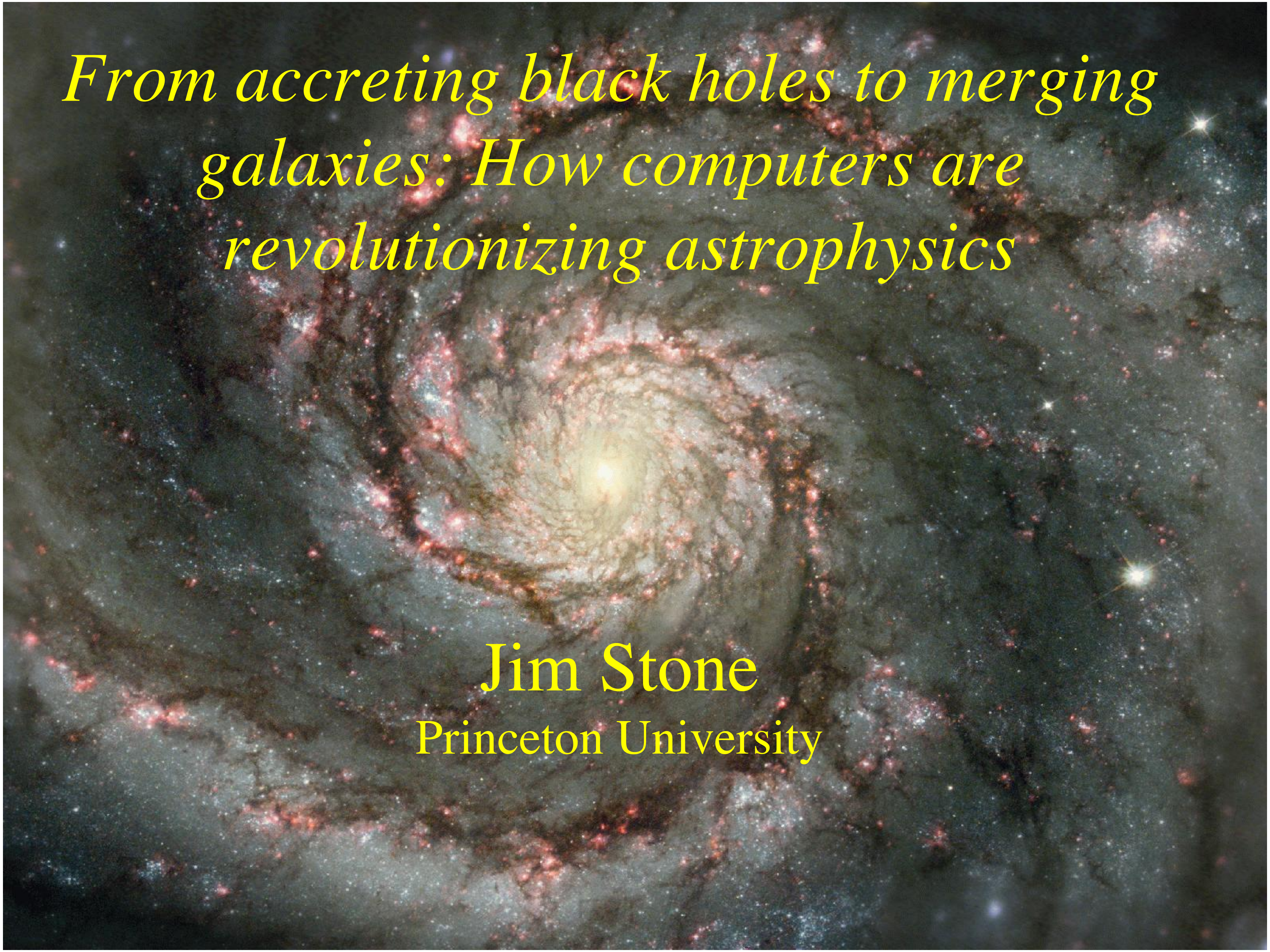

From accreting black holes to merging galaxies: How computers are revolutionizing astrophysics

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Princeton University

We are all aware of how our lives have been "improved" by the digital revolution.

But how has the increase in computer performance affected science (in particular astrophysics)?

A lot!

In part because of faster computers.

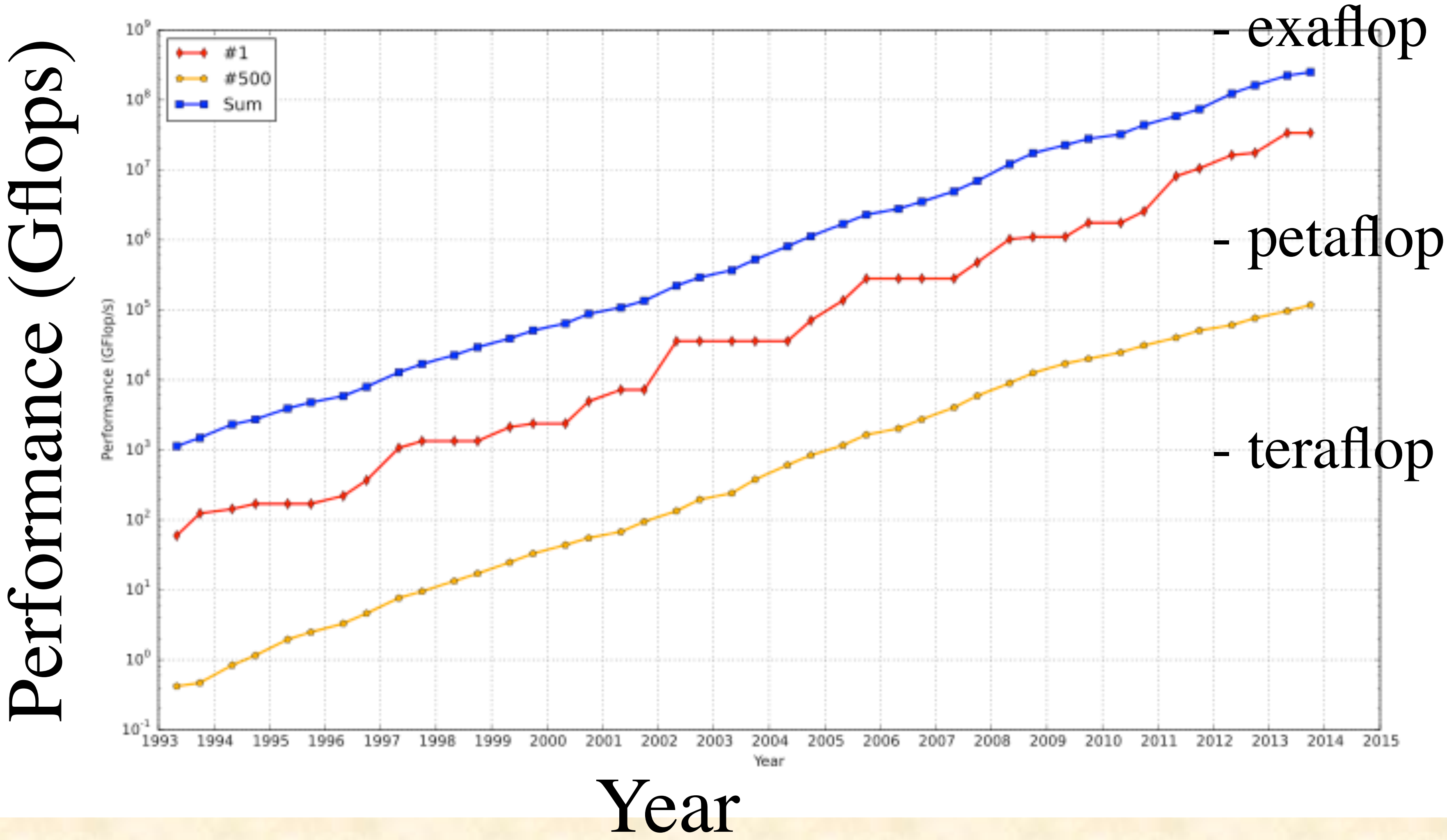
In part (mostly) because of much faster and more accurate software.

