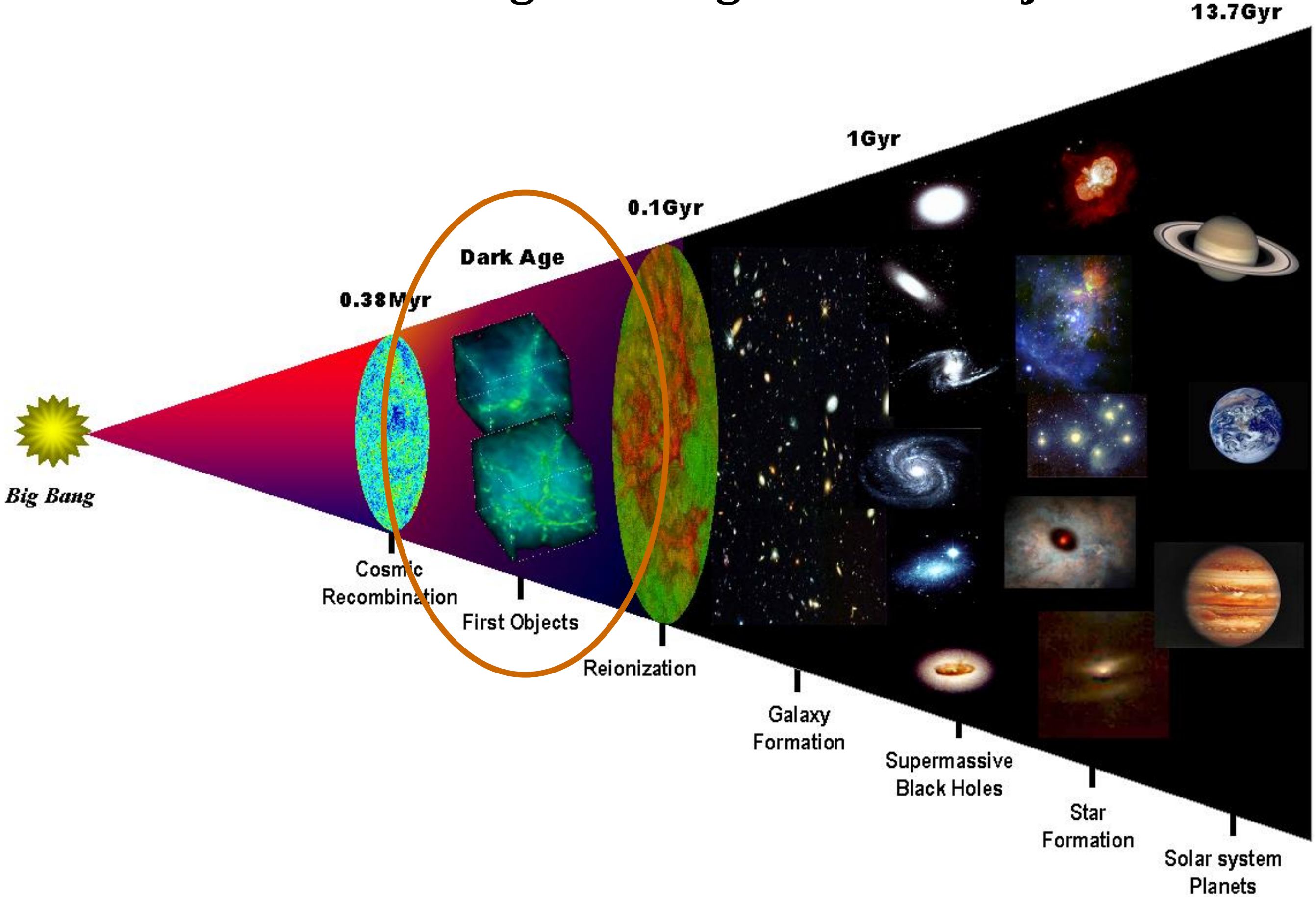
FIRST

The Origin of FIRST Generation Objects

Fusional Integrator for Radiation-hydrodynamic Systems in Tsukuba University for elucidating FIRST generation objects



