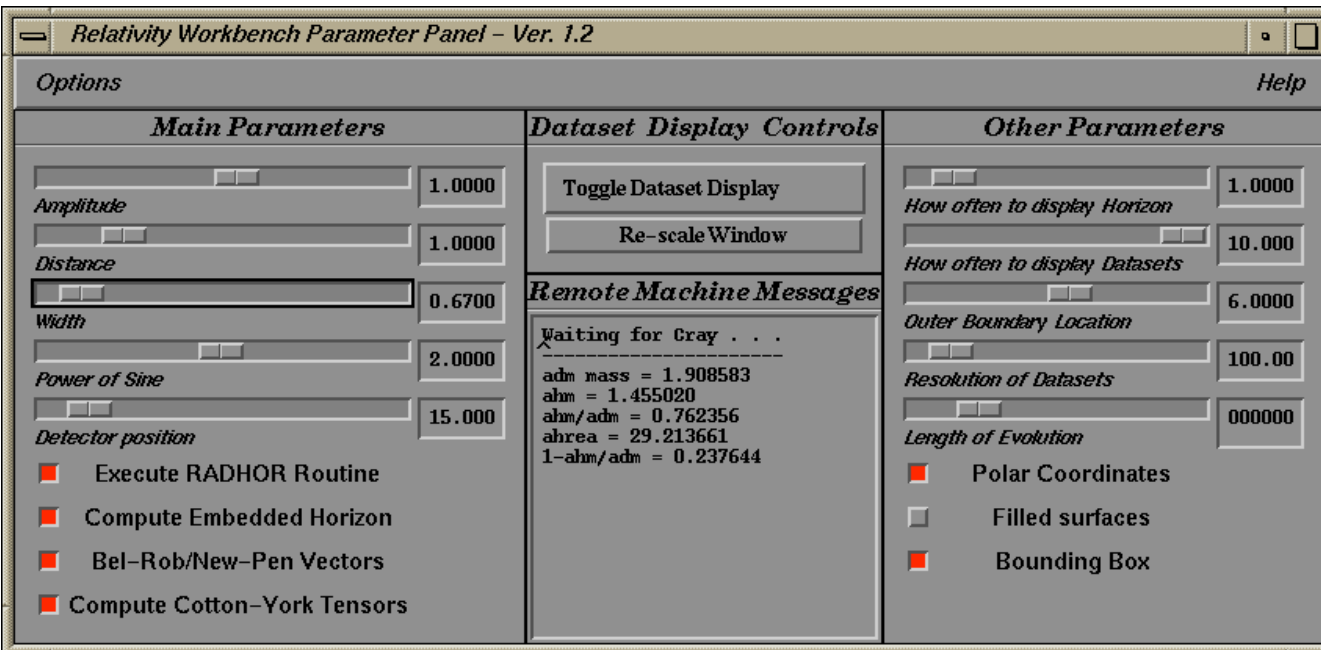
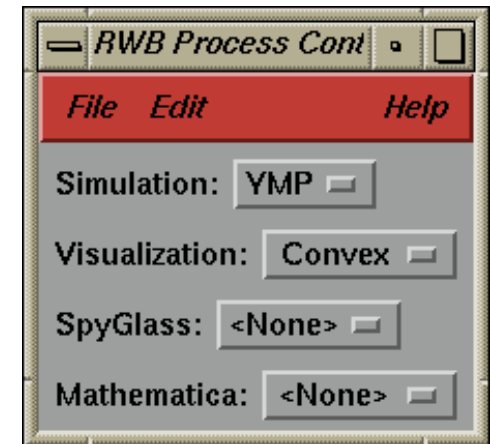


Relativity Workbench (1992)

Inspired by Mike Norman

- Above work very tedious! Want workflow, resource selection, live viz, etc
- Choose resources, compute initial data, visualize
- Evolve, visualize
- Archive, store results
- Early grid, portal ideas!

G. Heinz



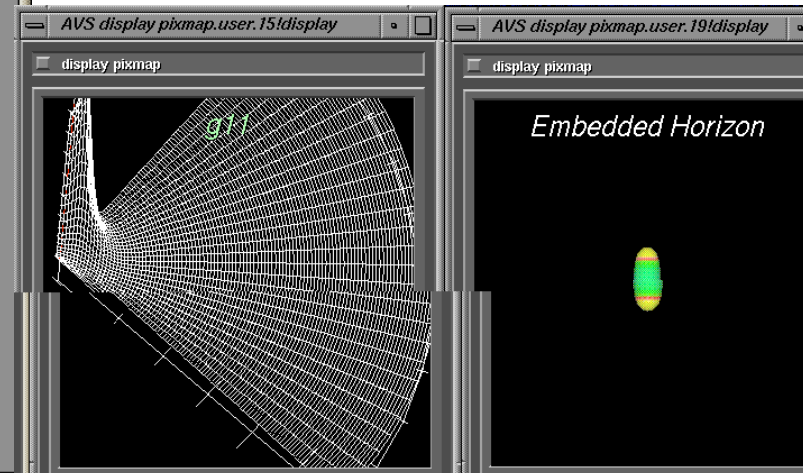
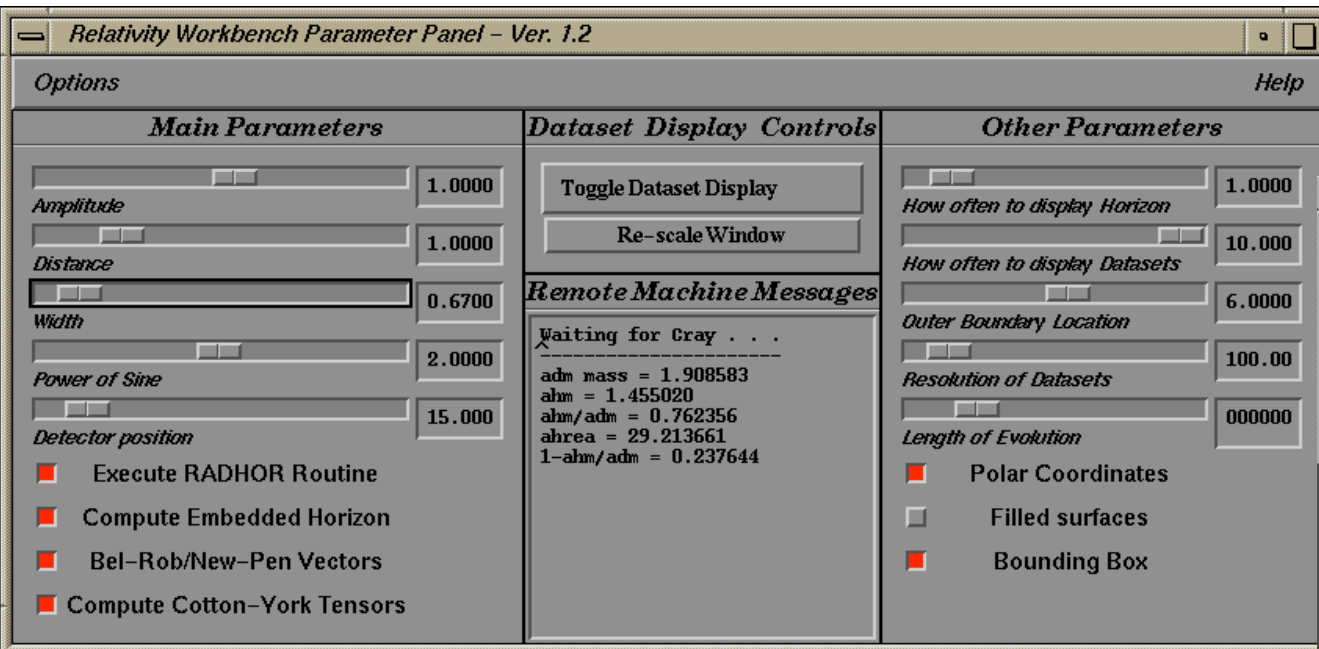
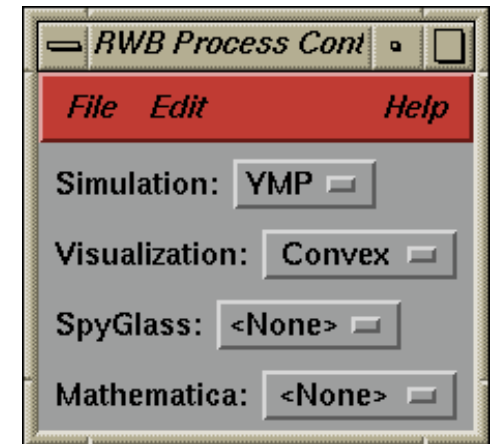


Relativity Workbench (1992)

Inspired by Mike Norman

- Above work very tedious! Want workflow, resource selection, live viz, etc
- Choose resources, compute initial data, visualize
- Evolve, visualize
- Archive, store results
- Early grid, portal ideas!

G. Heinz

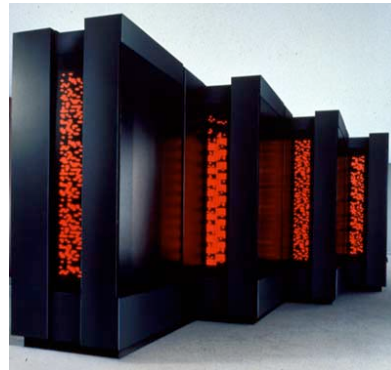




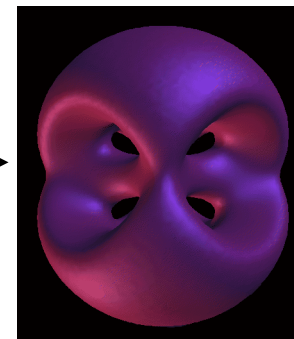
CAVE, SC93, 94, 97

- Golden Age of numerical relativity, but takes so long!
 - Visualizing results: could not wait for physics!
- Developed 3D visualization during simulation
 - Why? Better science, better understanding, fewer errors

G, H codes for EEs. CM-5 allowed 3D!



CM-5



CAVE

Joan Massó,
John Shalf, Tom
DeFanti, Trina
Roy, Jon
Goldman,
Carolina Cruz-
Neira, et al

- SC97: Garching, Germany - San Jose
- Wanted multiple views of all functions (50 3D arrays!), different viz targets, ease of use



SC95 I-WAY

- Pivotal event
 - “Metacomputing” discussed for few years (Catlett, Smarr, et al)
 - EE’s could use all SCs available: how?
- Tom DeFanti, Ian Foster, et al
 - Networks, software layers
 - NCSA relativity group among apps
 - Single MPI job across NCSA, PSC, SDSC, Cornell, viz’d in CAVE
 - Projects “successful”, Heros of SC95!
- Software projects emerge
 - Globus Toolkit and Grids
 - Cactus Toolkit for applications: learn from above

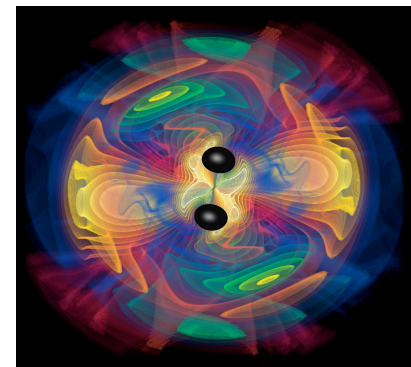
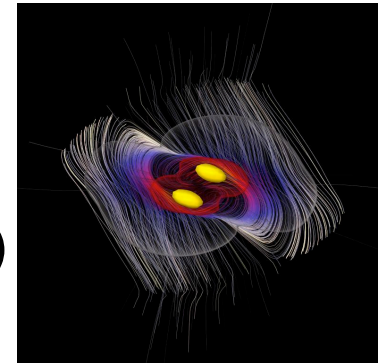




Lessons Learned

Computational Science is Hard

- Requires incredible mix of technologies & expertise!
- Many scientific/engineering components
 - Physics, astrophysics, CFD, engineering,...
- Many numerical algorithm components
 - Finite difference? Finite volume? Finite elements?
 - Elliptic equations: multigrid, Krylov subspace,...
 - Mesh refinement, multipatch
- Many different computational components
 - Parallelism (HPF, MPI, PVM, ???)
 - Architecture (MPP, DSM, Vector, PC Clusters, FPGA, ???)
 - I/O (generate TBs/simulation, checkpointing...)
 - Visualization of all that comes out!
- New technologies
 - Grid computing
 - Steering, data archives
 - Symbolic code generation to do all above (possible!)
- *Abstractions: enable all disciplines, areas of CS...*