Faster computers.

Top 500 list
www.top500.org

Since 1993, linear algebra benchmark is used to measure performance of machines worldwide.

Every six months, a list of the 500 best performing machines is released.



Performance increase since 1993 is staggering.

The story of mario

a lesson in the rapid pace of progress

- Cray C90, 16Gflops, 4Gb main memory, 130Gb disks
- Installed at Pittsburgh Supercomputer Center (PSC) in 1993
- List price: $35M

- By 1996, Cray T3E at PSC outperformed `mario` by factor of 10
- Decommissioned in 1999.
- Sold on e-bay in 2000 for $50k *as living room furniture*

- Today, the iPhone is more powerful.

World's fastest computer

- "Tianhe-2" (MilkyWay-2) in China, 30 PetaFlops
- Roughly ten-million-times faster than a PC

World’s second fastest computer

- “Titan” at Oak Ridge National Laboratory
- 300,00 cores, 20 PetaFlops
- Occupies entire building, uses 8MW electricity

But how can scientists harness the power of these computers?

After all, computers can only perform operations on *bits* (0 and 1).

Bit operations can be combined into algorithms for

- addition/subtraction
- multiplication/division
- logic (if…then….else)

e.g. multiply by 2 can be achieved by left-shift of bits

00000110 = 6

00001100 = 12

If all you can do is add/subtract and multiply/divide, then you are limited to algebra. *How do we reduce more complex mathematics to algebra?*

Numerical Analysis

Branch of applied mathematics concerned with finding ways to approximate solutions of complex systems of equations.

Example, simple functions ($\sin x$, $\cos x$, $\exp x$, etc.) can be approximated using series expansion, rational functions, etc.

Derivatives can be approximated by finite-differences

$$\frac{df}{dx} \approx \frac{f(x+h) - f(x)}{h}$$

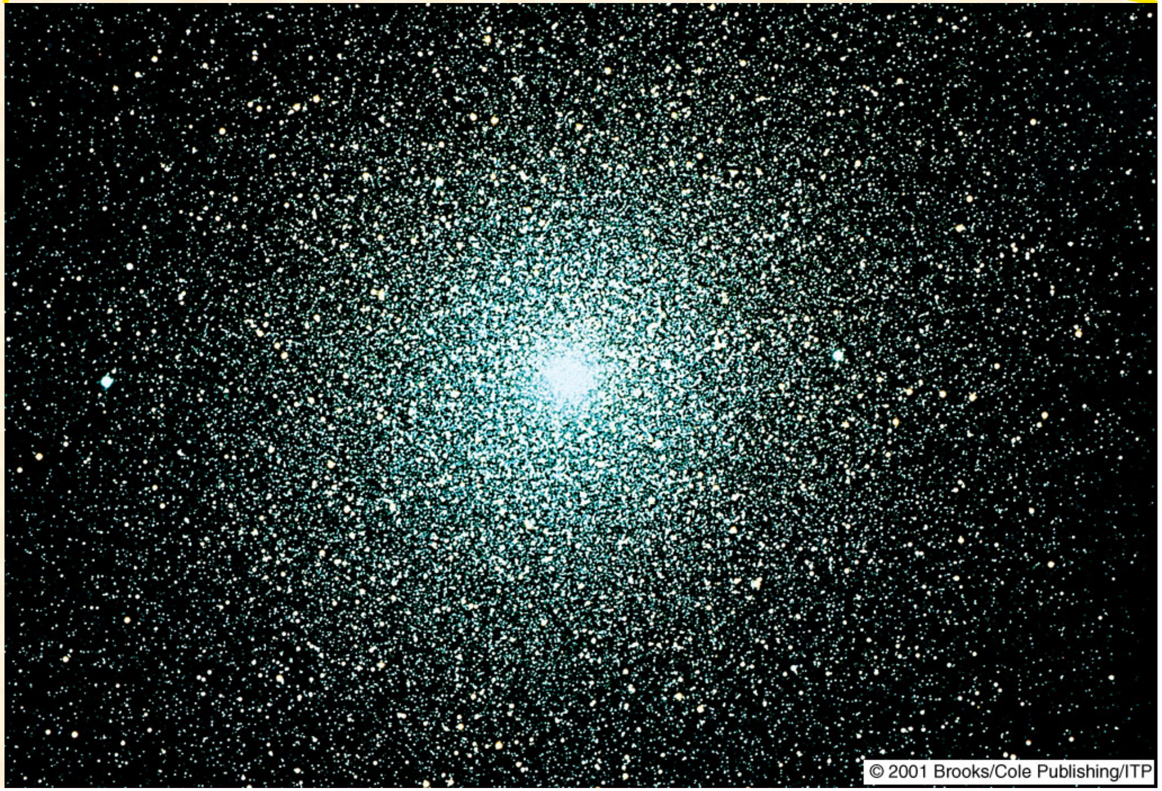
Turns a basic operation in calculus (differentiation) into algebraic operations (subtraction and division).

Such *numerical algorithms* can be developed for any operation in mathematics.