FIRST Project

Grants-in-Aid for Specially Promoted Research, MEXT in Japan

"Elucidation on the origin of *first* generation objects in the Universe with Heterogeneous Multi-Computer System"

2004~2007

Total budget is 428 million yen (US$3.6 million)

Division of Computational Astrophysics

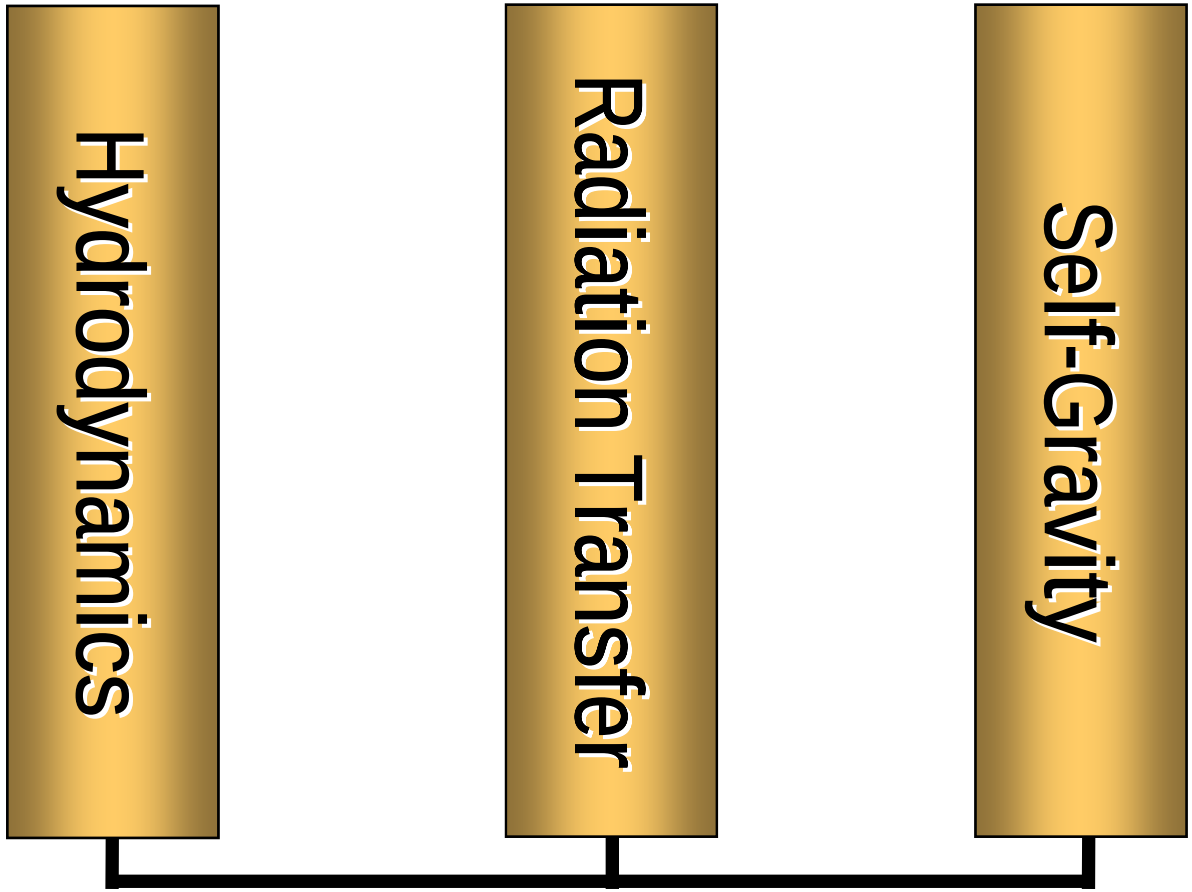
M. Umemura
K. Yoshikawa (2007-)
H. Hirashita
Y. Kato (2005-)
T. Suwa (2005-)
T. Akahori (2007-)
J. Sato (2004-2006)
T. Nakamoto (Tokyo I.Tech)
H. Susa (U Kounan)
M. Mori (U Senshu)