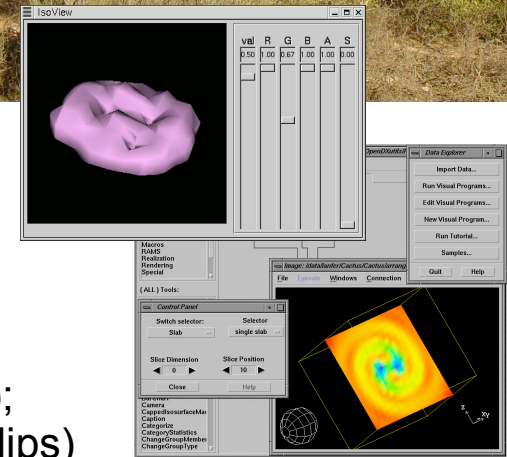
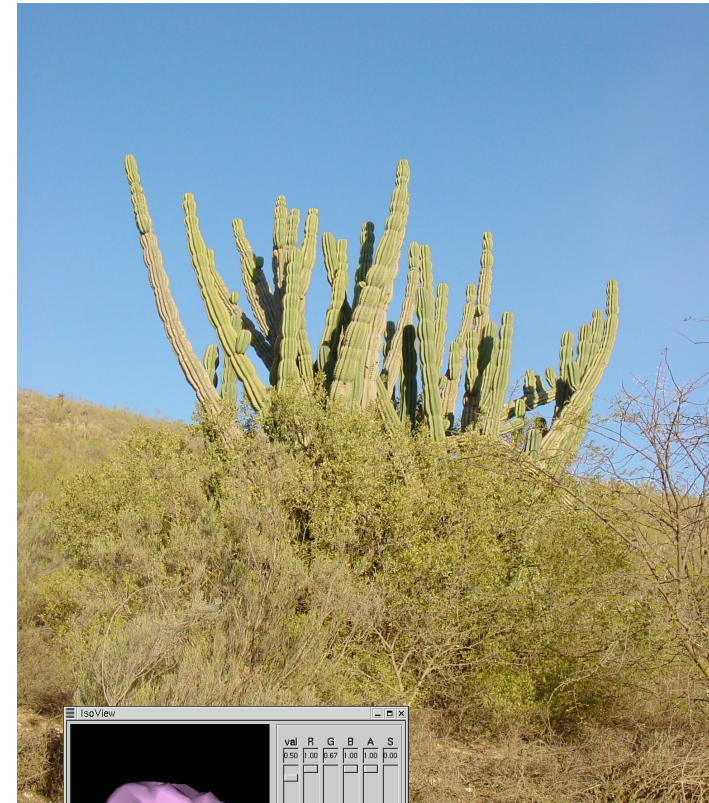


More Modern Approaches



Cactus Emerges after GC, IWAY

- Free, modular, portable environment for collaboratively developing parallel, HPC multi-D simulations (Component-based)
- Developed for Numerical Relativity, now general framework for parallel computing
- Finite difference, AMR (Carpet, Samrai, Grace), new FE/FV, multipatch, unstructured meshes
- Interfaces to advanced I/O, elliptic solvers
- Active user and developer communities, main development now at LSU and AEI.
- Open source, documentation, etc



Paul Walker (JP Morgan), Joan Massó (Grid Systems), John Shalf (LBNL);
Tom Goodale (Cardiff/LSU), Gabrielle Allen (LSU), Gerd Lanfermann (Phillips)

Microsoft, SGI, Intel, Sun, HP support...

www.CactusCode.org



Cactus Structure

Core “flesh” with plug-in “thorns”

Plug-In “Thorns”
(modules)

Fortran/C/C++

input/output

interpolation

SOR solver

wave evolvers

multigrid

coordinates

extensible APIs

ANSI C

parameters

scheduling

Core “Flesh”

error handling

make system

grid variables

boundary conditions

Computational
Tools !!

AMR, unigrid,
unstructured

remote steering

Your Physics !!

black holes

equations of state



Cactus Structure

Core “flesh” with plug-in “thorns”

Plug-In “Thorns”
(modules)

Fortran/C/C++

input/output
interpolation

SOR solver

wave evolvers

multigrid

coordinates

extensible APIs

ANSI C

parameters

scheduling

Core “Flesh”

error handling

make system

grid variables

boundary conditions

Abstractions, interfaces:

- Users don't want to write MPI!
- Plug in different AMR, parallel I/O, elliptic solvers

Computational
Tools !!

AMR, unigrid,
unstructured

remote steering

Your Physics !!

black holes

equations of state



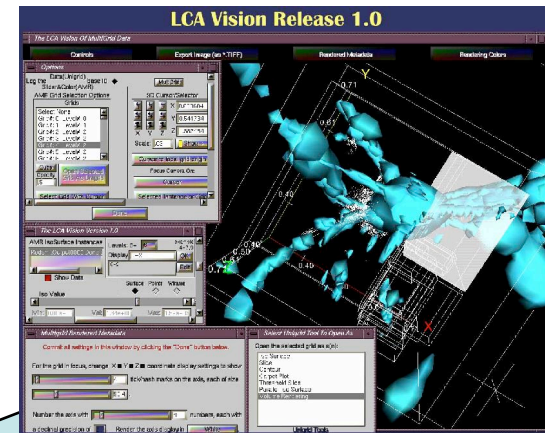
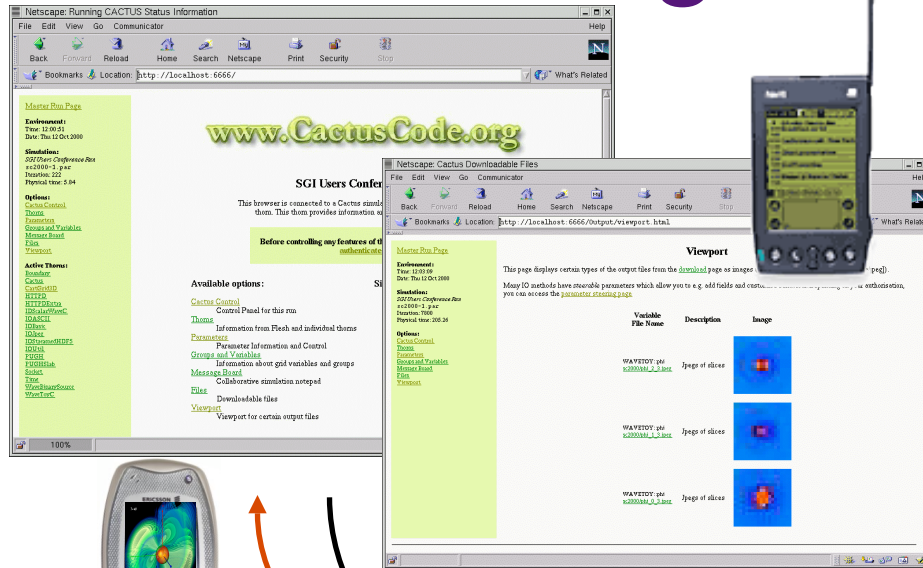
Users and Toolkits

- Many numerical relativity groups around the world
 - Over 100 publications
 - Maya, Whisky, Lazarus, ...
- Others:
 - CFD
 - Quantum Gravity
 - Chemical Engineering
 - Crack Propagation
 - Environmental modeling
 - Plasma physics
 - Computer science
 - Astrophysics
 - Cosmology
 - [Biology/Materials]
- **Toolkits**
 - Cactus Computational Toolkit
 - Einstein Toolkit
 - Many modules
 - *Kranc generates entire Cactus codes from Mathematica: Sascha Husa, AEI, Jena*
 - CFD Toolkit (CCT, KISTI booth)
 - (Biology Toolkit)
- **Teaching**
 - Over 30 student thesis/diploms





Notification, Remote Interactive Viz & Steering

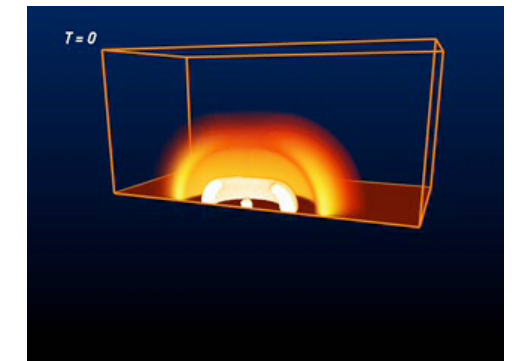
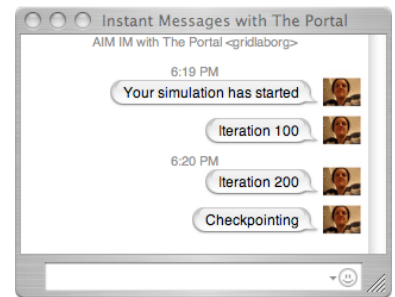
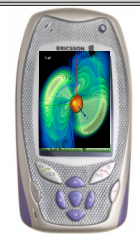


Any Viz Client:
LCA Vision, OpenDX

Changing steerable parameters

- Parameters
- Physics, algorithms
- Performance

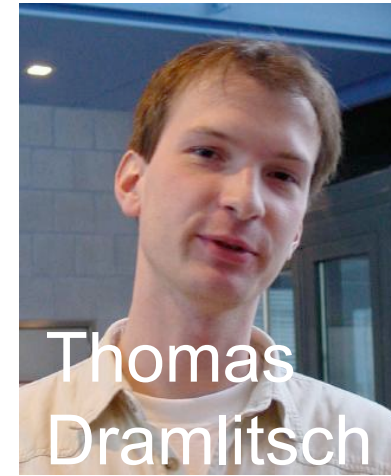
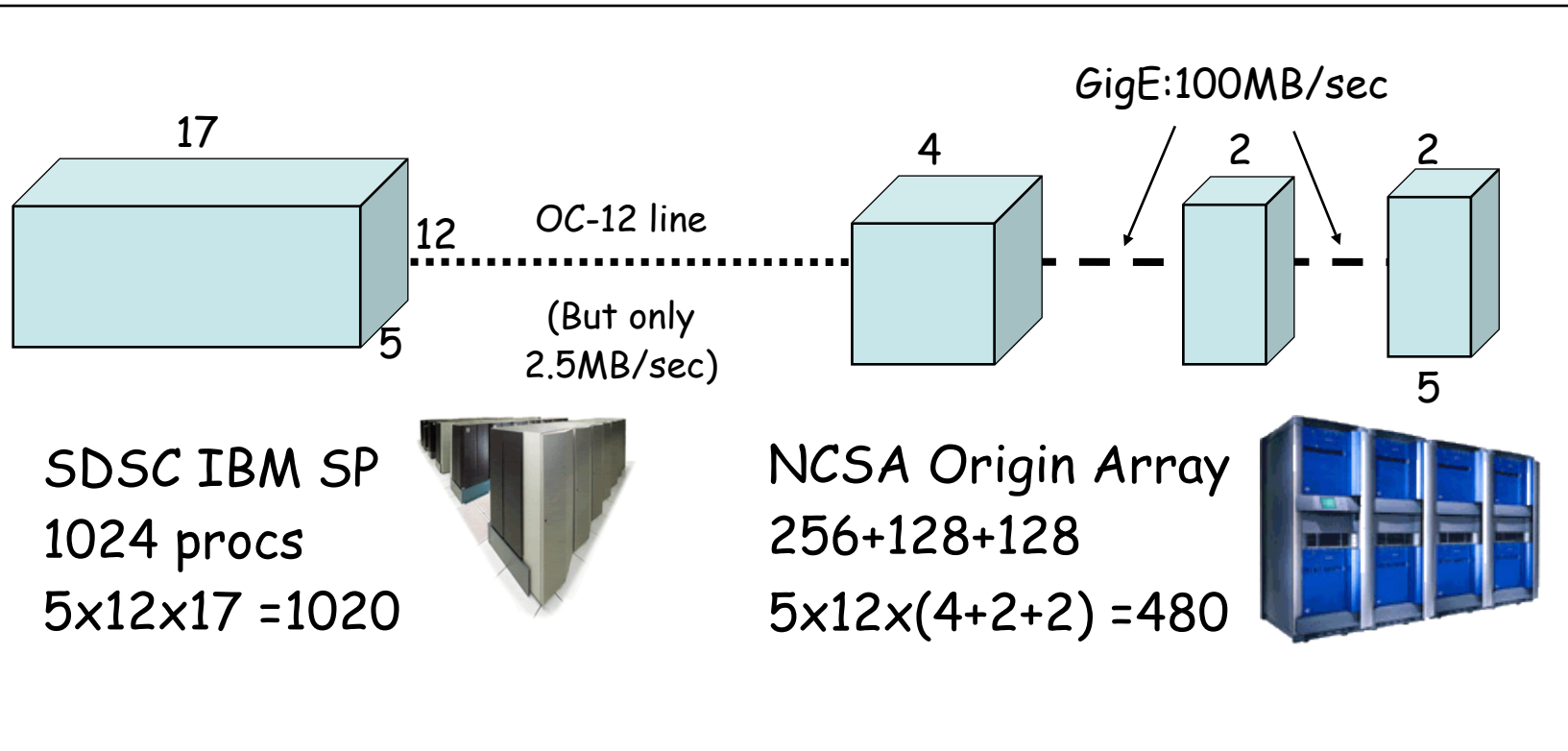
Streaming HDF5
Autodownsample



TiKSL & GriKSL DFN grants at AEI, now EnLIGHTened and other



Grids 1: Dynamic, Adaptive, Distributed Computing



Thomas Dramlitsch



Matei Ripeanu

Cactus + MPICH-G2

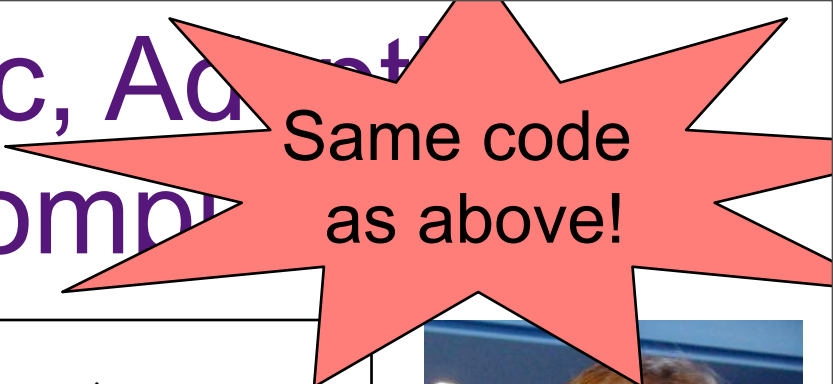
Communications dynamically adapt to application and environment