Using *numerical algorithms*, scientists can use computers to solve complex mathematical models of physical systems.

Example: Consider the motion of N stars under the influence of their mutual gravitational attraction.

Example:
Stellar dynamics in a globular cluster
$N \sim 10^6$



Stellar dynamics in a globular cluster

Movie from Frank Summers, AMNH

Mathematical model of stellar dynamics.

Newton's Laws of motion and gravity

$$\frac{d^2 x_i}{dt^2} = \frac{F_i}{M_i}, \qquad i = 1, N$$

$$F_i = \Sigma_j \frac{G M_i M_j}{R_{ij}^2}$$

Elements of a numerical algorithm:

1) Integration scheme for equation of motion F=ma
2) Method to evaluate gravitational force

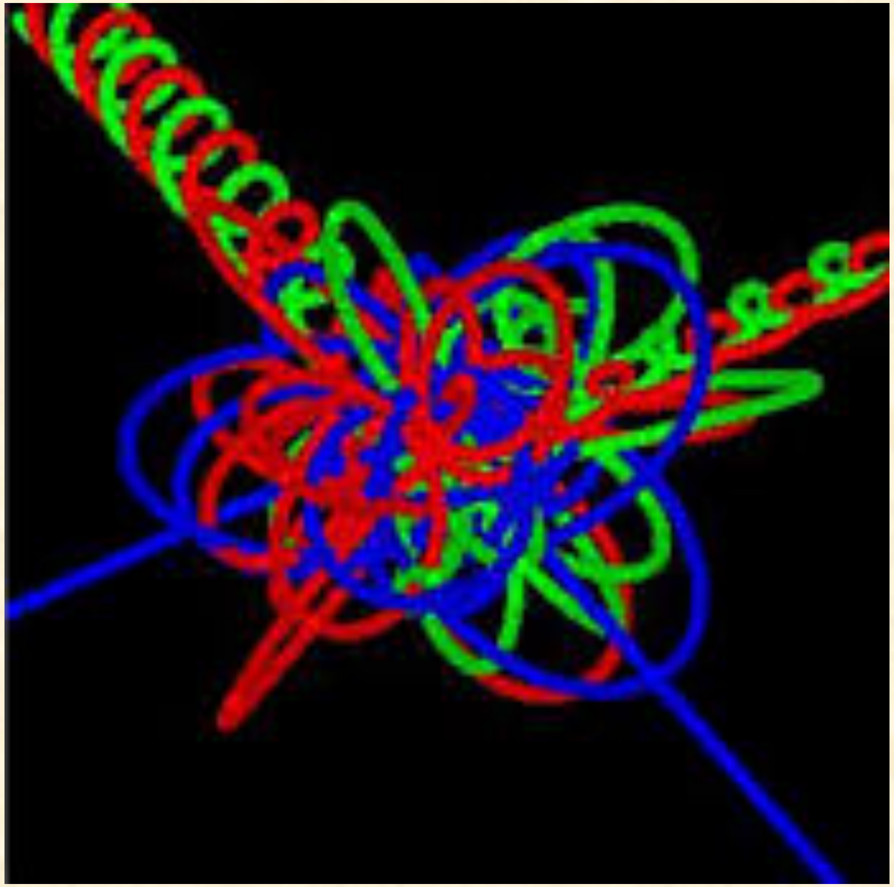
Challenges:

Stellar orbits can be chaotic -- requires control of error in integration

Direct summation of force requires N^2 operations

The problem of computing orbits

For $N > 2$, no analytic solution for stellar motion possible.



The N^2 force problem.

For N=1000 (open cluster):

- Direct summation easy

For $N=10^6$ (globular cluster)

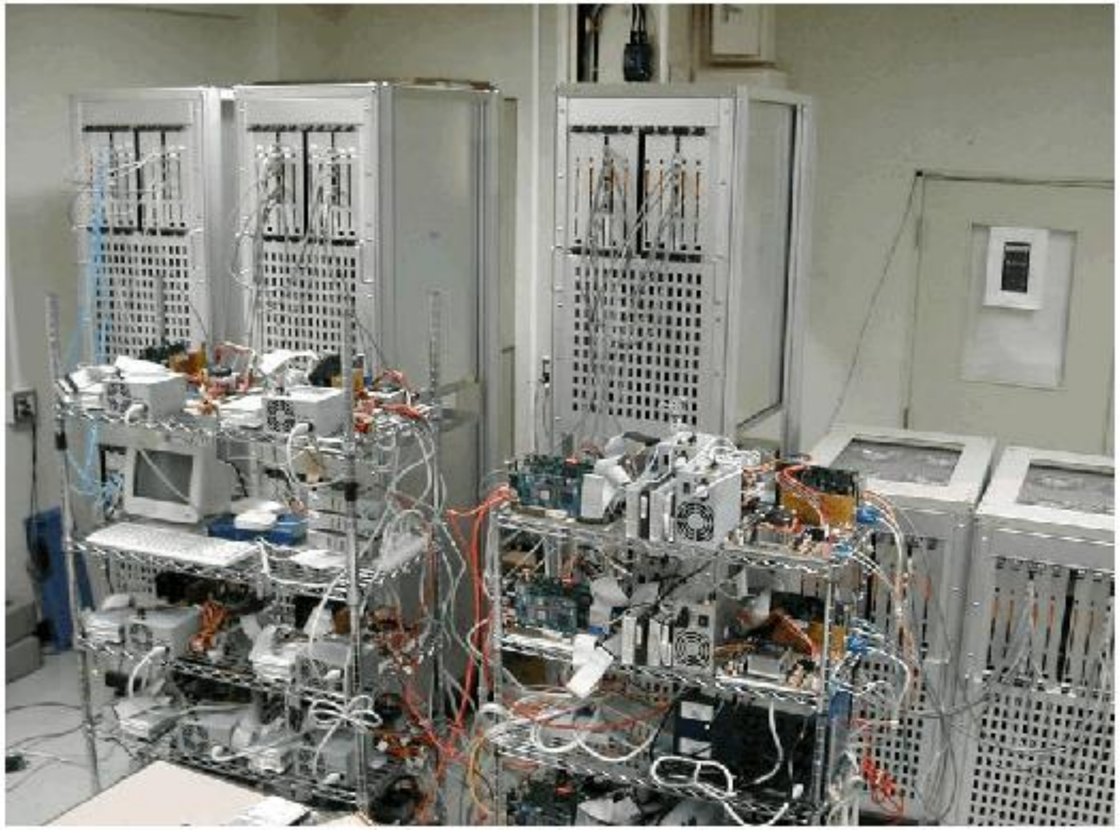
- Direct summation hard

For $N=10^{11}$ (galaxy)