Division of High Performance Computing Systems

M. Sato (2004)
T. Boku
D. Takahashi
O. Tatebe (2006-)

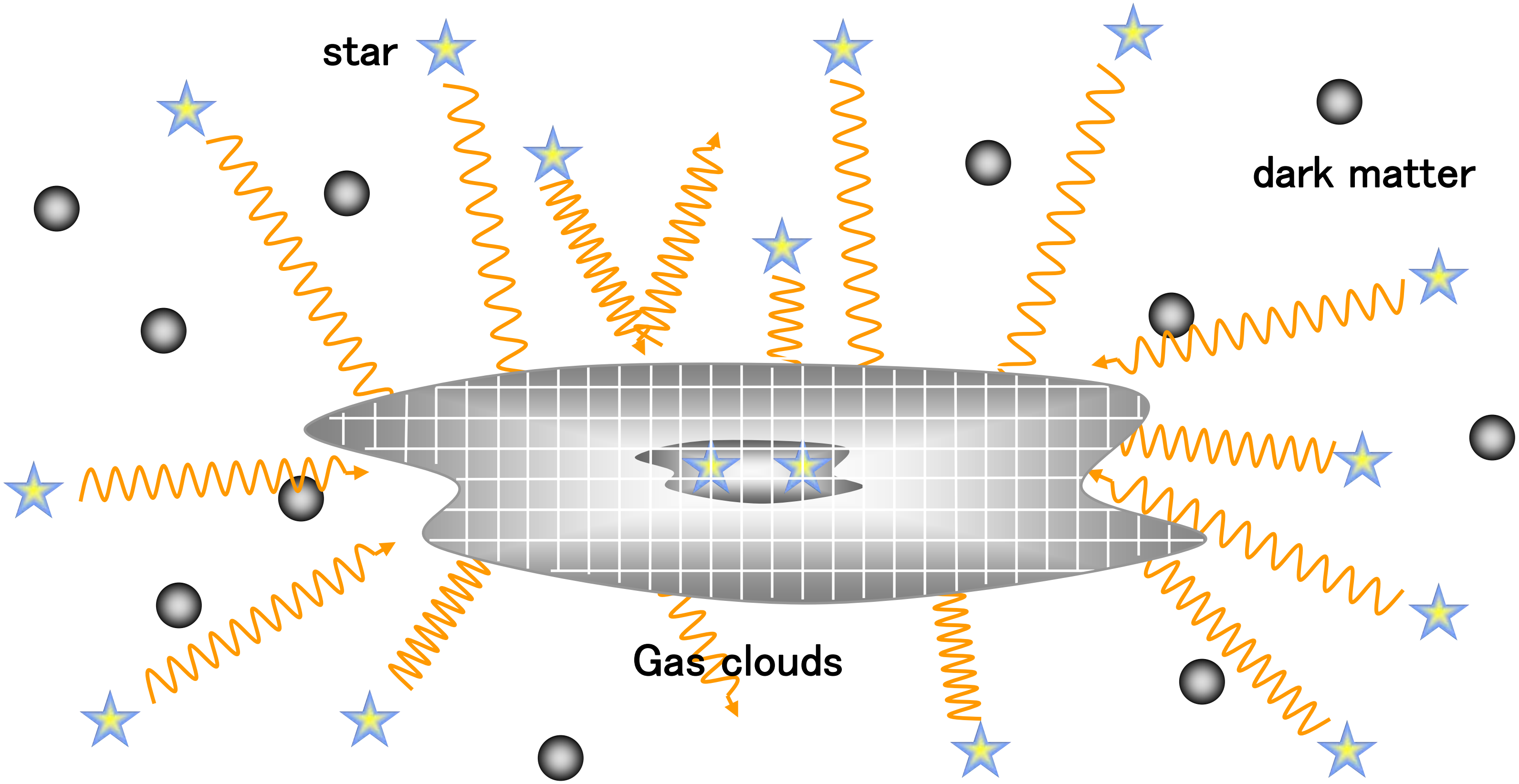
<u>Core Members</u>

Tree Requisite Calaculations



Astrophysical Radiation Hydrodynamics

Radiation Hydrodynamics



6D Radiation Hydrodynamics (space, directions, frequencies)

$$\text{operations} \propto N_x N_y N_z \cdot N_\theta N_\varphi \cdot M_\nu = 5\ \text{Tera} \quad (N = 100, N_\nu = 500)$$

Development of Next Generation Massive Parallel Computer Project (1997 - 2001)

U Tsukuba & U Tokyo

HMCS: Heterogeneous Multi-Computer System

Self-gravity

GRAPE−6

1Tflops×8

PCI×8

Cluster

(Parallel IO)