Any Cactus application. Scaling: 15% -> 85%

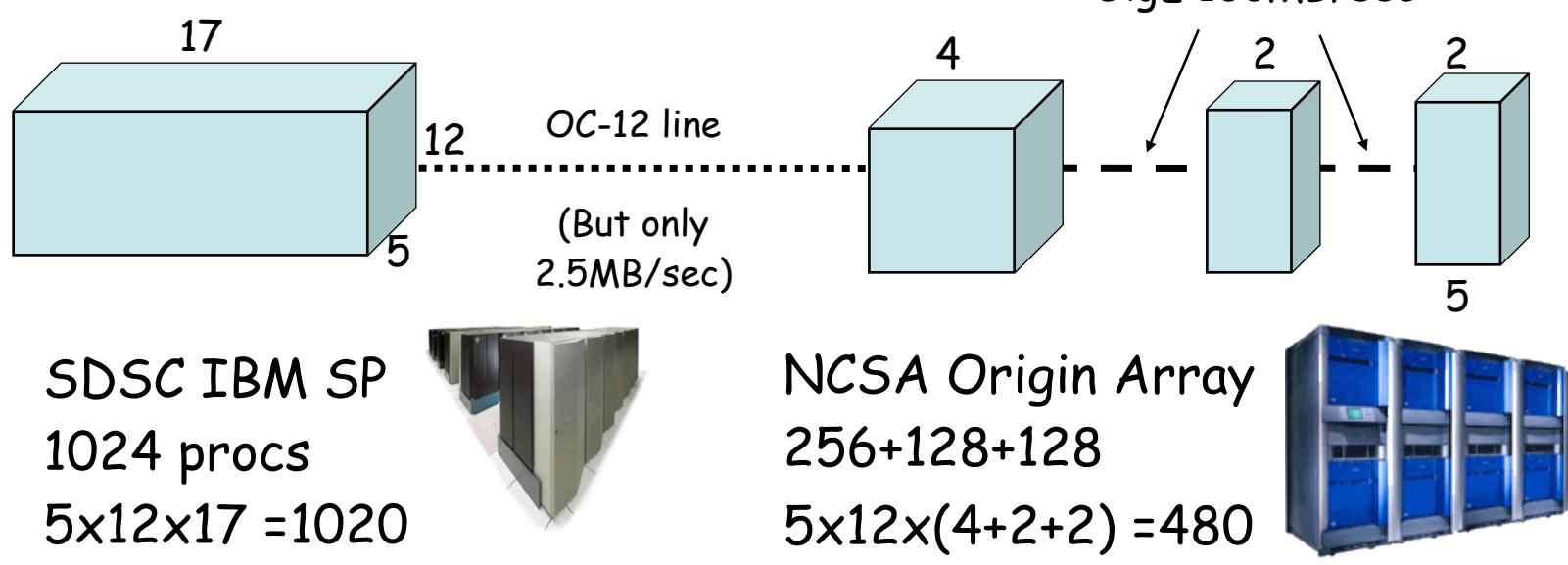
"Gordon Bell Prize" (SC01)



Grids 1: Dynamic, Adaptive Distributed Computation



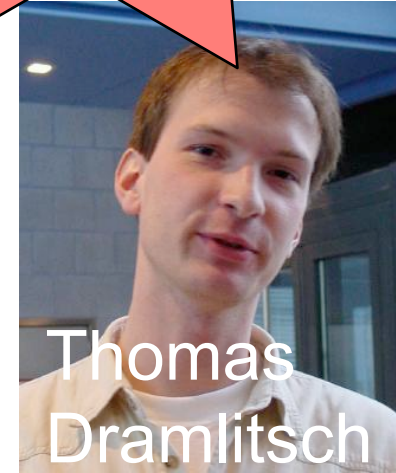
Same code as above!



SDSC IBM SP
1024 procs
 $5 \times 12 \times 17 = 1020$



NCSA Origin Array
 $256 + 128 + 128$
 $5 \times 12 \times (4 + 2 + 2) = 480$



Thomas Dramlitsch



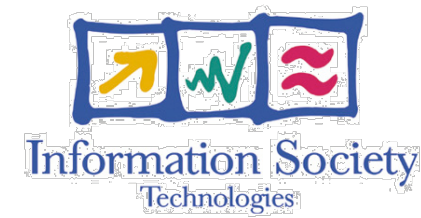
Matei Ripeanu

Cactus + MPICH-G2
Communications dynamically adapt to application and environment
Any Cactus application. Scaling: 15% -> 85%

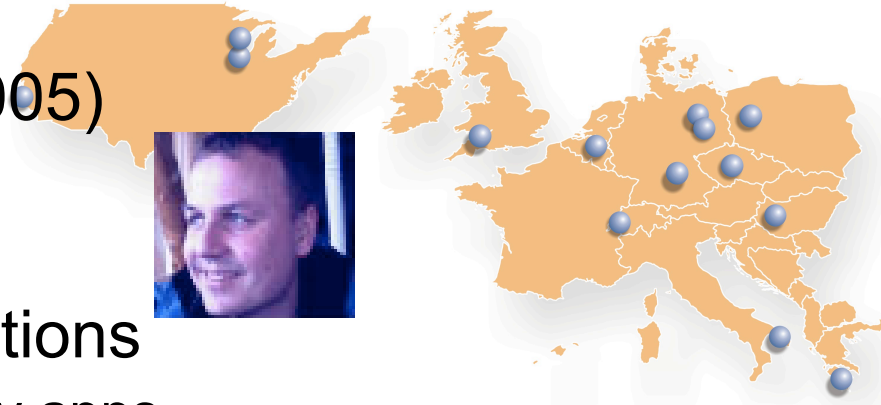
"Gordon Bell Prize" (SC01)



Grids 2: GridLab



- EU 5th Framework (2002-2005)
 - 6 Million Euros
 - Led by Jarek Nabrzyski
- Focused on tools for applications
 - Cactus and numerical relativity apps
 - Gravitational Wave Data Analysis (Triana)
 - Dynamic scenarios: Early DDDAS combine GW + Numrel
- Dynamic grid apps, infrastructure, users all can:
 - Be aware of environment: services, allocation, bandwidth?
 - Decide: migrate, spawn, access data
 - Publish information: what is the app/user doing?
- 12 workpackages, including:
 - Grid services, apps, testbed, **GAT**, **Portals**, brokers, mobile...



PSNC
 AEI
 ZIB
 MASARYK
 SZTAKI
 ISUFI
 Cardiff
 NTUA
 VU
 Chicago
 ISI
 Wisconsin
 Sun
 Compaq

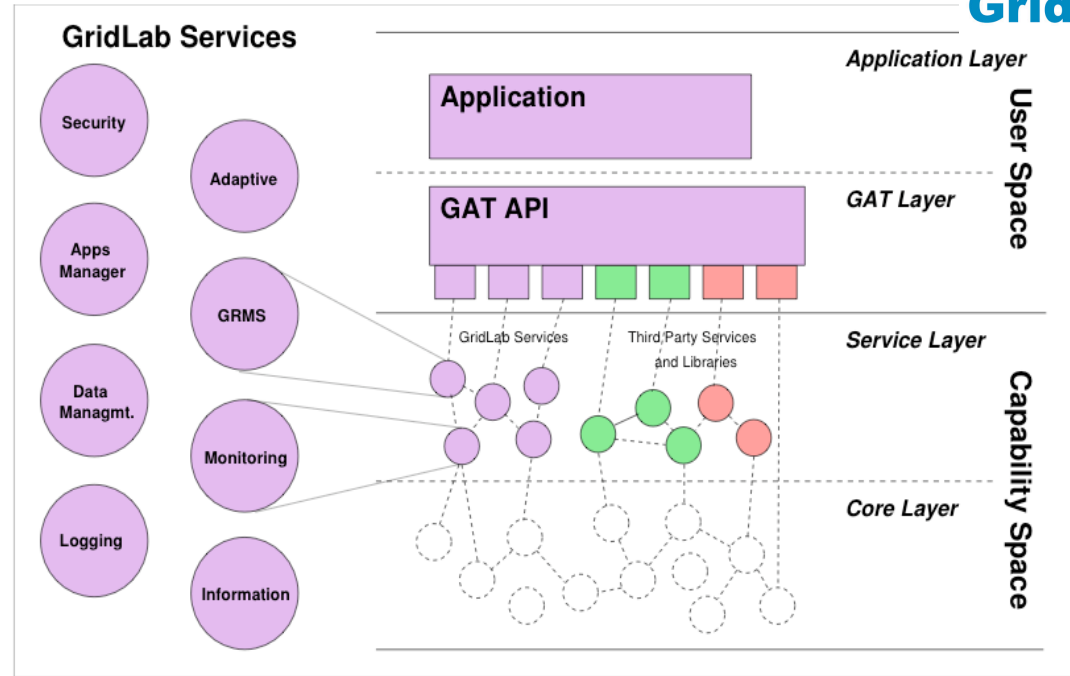
Successful 5th Framework project --- came from GR, Cactus, other EU projects, early Globus work



Grid Application Toolkit & SAGA



- Abstract programming interface between apps and Grid services: “Cactus for Grid”. Adaptors! App runs everywhere with same code
- Designed for what apps need (move file, run remote task, migrate, write to remote file)
- Motivated by numerical relativity
- GAT led to OGF Working Group to develop a “Simple API for Grid Applications” or SAGA
 - Focus on scientific and engineering applications, simplicity
 - Better API based on use case studies
- **SAGA is centerpiece for OGF at application level**
 - 60-day comment period now for specification
- OMII calling for proposals to implement SAGA
- C++ implementation at LSU ongoing



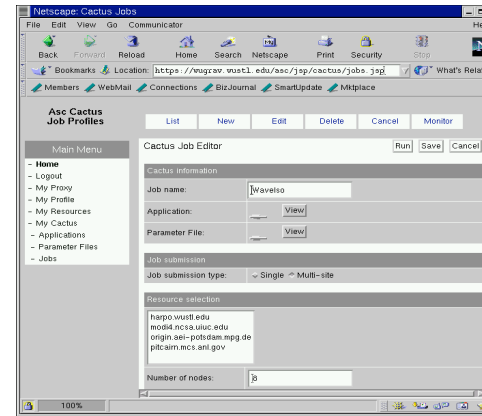


GridSphere



Information Society
Technologies

- GridSphere portal framework, developed in GridLab at AEI
 - Origins in '92 relativity workbench, NSF ASC project
- Generic JSR 168 compliant portlet container
- Architecture for “pluggable” web applications
- Core portlets, Grid Portlets, Cactus Portlets, D-Grid, LSU projects
- Over 250 subscribed to user mail list, around 500 unique web visits/month



 powered by gridsphere



Michael
Russell,
PSNC



Oliver
Wehrens,
AEI, LSU



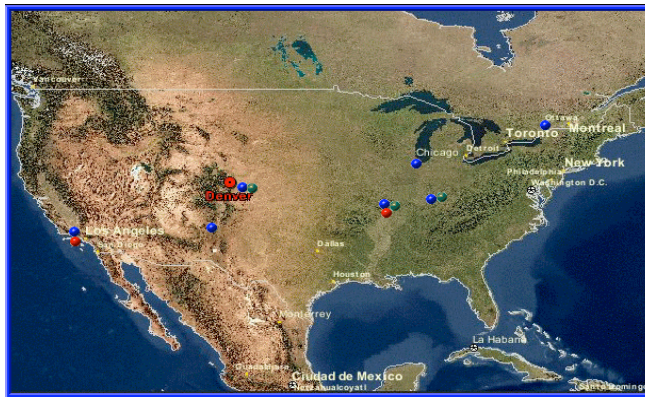
Jason
Novotny,
SDSC



Return to Future: Properly Engineered Software

Task Farming, Spawning & Migration combined

Main Cactus BH Simulation starts in Berkeley

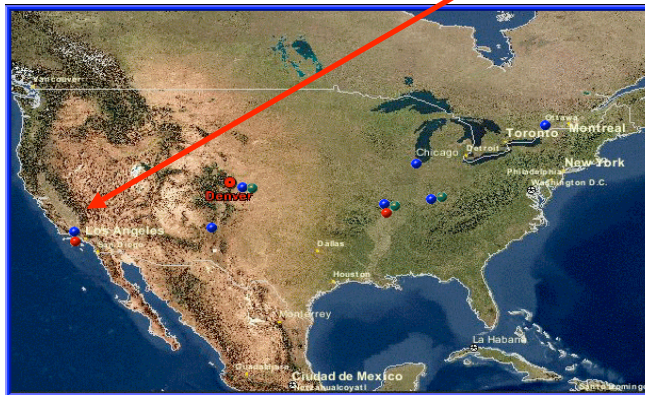
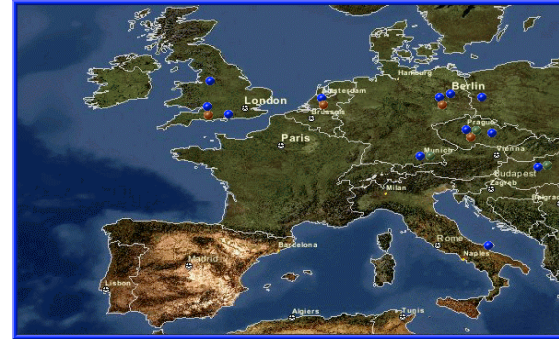