- Direct summation impossible

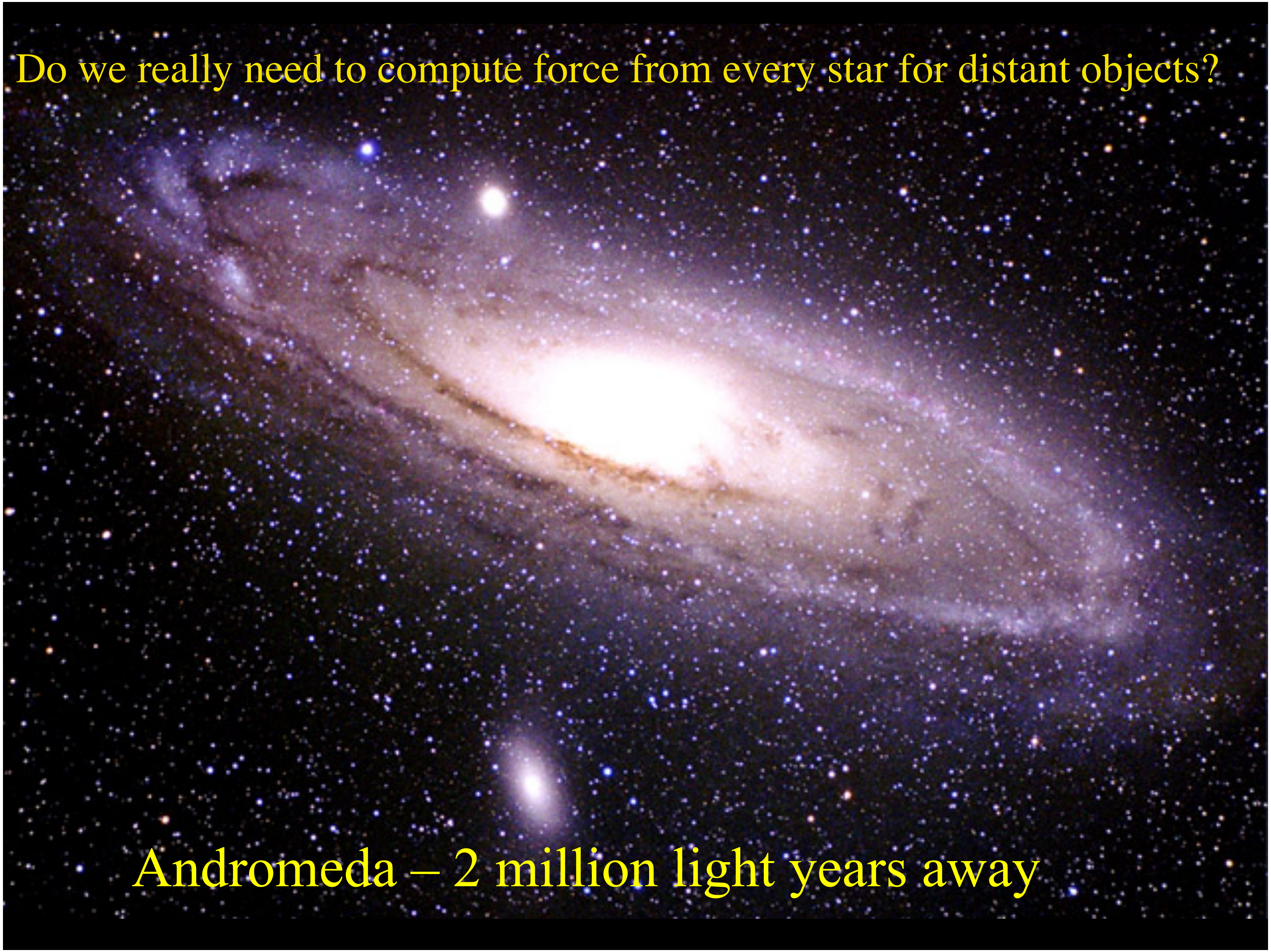
Solving the force problem with hardware.

The 64-Tflops GRAPE-6 system



Special purpose hardware to compute force:

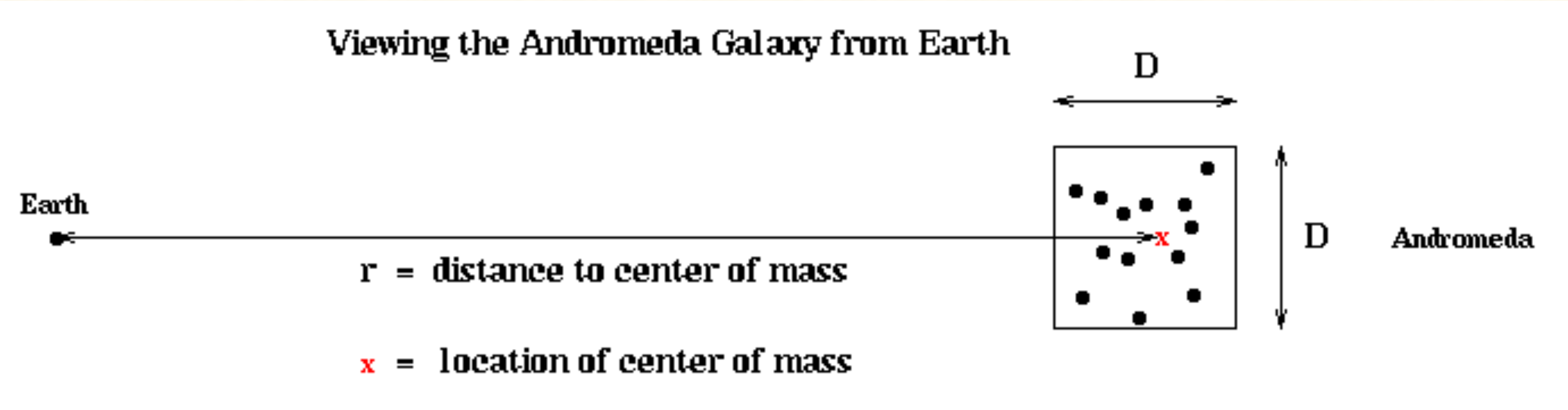
$$F_i = \Sigma_j \frac{GM_iM_j}{R_{ij}^2}$$