100base TX

16IOU

HUB

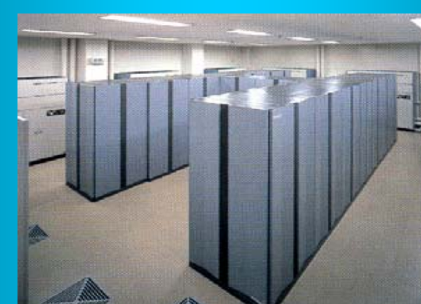
16IOU

Radiation Hydrodynamics

CP−PACS

2048PU~0.6Tflops

RDMA: 300MB/s



Necessity for New Type of Heterogeneous Computer System

Objective

- Radiation Hydrodynamics with 10 million particles
- Computational time of several months

Requirements

① Host： several Tflops

② Gravity calculation： several 10 Tflops

③ High communication bandwidth

Solution

① PC cluster

② Embedded special-purpose processor

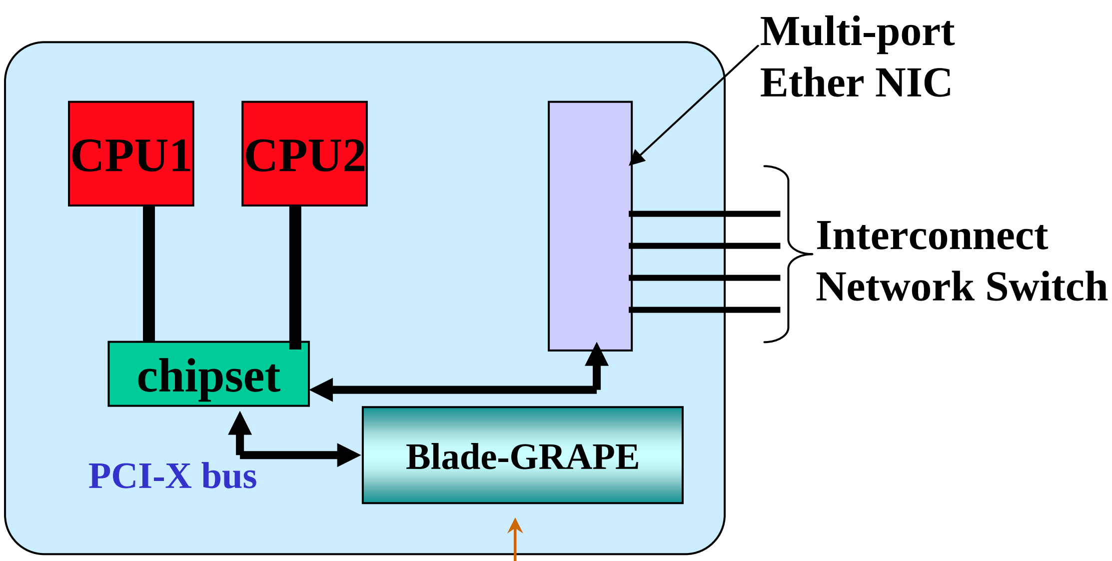
③ High performance network

“FIRST” Simulator

A New-type of Hybrid Cluster

PC cluster embedded with special board of gravity calculations.