Return to Future: Properly Engineered Software

Task Farming, Spawning & Migration combined

Main Cactus BH Simulation starts in Berkeley

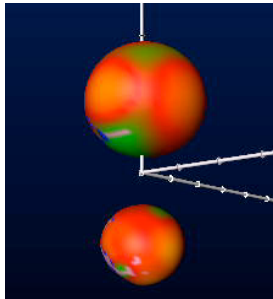




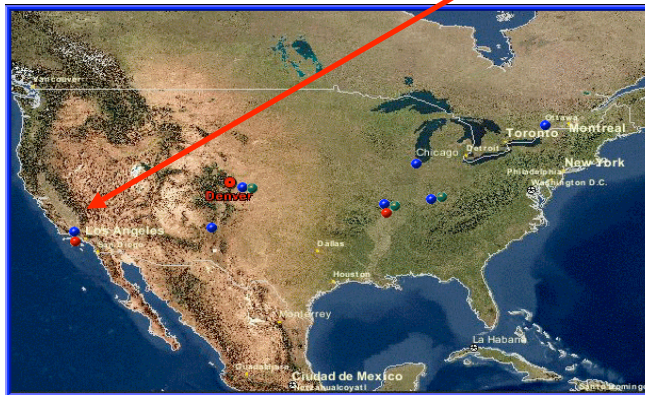
Return to Future: Properly Engineered Software

Task Farming, Spawning & Migration combined

All analysis tasks spawned automatically
to free resources worldwide



Main Cactus BH Simulation
starts in Berkeley

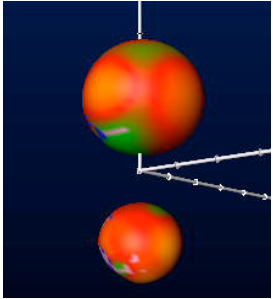




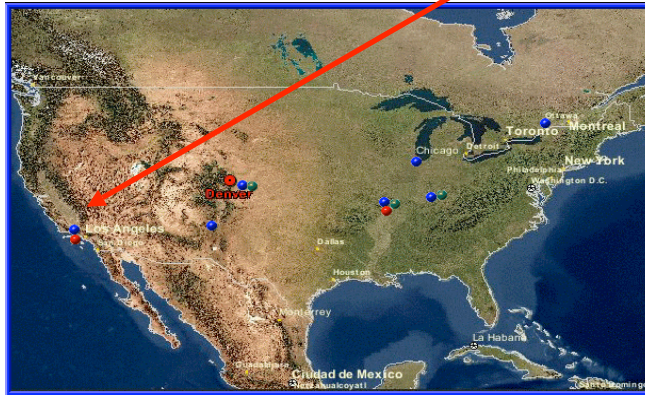
Return to Future: Properly Engineered Software

Task Farming, Spawning & Migration combined

All analysis tasks spawned automatically
to free resources worldwide



Main Cactus BH Simulation
starts in Berkeley



Dozens of small jobs sent
out to test parameters

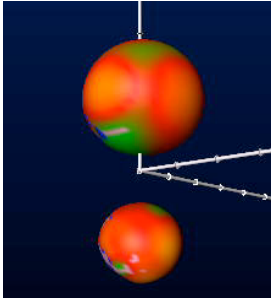




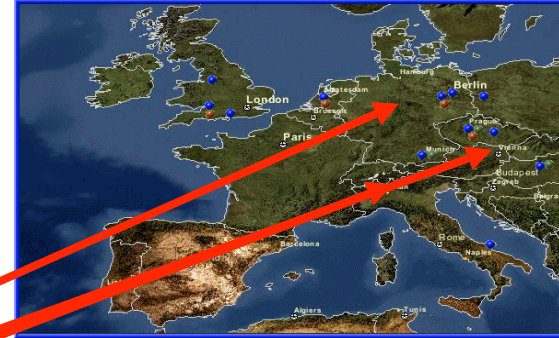
Return to Future: Properly Engineered Software

Task Farming, Spawning & Migration combined

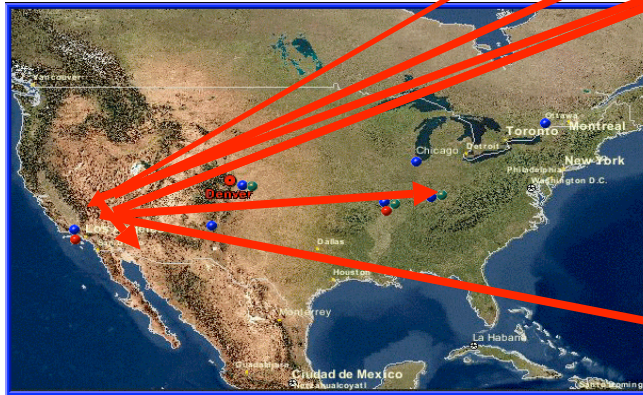
All analysis tasks spawned automatically
to free resources worldwide



Main Cactus BH Simulation
starts in Berkeley



Dozens of small jobs sent
out to test parameters

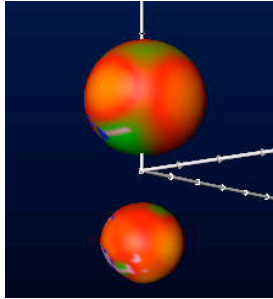




Return to Future: Properly Engineered Software

Task Farming, Spawning & Migration combined

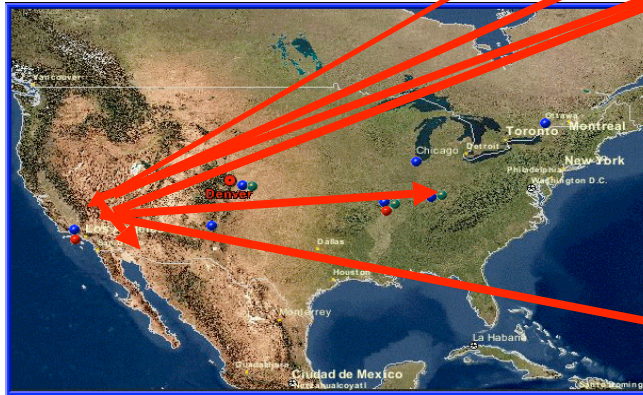
All analysis tasks spawned automatically
to free resources worldwide



Main Cactus BH Simulation
starts in Berkeley



Dozens of small jobs sent
out to test parameters



Data returned for main job

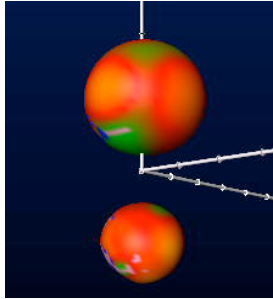




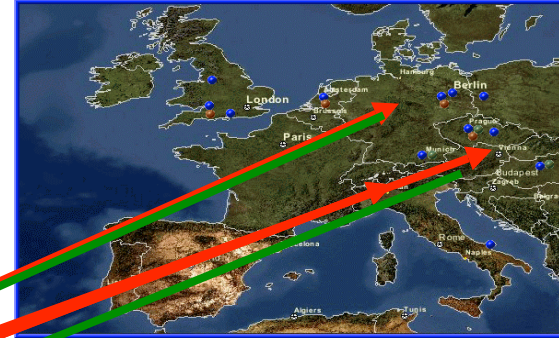
Return to Future: Properly Engineered Software

Task Farming, Spawning & Migration combined

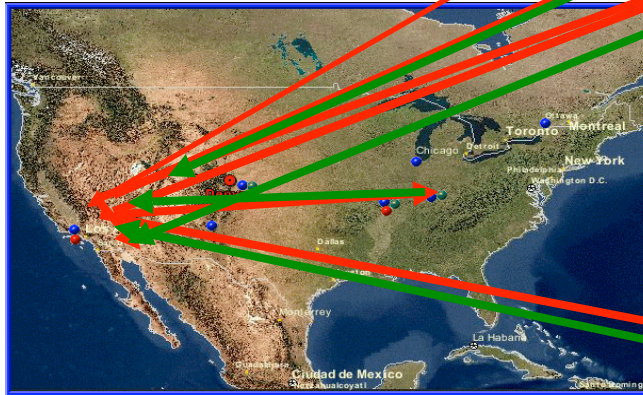
All analysis tasks spawned automatically
to free resources worldwide



Main Cactus BH Simulation
starts in Berkeley



Dozens of small jobs sent
out to test parameters



Data returned for main job

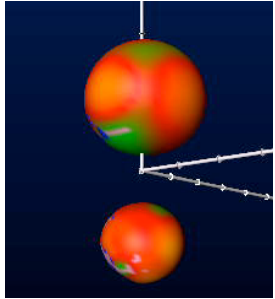




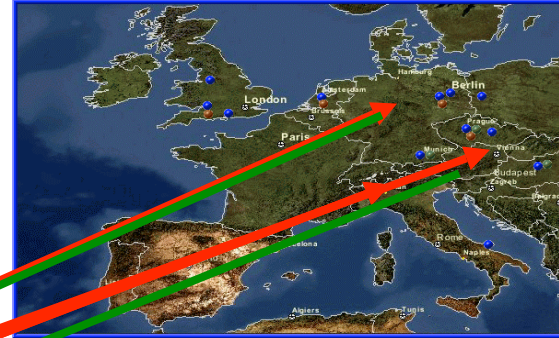
Return to Future: Properly Engineered Software

Task Farming, Spawning & Migration combined

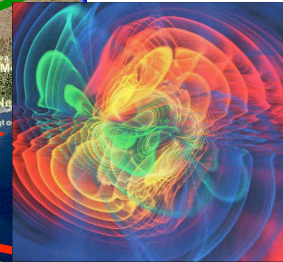
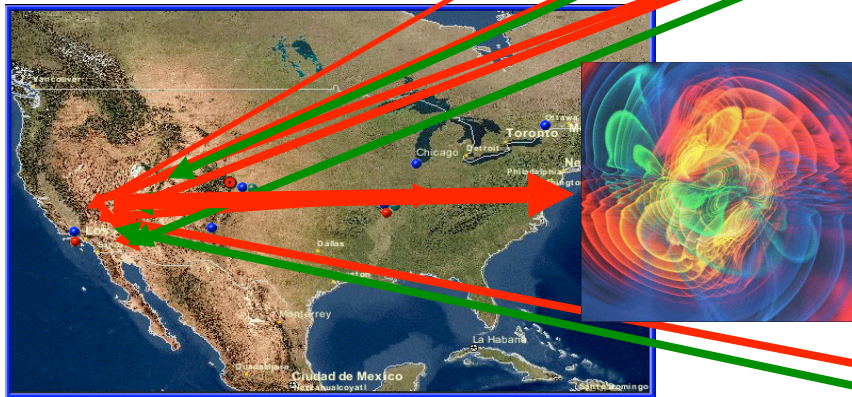
All analysis tasks spawned automatically
to free resources worldwide



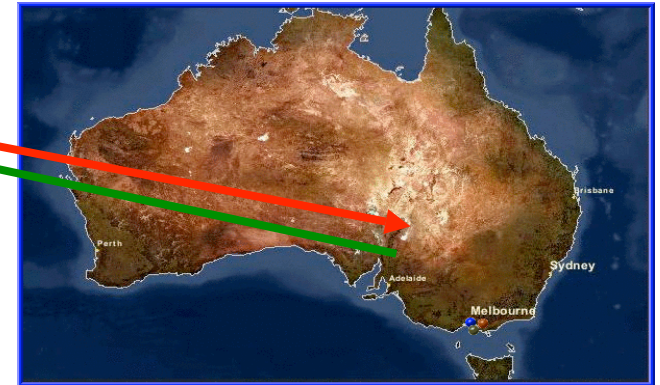
Main Cactus BH Simulation
starts in Berkeley



Dozens of small jobs sent
out to test parameters



Data returned for main job



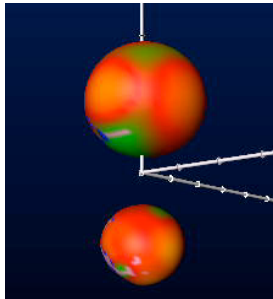
Huge job generates remote data to be
visualized in Baltimore



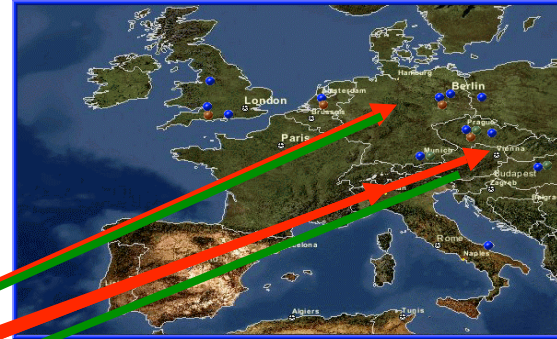
Return to Future: Properly Engineered Software