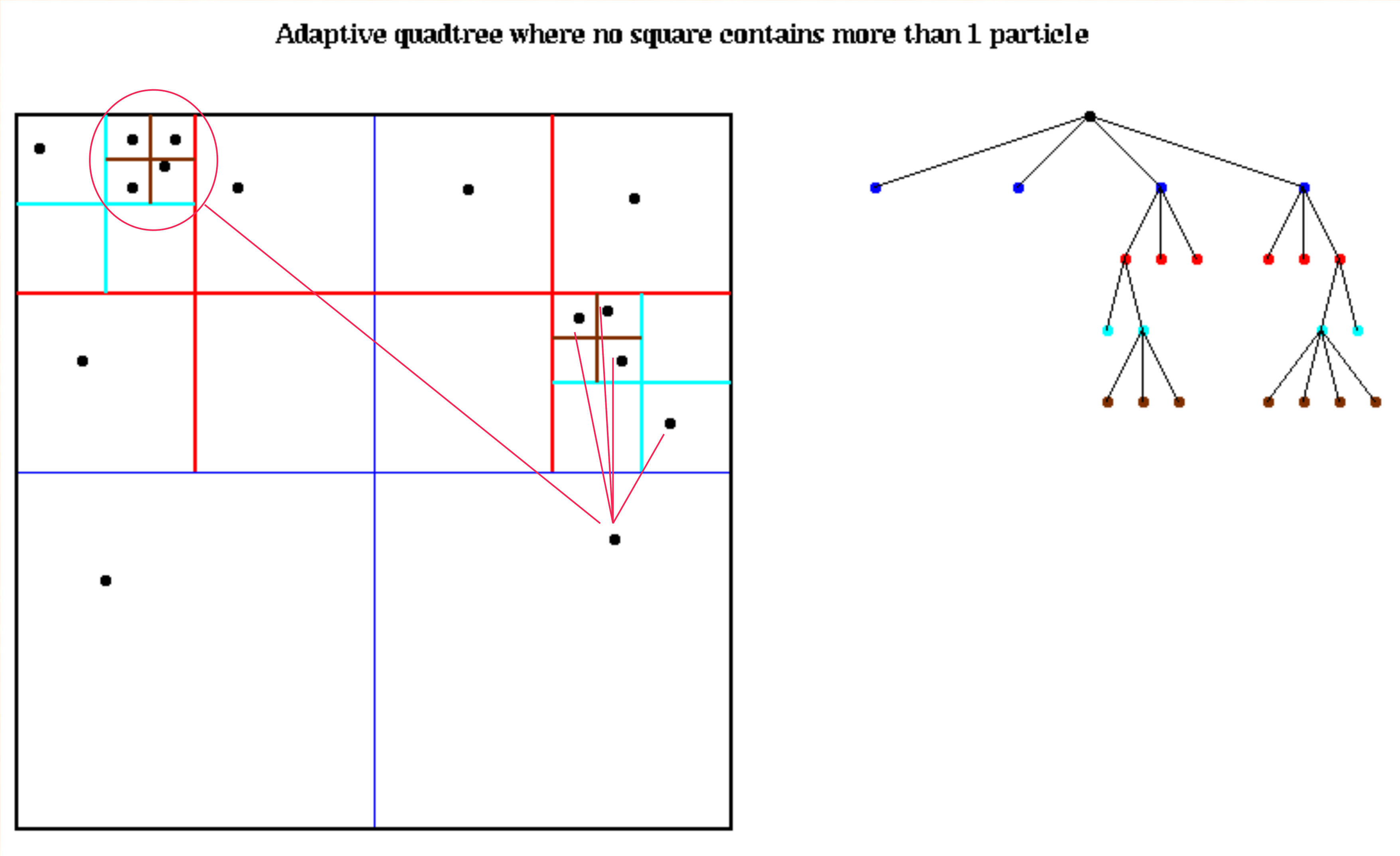

Do we really need to compute force from every star for distant objects?
Andromeda – 2 million light years away

Faster and More Accurate Software

Solving the force problem with software -- tree codes

Distance = 25 times size





If angle subtended by the particles contained in any node of tree is smaller than some criterion, then treat all particles as one.

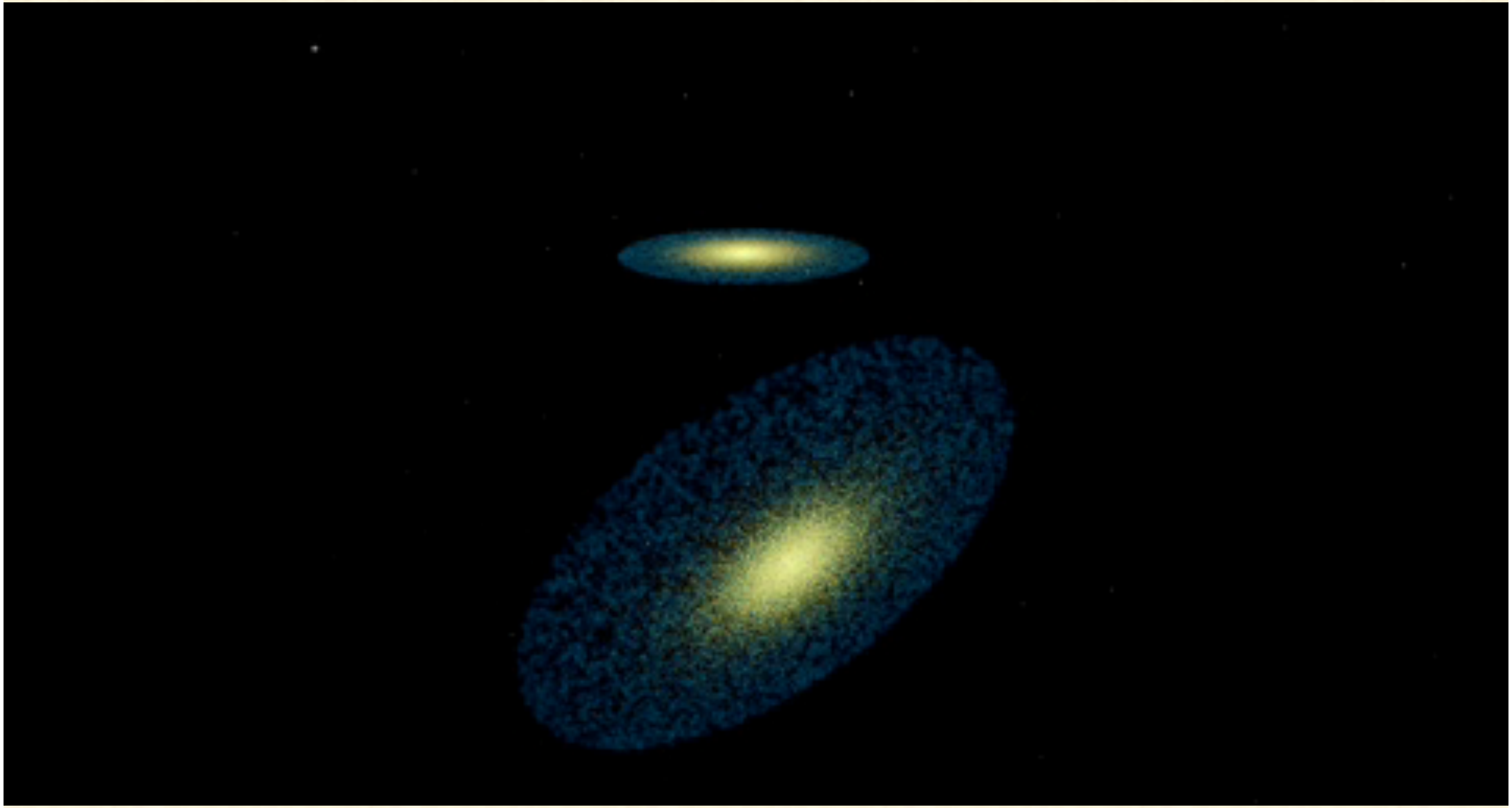
Results in an Nlog(N) algorithm.