Task Farming, Spawning & Migration combined

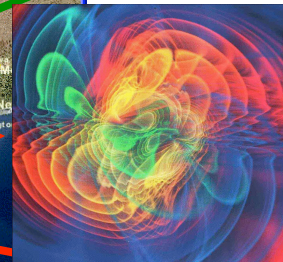
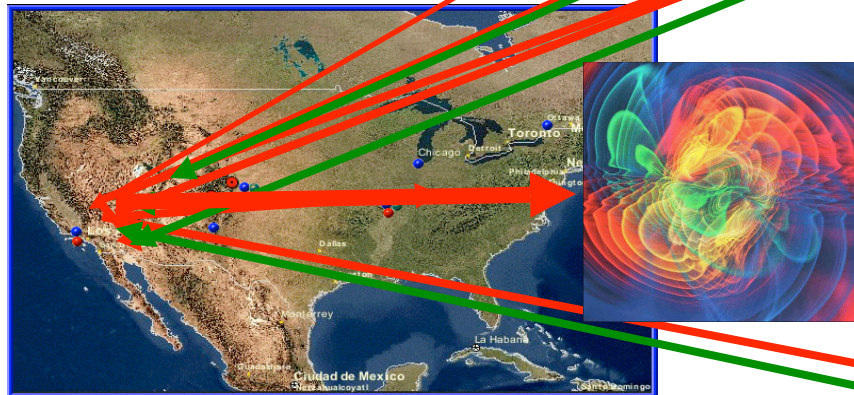
All analysis tasks spawned automatically
to free resources worldwide



Main Cactus BH Simulation
starts in Berkeley



Dozens of small jobs sent
out to test parameters



Data returned for main job

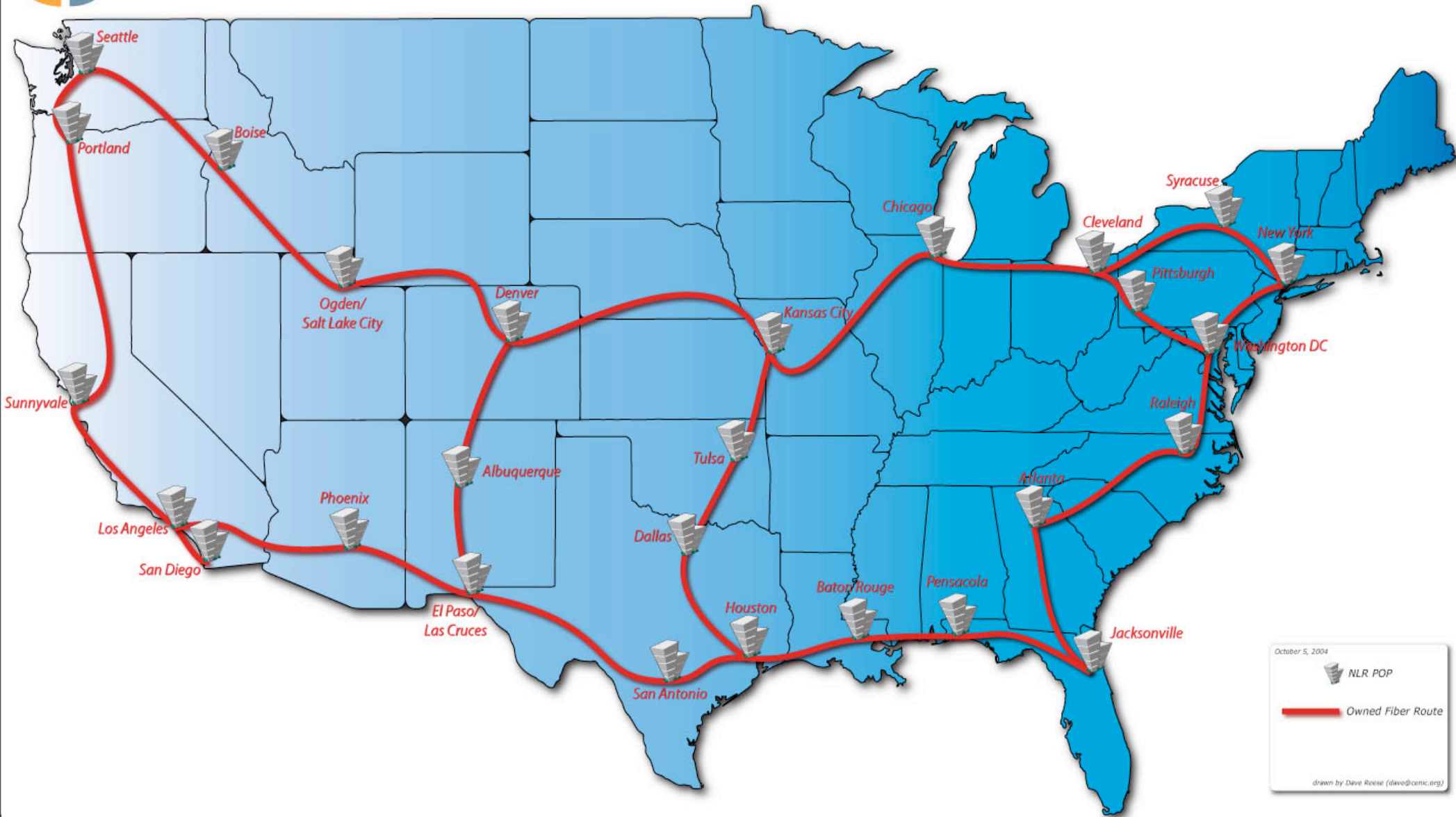


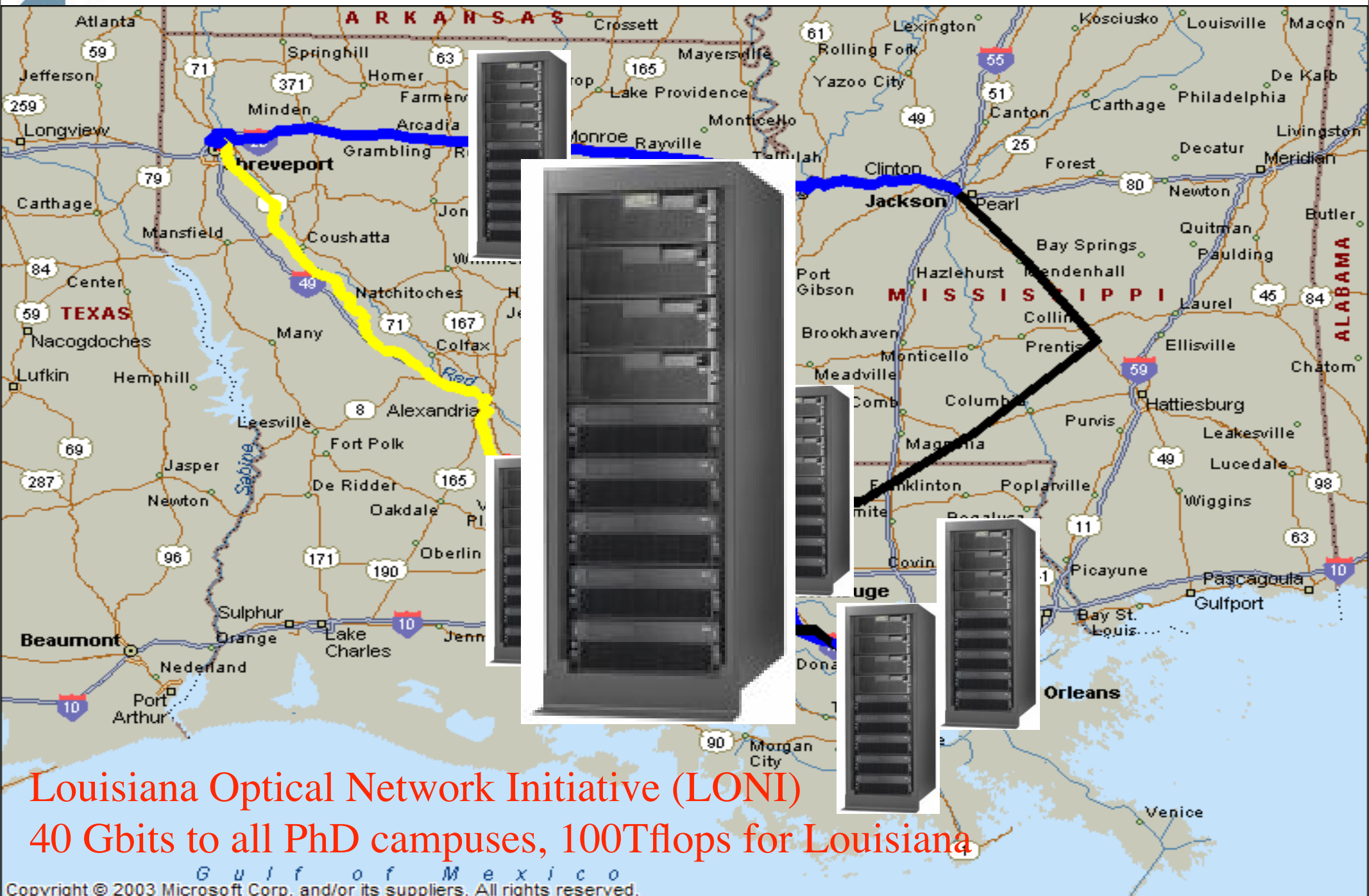
Huge job generates remote data to be
visualized in Baltimore

Physics code to do all this can be
generated via symbolic algebra!



National LambdaRail Architecture





Louisiana Optical Network Initiative (LONI)
40 Gbits to all PhD campuses, 100Tflops for Louisiana

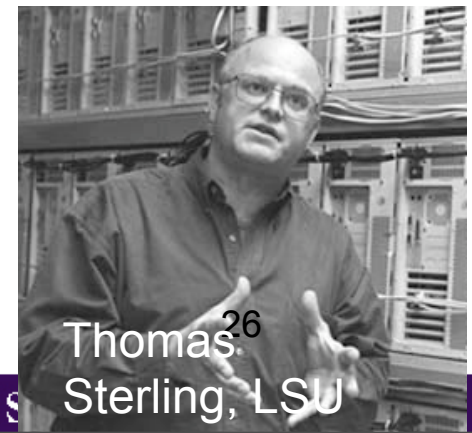
Gulf of Mexico



Optical Nets Enable Old & New Paradigms

Huge BH simulation, outputs ~TBs data, must be interactively viz'd & analyzed by international collaboration

- Many practical problems found above go away!
- New Distributed Computing, Data, and Viz Services
 - Data larger than memory, disk slow: multiple streaming data servers
 - Co-scheduling machines, data, and network for single event: MacLaren HARC
 - Lambda Provisioning: Karmous-Edwards EnLIGHTened NSF project
 - Same application must work with multiple nets, services: GAT/SAGA
- High Resolution: not science w/o details, analysis
 - Uncompressed HD stream: near latency-free remote viz at 1.5Gbit/sec
 - Video for colleagues: see details, read equations
 - Sterling HPC class: from LSU but LA, AR, Brno (Czech)



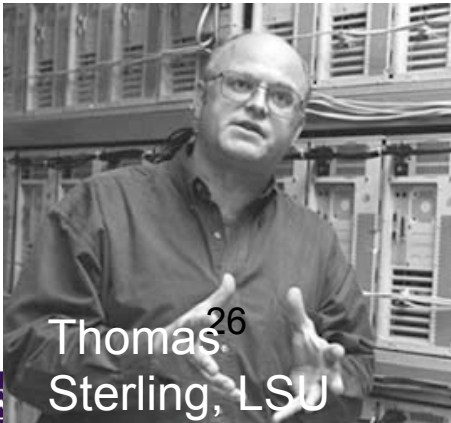
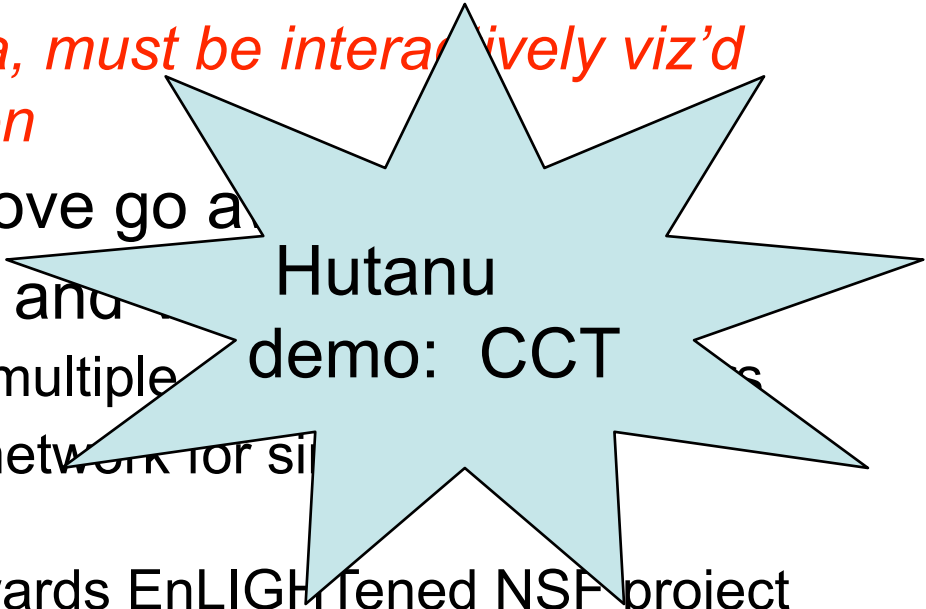
Thomas²⁶
Sterling, LSU



Optical Nets Enable Old & New Paradigms

Huge BH simulation, outputs ~TBs data, must be interactively viz'd & analyzed by international collaboration

- Many practical problems found above go a
- New Distributed Computing, Data, and
 - Data larger than memory, disk slow: multiple
 - Co-scheduling machines, data, and network for sil
MacLaren HARC
 - Lambda Provisioning: Karmous-Edwards EnLIGHTened NSF project
 - Same application must work with multiple nets, services: GAT/SAGA
- High Resolution: not science w/o details, analysis
 - Uncompressed HD stream: near latency-free remote viz at 1.5Gbit/sec
 - Video for colleagues: see details, read equations
 - Sterling HPC class: from LSU but LA, AR, Brno (Czech)

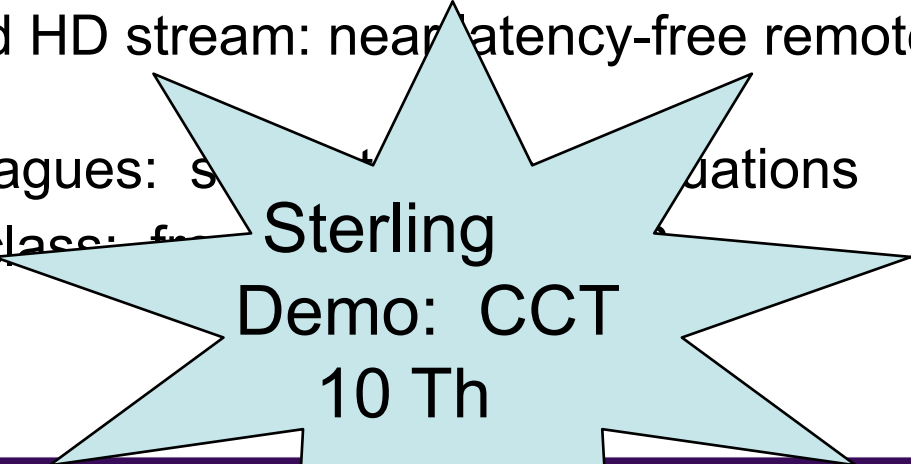
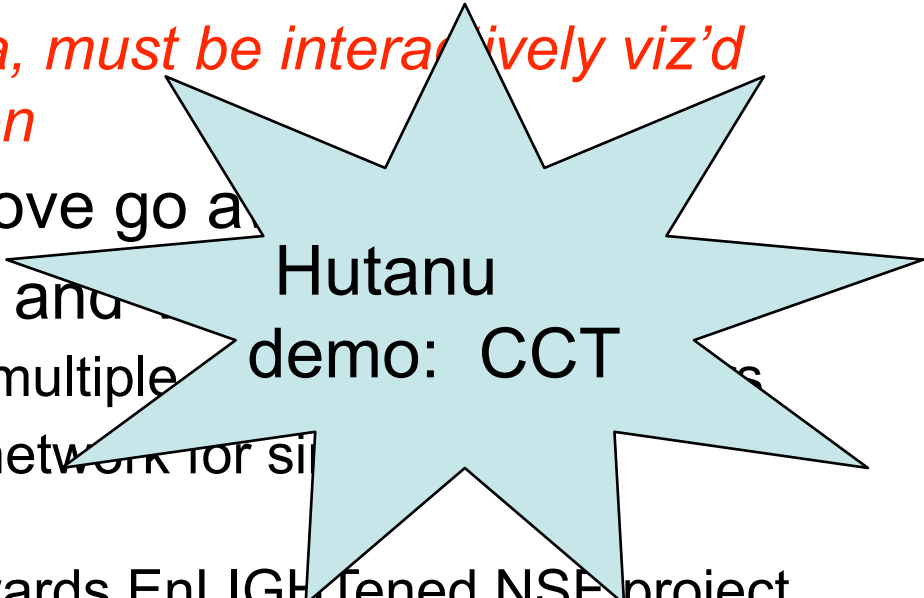




Optical Nets Enable Old & New Paradigms

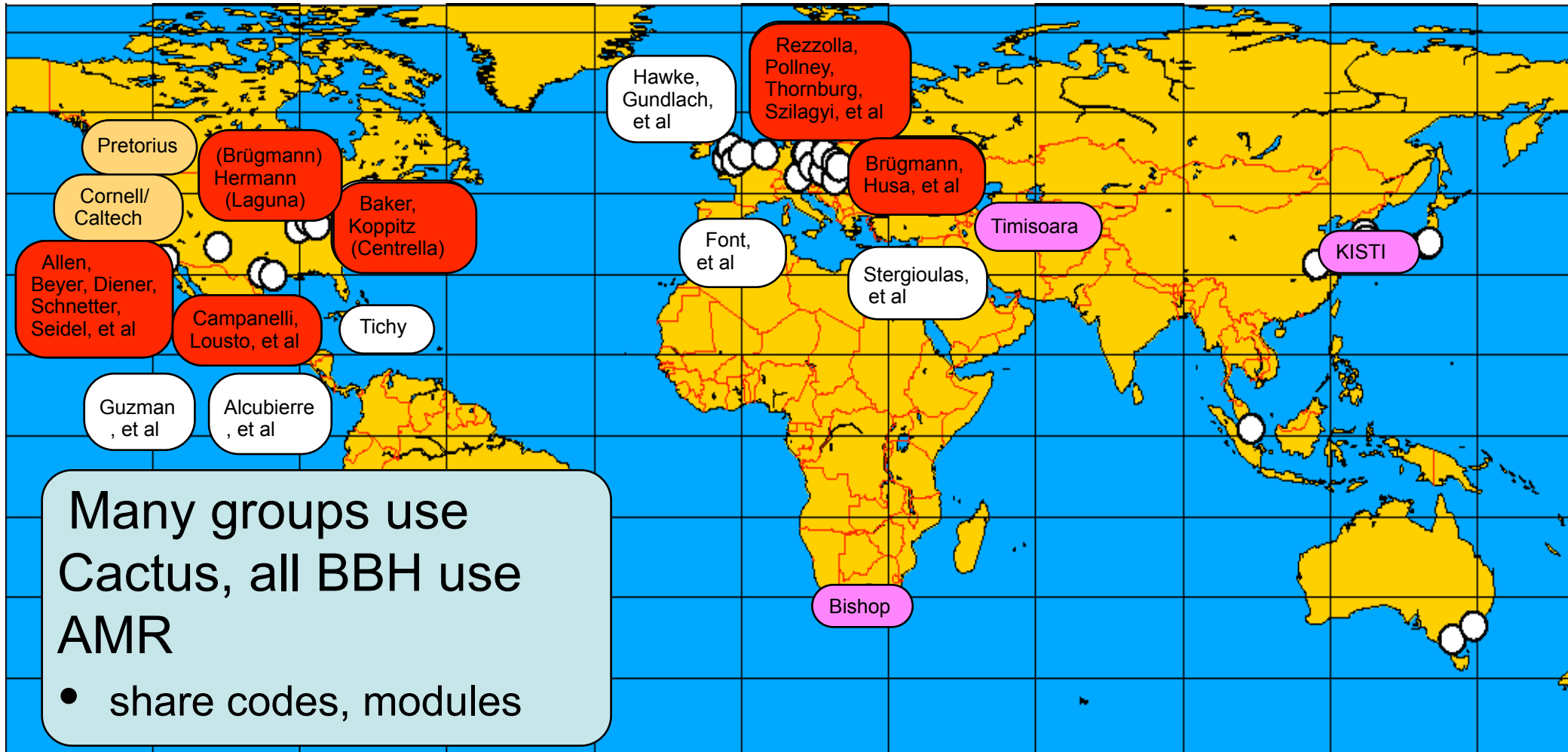
Huge BH simulation, outputs ~TBs data, must be interactively viz'd & analyzed by international collaboration

- Many practical problems found above go a
- New Distributed Computing, Data, and
 - Data larger than memory, disk slow: multiple
 - Co-scheduling machines, data, and network for sil
 - Lambda Provisioning: Karmous-Edwards EnLIGHTened NSF project
 - Same application must work with multiple nets, services: GAT/SAGA
- High Resolution: not science w/o details, analysis