Example: merging galaxies

Galaxies NGC 2207 and IC 2163

Hubble Heritage

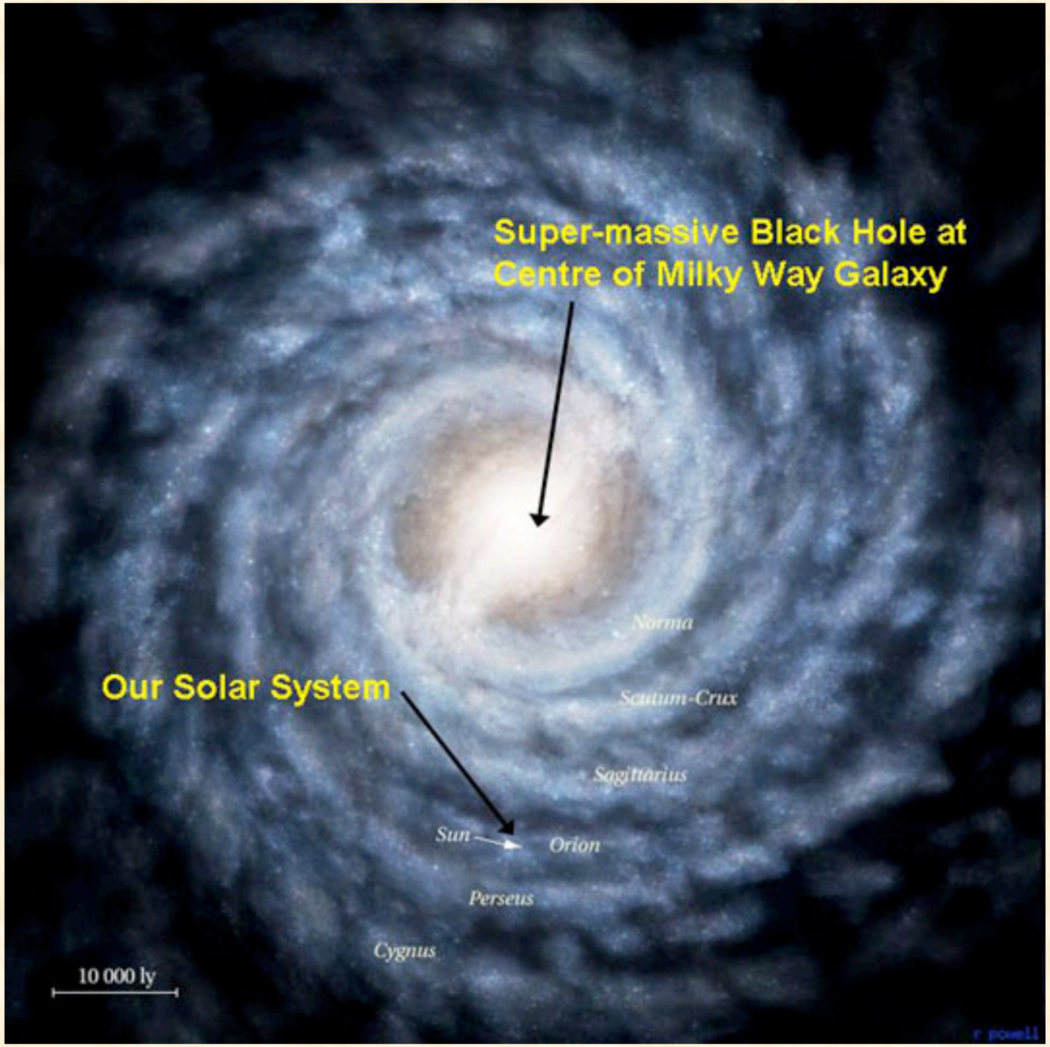
Example: merging galaxies



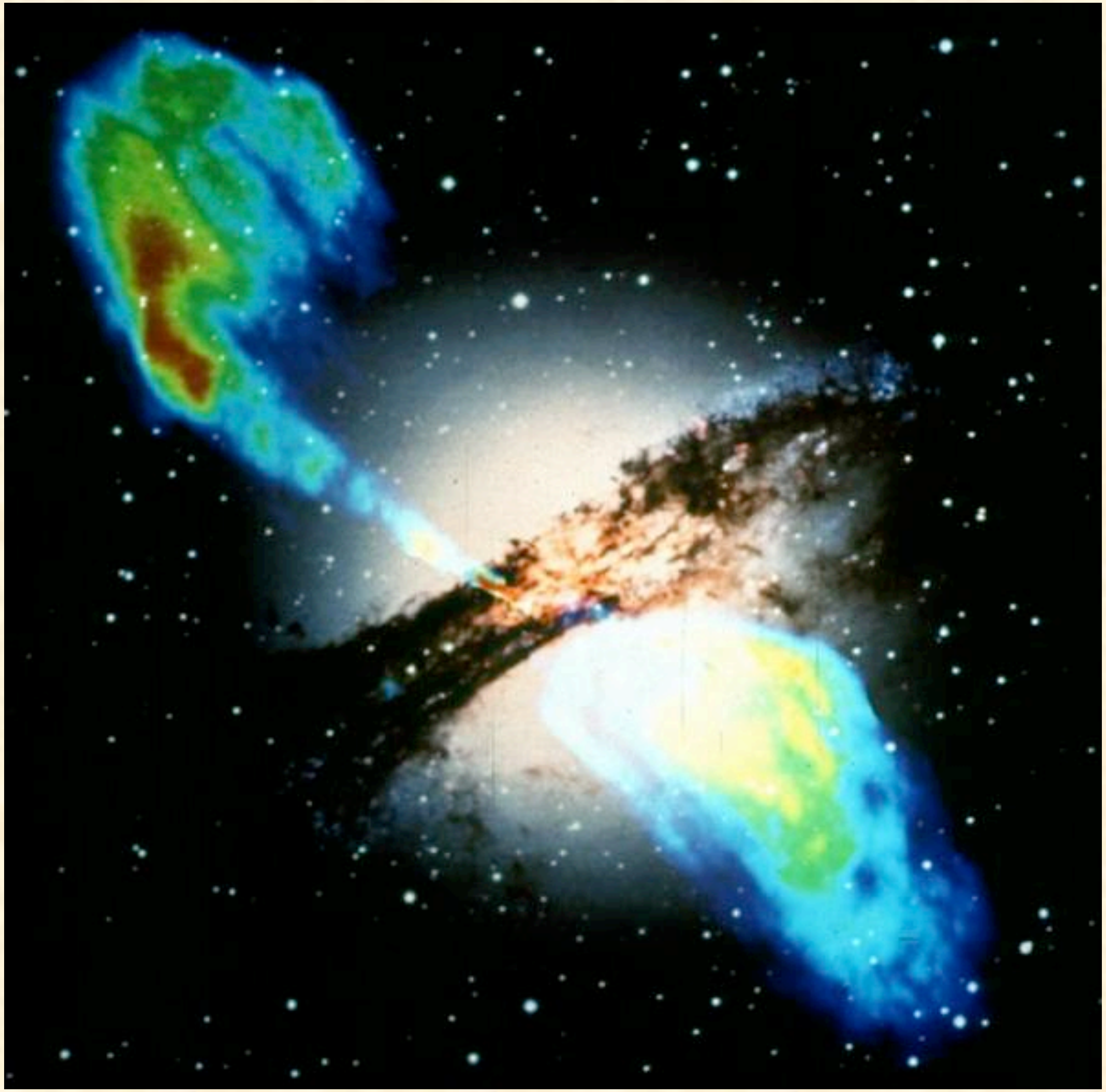
Calculation by Chris Mihos, Vanderbilt U.

Last example: accretion onto black holes