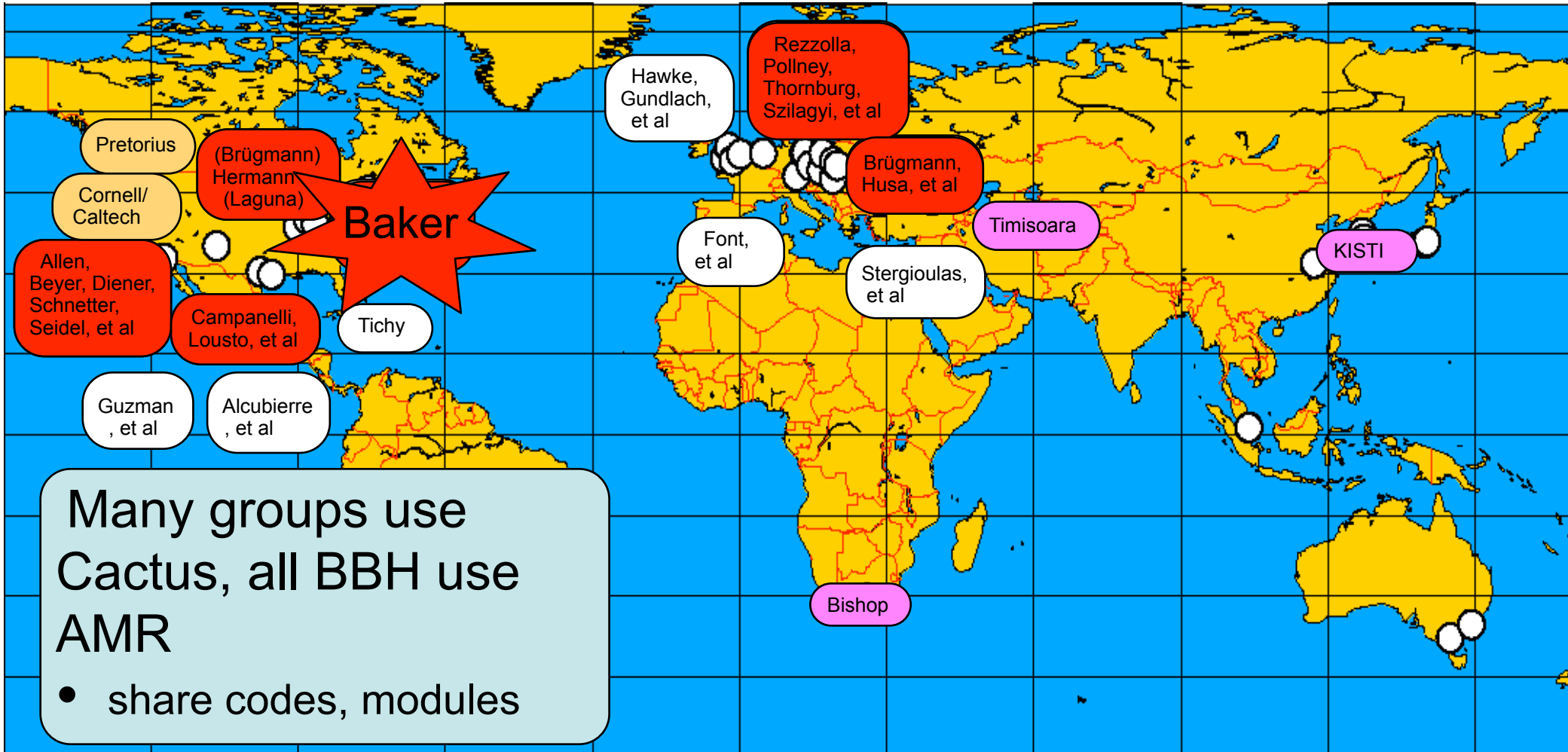


Current Major Numerical Relativity Efforts in Binary BH, NS, SN





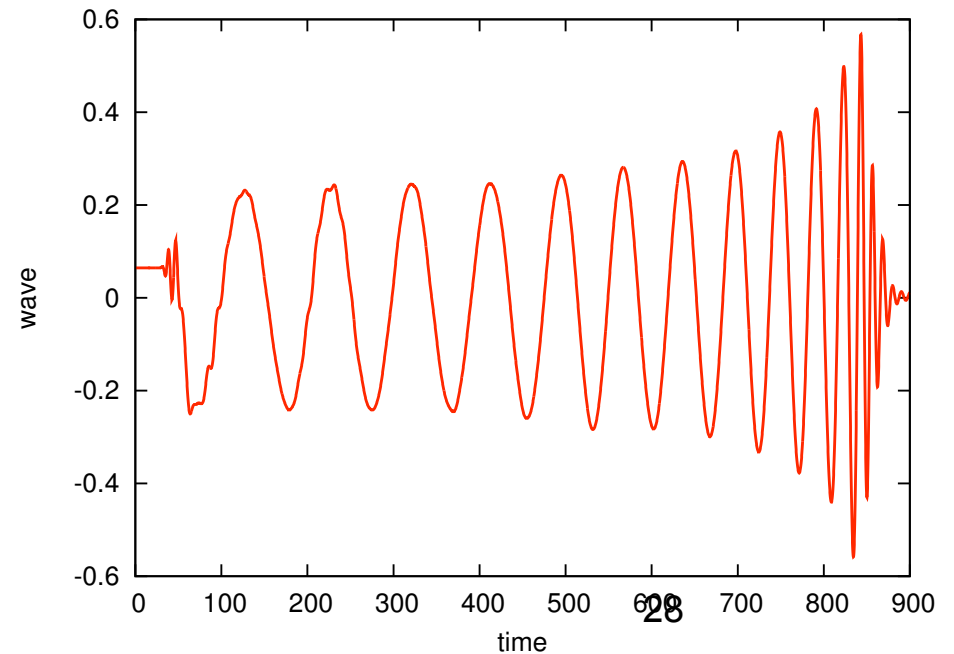
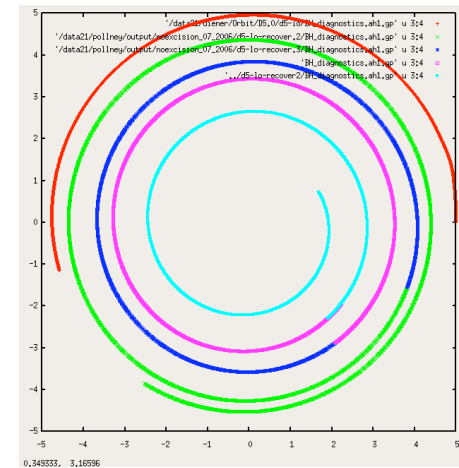
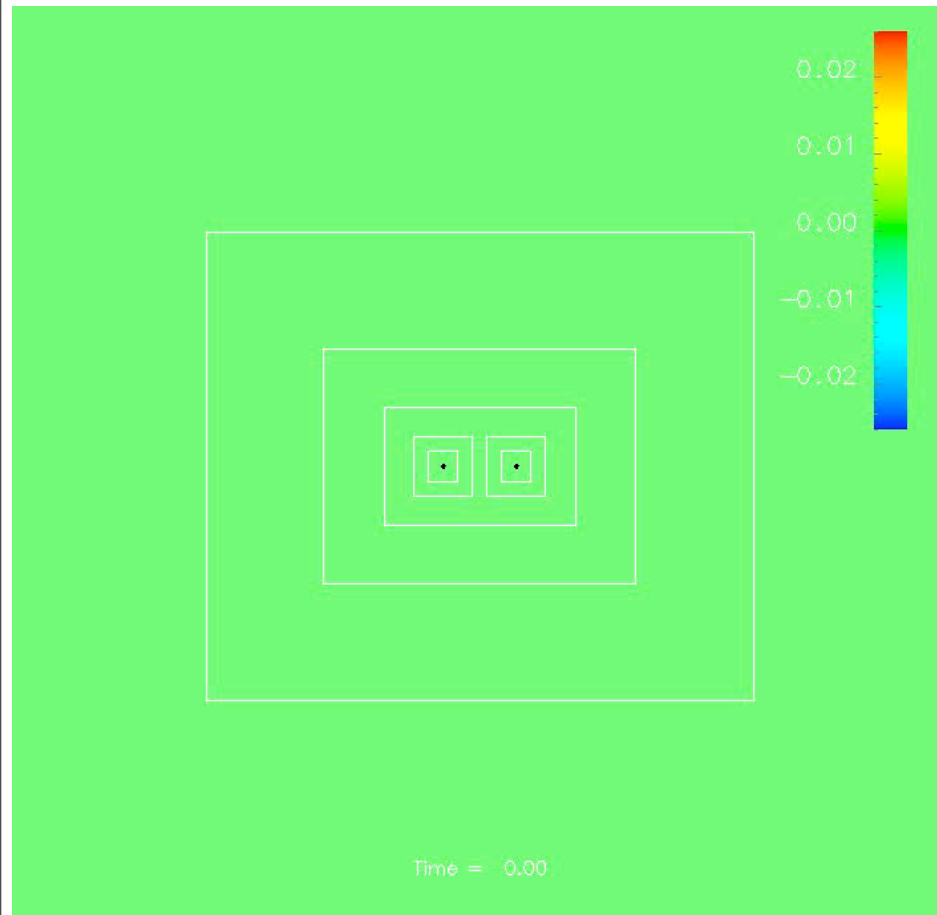
Current Major Numerical Relativity Efforts in Binary BH, NS, SN





State of Art Black Hole Binaries

Many groups orbiting BHs!



Peter Diener, LSU

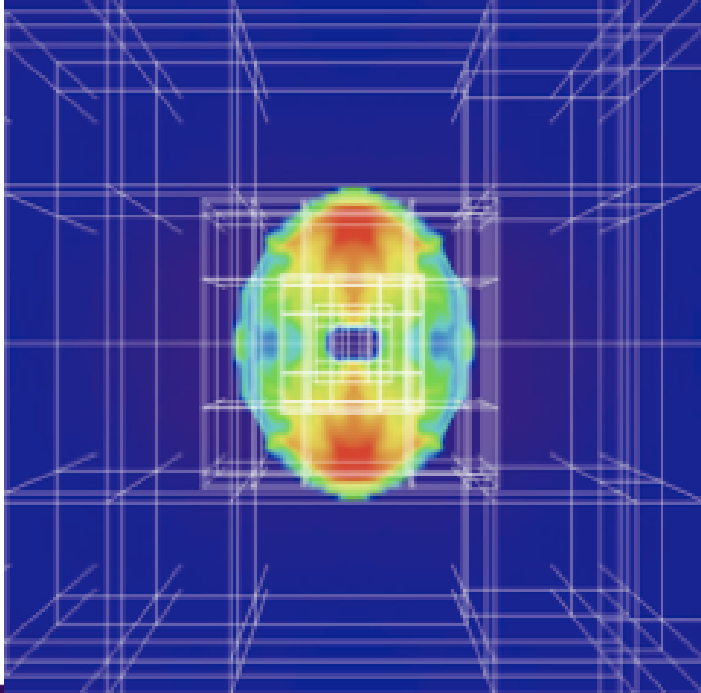


Full GR Iron Core Collapse

Connecting Numerical Relativity with Supernova Theory

- Cactus 3D refined grid with Carpet AMR driver & 9 refinement levels
 - Resolves entire pre-collapse core (~3000 km) and final proto-neutron star (~30km)
 - Whisky GR Hydro code developed by AEI, Southampton, Trieste, Valencia, Thessaloniki collaboration
 - Microphysics

Christian Ott, AEI & U. Arizona



- Closing in on Holy Grail of 3D GR core-collapse simulations
- First consistent 3D GR core-collapse of rotating iron cores
- Cores stay very axisymmetric until “bounce”, then waves boosted by GR

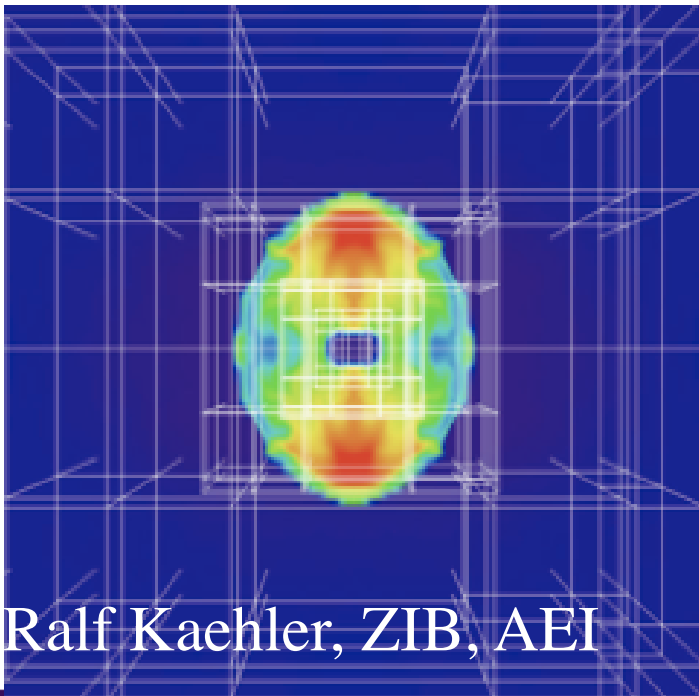


Full GR Iron Core Collapse

Connecting Numerical Relativity with Supernova Theory

- Cactus 3D refined grid with Carpet AMR driver & 9 refinement levels
 - Resolves entire pre-collapse core (~3000 km) and final proto-neutron star (~30km)
 - Whisky GR Hydro code developed by AEI, Southampton, Trieste, Valencia, Thessaloniki collaboration
 - Microphysics

Christian Ott, AEI & U. Arizona



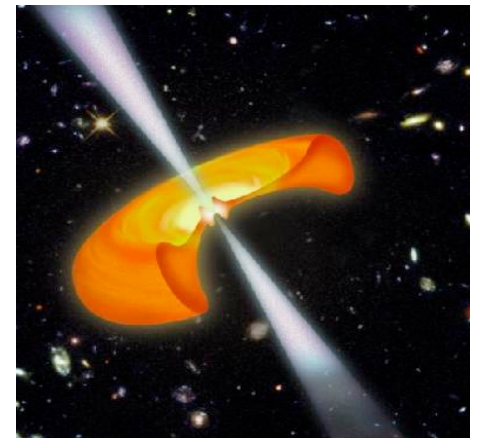
Ralf Kaehler, ZIB, AEI

- Closing in on Holy Grail of 3D GR core-collapse simulations
- First consistent 3D GR core-collapse of rotating iron cores
- Cores stay very axisymmetric until “bounce”, then waves boosted by GR



Relativistic Astrophysics in 2010

- Full 3D GR simulations of binary systems for dozens or orbits and merger to final black hole
 - All combinations of black holes, neutron stars, and exotic objects like boson stars, quark stars, strange stars
 - Full 3D GR simulations of core collapse, supernova explosions, accretion onto NS, BH
 - Gamma-ray bursts
- All likely to be observed by LIGO, GEO, Virgo
- Resolve from 10,000 km down to 100 m on a domain of 1,000,000 km³ for 100 secs of physical time
 - ~20Kflops per gridpoint, ~500 grid functions
 - 16 levels of refinement
 - Weeks on Pflops/sec sustained performance
 - 100 TB memory (size of checkpoint file needed)
 - PBytes storage for full analysis of output





Petascale Challenges for GR (*Scary*)

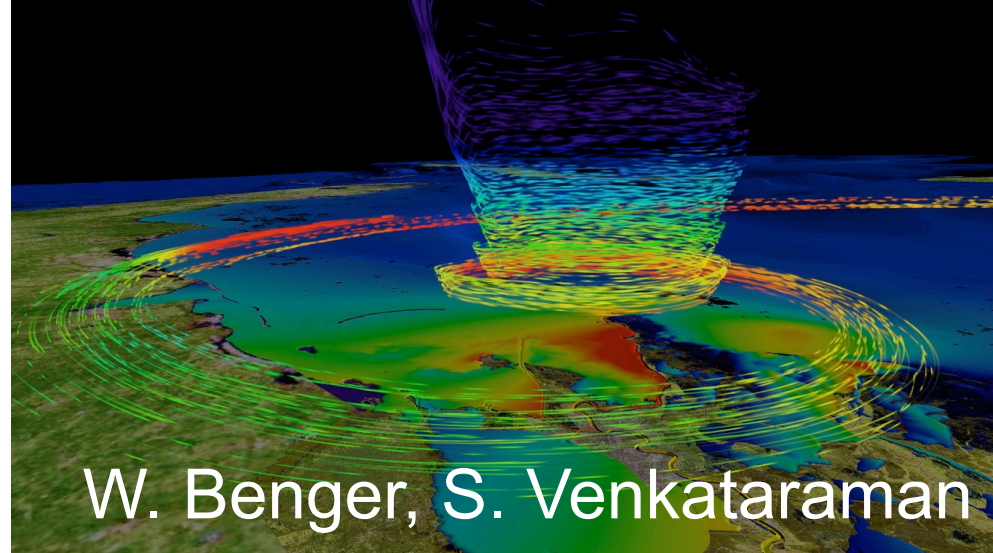
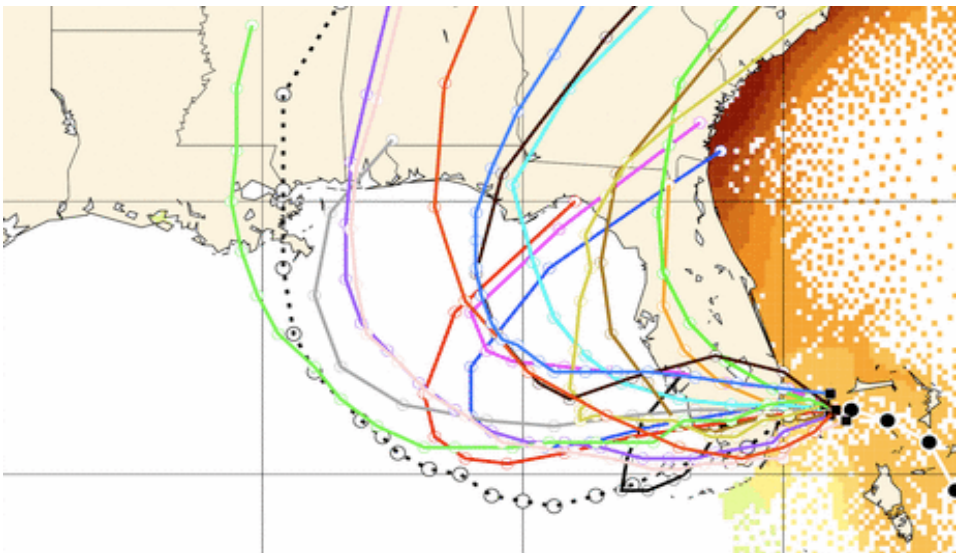
- Basic numerical algorithms in place (new!)
 - Dozens of groups compute GR, share common tools for petascale
- Most AMR codes scale to ~ 64 processors, but petascale machine will have 500K processors!
 - Serious work to do on scaling, dynamic loadbalancing, fault tolerance, software environments, debugging tools
- Consider novel ways to break up jobs
 - Farming off non-parallelizable analysis tasks, viz, coupling codes, spawning, integrating with data analysis
 - Consider petascale machine as your grid!
- Handling all the data: storing, retrieving, visualizing, analyzing. Lambda provisioning for steering, migration, viz
- Parameter space! Metadata to describe 10^{6+} simulations



Ideas Apply to Coastal Modeling



- Event driven computing: GWs detected, hurricane coming, etc!
- Respond to data, observation, computational resources: DDDAS
 - Use computer simulations to model winds and water: surge and waves, farm on grid, couple models, data acquisition, ensembles, invoke new algorithms
- Need to have lots of CPUs ready to go!
- Where should we evacuate? Where should we rebuild?