Observations have revealed supermassive black holes exist at the center of nearly all galaxies.



Accretion onto a black hole produces jets.



Centaurus A

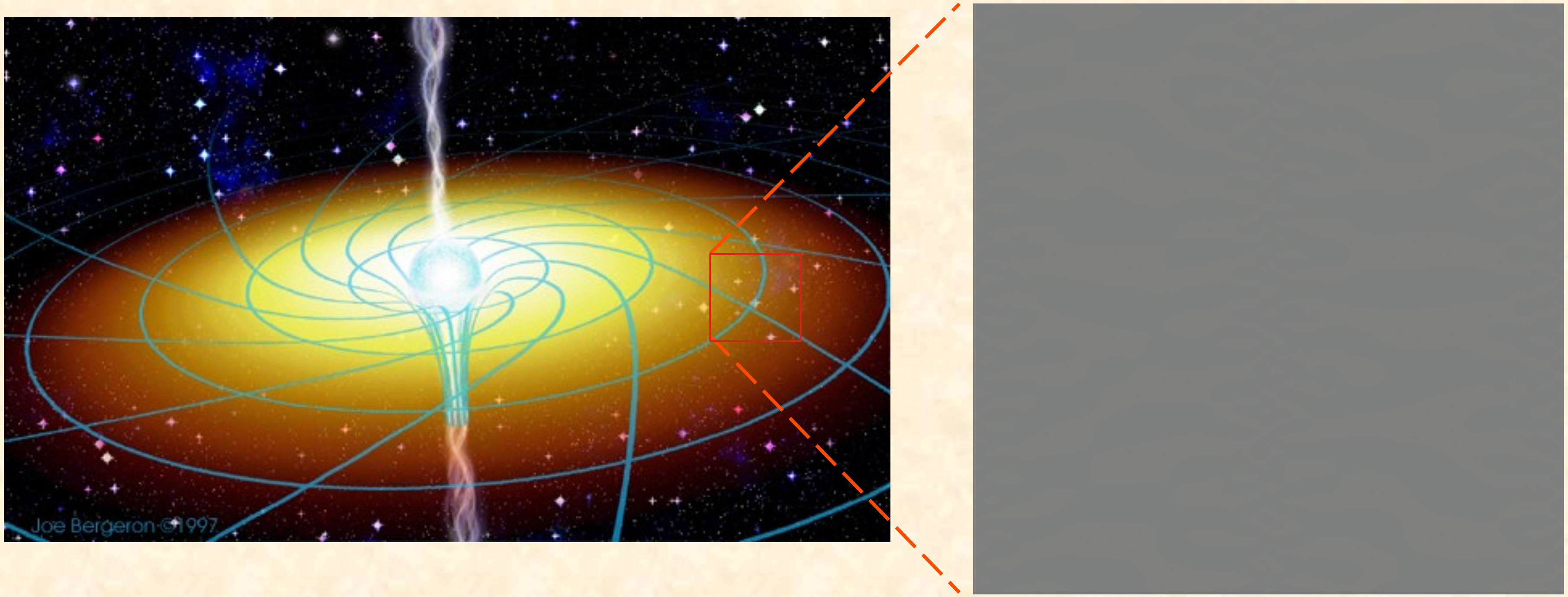
Artist's impression of an accreting black hole.

Black hole at galactic center accretes surrounding *plasma* (gas of charged particles).