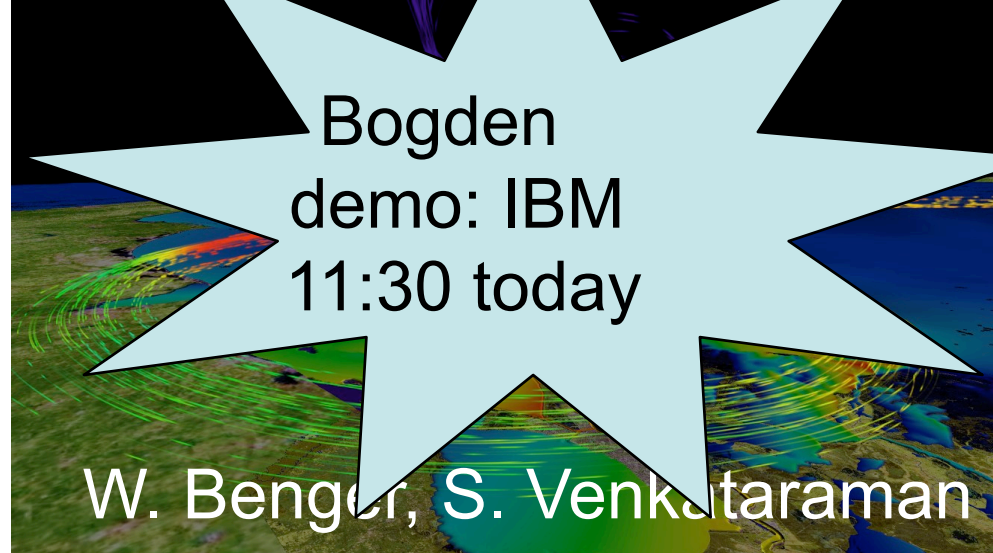
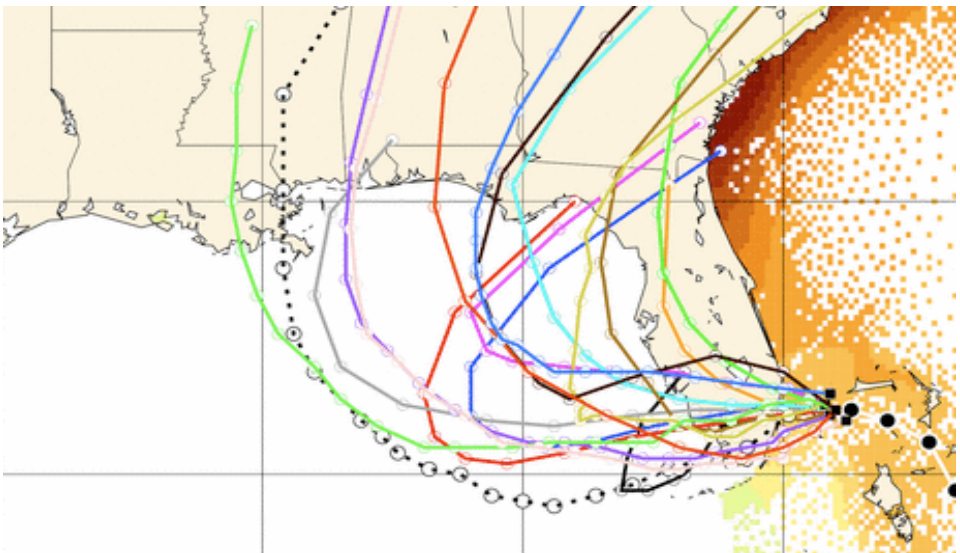
W. Benger, S. Venkataraman



Ideas Apply to Coastal Modeling



- Event driven computing: GWs detected, hurricane coming, etc!
- Respond to data, observation, computational resources: DDDAS
 - Use computer simulations to model winds and water: surge and waves, farm on grid, couple models, data acquisition, ensembles, invoke new algorithms
- Need to have lots of CPUs ready to go!
- Where should we evacuate? Where should we rebuild?



Bogden
demo: IBM
11:30 today

W. Benger, S. Venkataraman



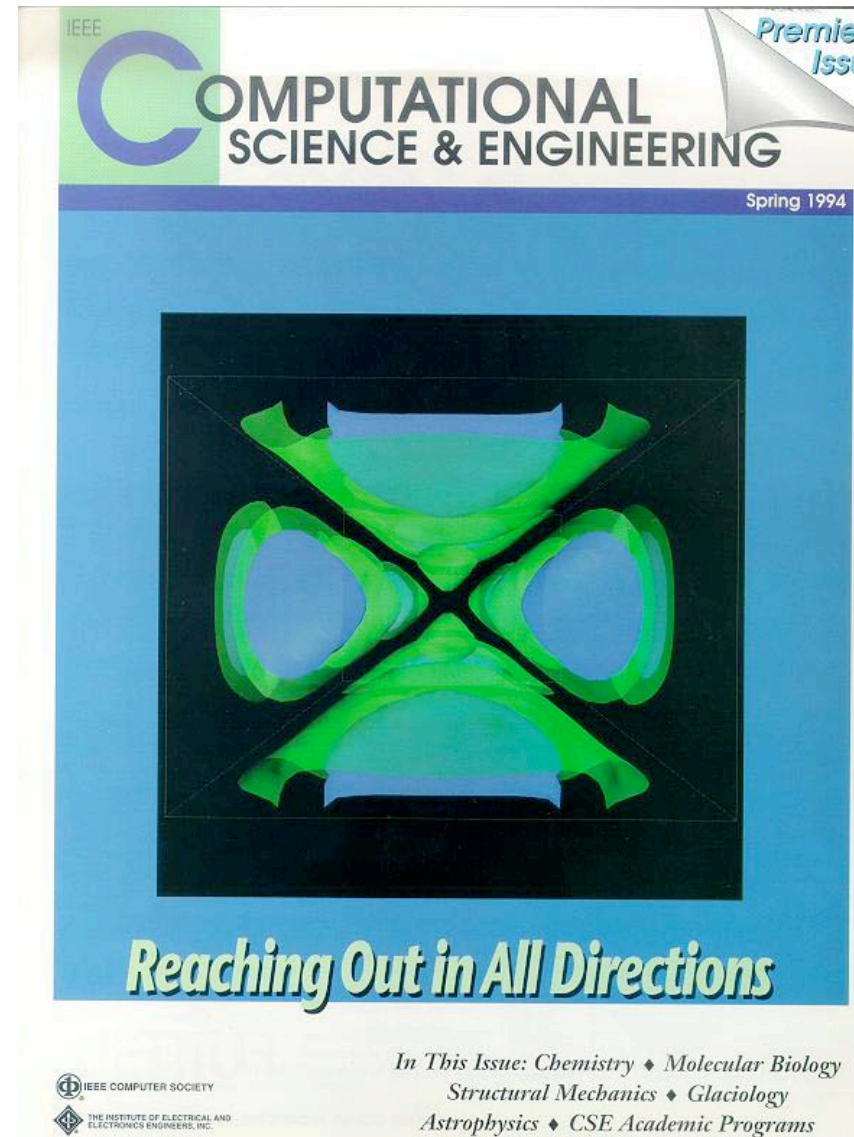
Lessons Learned for Future

- Be creative: “Imagination is more important than knowledge.” Albert E.
- Petascale machines
 - 500K processors is a universe unto itself
 - Consider not just scaling, but code-coupling, spawning, data integration, DDDAS ideas
- Abstractions are critical for
 - application scientists, computer scientists
 - collaborations
- Scientists, hardware, software, technology groups need to work together



Summary

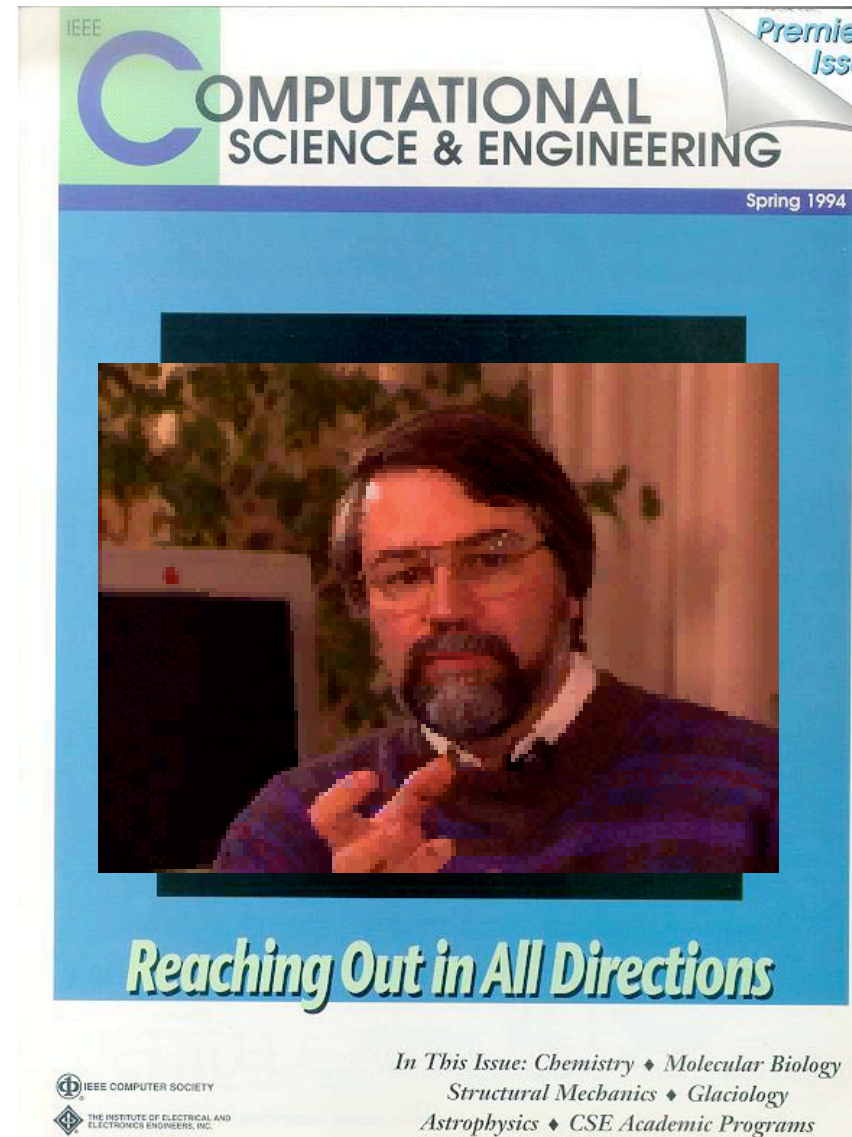
- Major breakthroughs in numerical relativity
- Einstein's impact on HPC, computational science is huge!
 - Will be for years
- Numerical relativity has reached a new stage of maturity
 - Where CFD was decades ago
 - New era: Suddenly many groups capable of solving EEs!
 - Sharing software
- Many new challenges at petascale
- Look forward to tackling them with you!





Summary

- Major breakthroughs in numerical relativity
- Einstein's impact on HPC, computational science is huge!
 - Will be for years
- Numerical relativity has reached a new stage of maturity
 - Where CFD was decades ago
 - New era: Suddenly many groups capable of solving EEs!
 - Sharing software
- Many new challenges at petascale
- Look forward to tackling them with you!





Thanks

- NCSA & environs
 - Larry Smarr, Paul Walker, Joan Massó, John Shalf, Wai-Mo Suen (WashU), Ian Foster (ANL/UC)
- AEI, ZIB, RZG
 - Gabrielle Allen, Werner Benger, Thomas Damlitsch, Tom Goodale, Ralf Kaehler, Hartmut Kaiser, Ian Kelley, Thomas Radke, Gerd Lanfermann, Andre Merzky, Bernard Schutz, Oliver Wehrens, Michael Russell, Jason Novotny, Christian Ott, many others...
- GridLab
 - Jarek Nabrzyski, Giovanni Aloisio, Peter Kacsuk, Thilo Kielmann, Ludek Matyska, Alexander Reinefeld, Ian Taylor...
- LSU
 - CCT family (esp. Peter Diener, Erik Schnetter), Gov. Blanco
- NSF, DOE, DFN-Verein, EU, MPG, DFG
- Microsoft, Intel, SGI, Cisco, IBM, Sun, HP