If accreting plasma has any angular momentum, it will form a rotationally supported disk

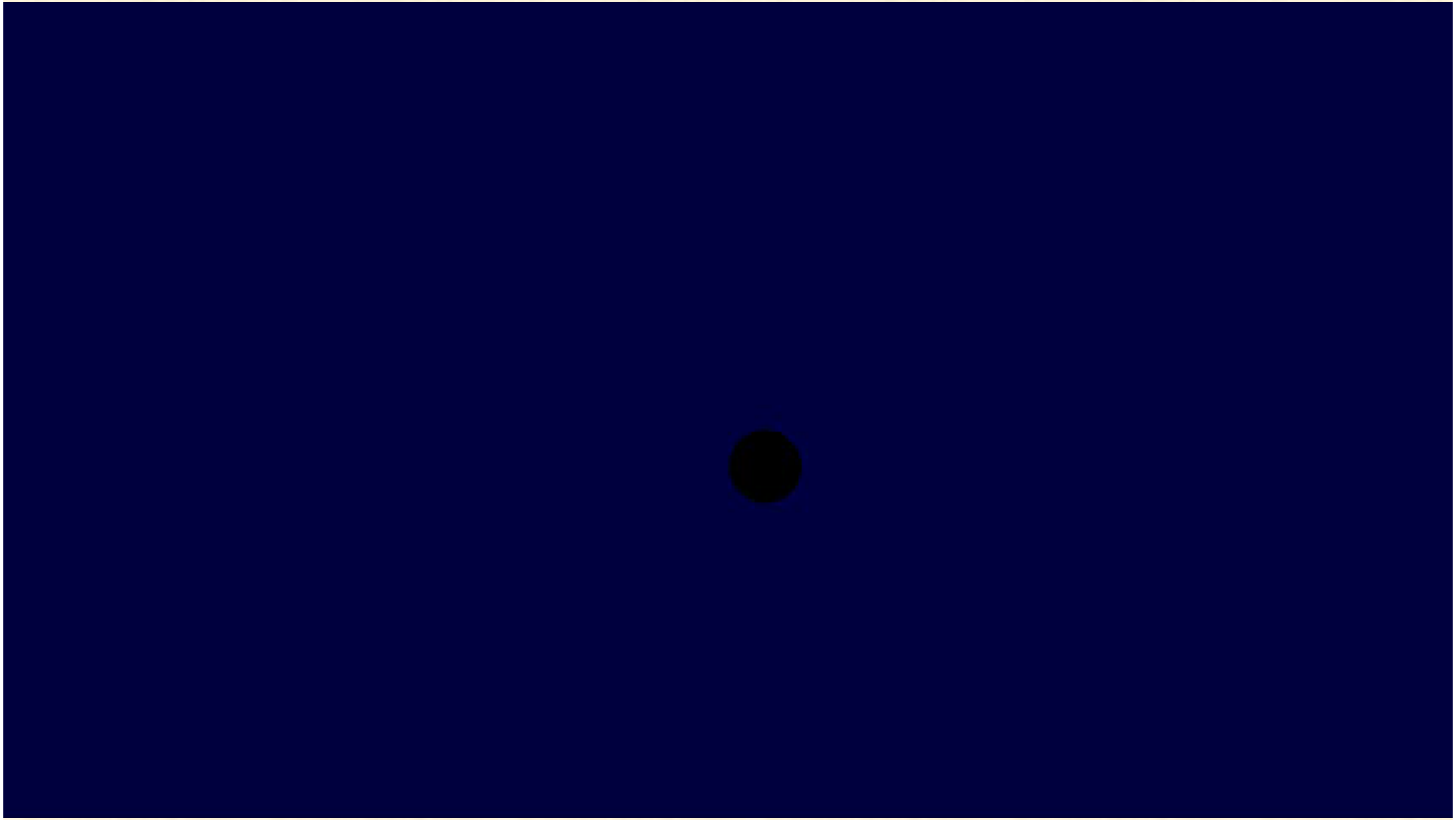
Accretion Disk Dynamics.

- Rotating disks of plasma around black holes are subject to an instability that generates turbulence.
- Turbulence produces angular momentum transport and accretion.
- Studying turbulence requires numerical methods for *magnetohydrodynamics* (MHD).



Animation of velocity fluctuations:

Accretion onto a rapidly rotating black hole produces jets.



Real GRMHD. Not an artist's impression!

GRMHD simulation by J. Hawley

Images rendered by A. Hamilton

Software: who writes the codes to solve all these different problems?

Currently, scientists write their own codes.

This is a major bottleneck to progress, since it requires expertise in software engineering, computer science, ***and*** astrophysics!

Why not use commercial software?

Goal of science is to explore frontiers of knowledge. Not even the algorithms, let alone the software, are available when new frontiers are studied.

Still, in future, most codes will be built with existing modules from many sources, with new extensions added on top.

Such ***Community Codes*** are accelerating progress.

MESA
Modules for Experiments in Stellar Astrophysics

MESA home

code capabilities

prereqs & installation

getting started

using pgstar

MESA output

beyond inlists (extending MESA)

troubleshooting

FAQ

MESA Council

Lars Bildsten
Aaron Dotter
Falk Herwig
Frank Timmes
Ed Brown
Rich Townsend
Matteo Cantiello

Hosted by Sourceforge
Generated by jekyll
Design by Andreas Viklund

MESA

Why a new 1D stellar evolution code?

The MESA Manifesto discusses the motivation for the MESA project, outlines a MESA code of conduct, and describes the establishment of a MESA Council. Before using MESA, you should read the **manifesto document**. Here's a brief extract of some of the key points

Stellar evolution calculations remain a basic tool of broad impact for astrophysics. New observations constantly test the models, even in 1D. The continued demand requires the construction of a general, modern stellar evolution code that combines the following advantages:

- **Openness**: anyone can download sources from the website.
- **Modularity**: independent modules for physics and for numerical algorithms; the parts can be used stand-alone.
- **Wide Applicability**: capable of calculating the evolution of stars in a wide range of environments.
- **Modern Techniques**: advanced AMR, fully coupled solution for composition and abundances, mass loss and gain, etc.
- **Comprehensive Microphysics**: up-to-date, wide-ranging, flexible, and independently useable microphysics modules.
- **Performance**: runs well on a personal computer and makes effective use of parallelism with multi-core architectures.

Users are encouraged to add to the capabilities of MESA, which will remain a community resource. However, use of MESA requires adherence to the MESA code of conduct:

- That all publications and presentations (research, educational, or outreach) deriving from the use of MESA acknowledge the MESA Instrument papers.

Latest News

- 24 Mar 2014
  » **Release 6208**
- 21 Mar 2014
  » **New MESA Website**
- 21 Mar 2014
  » **Release 6188**
- 13 Mar 2014
  » **New MESA SDK Version**
- 28 Feb 2014
  » **Release 6022**
- 03 Feb 2014
  » **Summer School 2014**
- 05 Jan 2014
  » **Release 5819**
- 23 Dec 2013
  » **New MESA SDK Version**
- 15 Nov 2013
  » **Release 5596**
- 10 Oct 2013
  » **Release 5527**

The Future of Computational Astrophysics

What is certain: increases in hardware performance will enable larger problems to be tackled numerically

What is needed:

- More accurate algorithms
- Community codes & visualization software
- More realistic physics
- Students trained in computation: they are the *real* future