2U server



special board of gravity calculations

FIRST Simulator

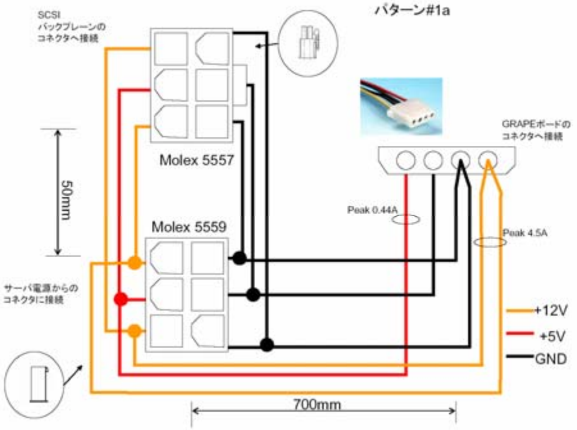
Blade-GRAPE X64

Blade-GRAPE

Embedded Special Purpose Processor for Gravity

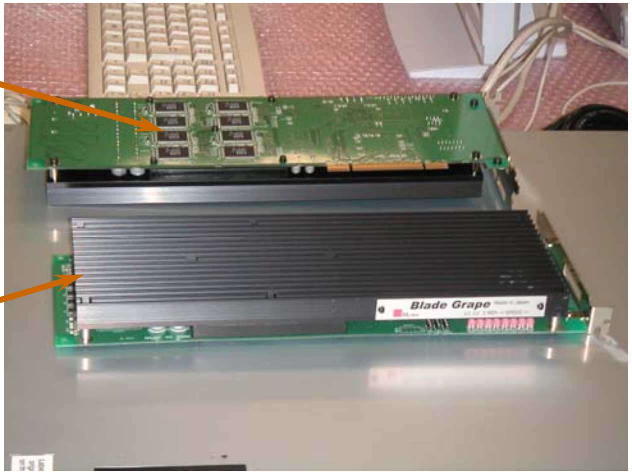
(Newly-developed in 2005)

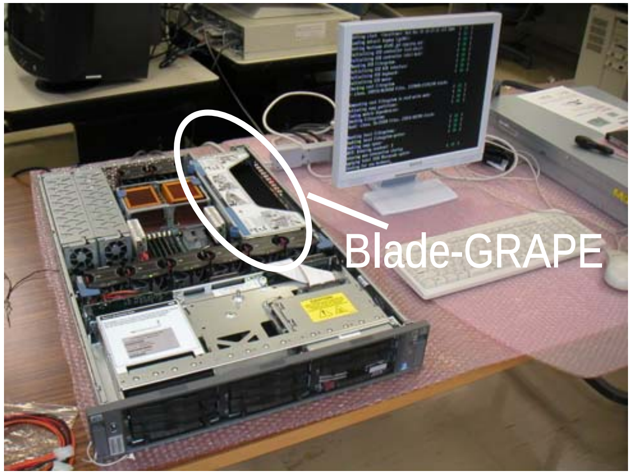
- 2 PCI-X bass full slots for 2U server
- 10 layers in a board
- 4 GRAPE6 chips = **136.8GFLOPS**
- electric power of 54W
  (from power supply for disk drive)
- memory of 16MB（260 thousand particles）



GRAPE6 chips
×4

heat-sink





Cooperation

Hamamatsu Metrics Co.

First Model of “FIRST” Simulator

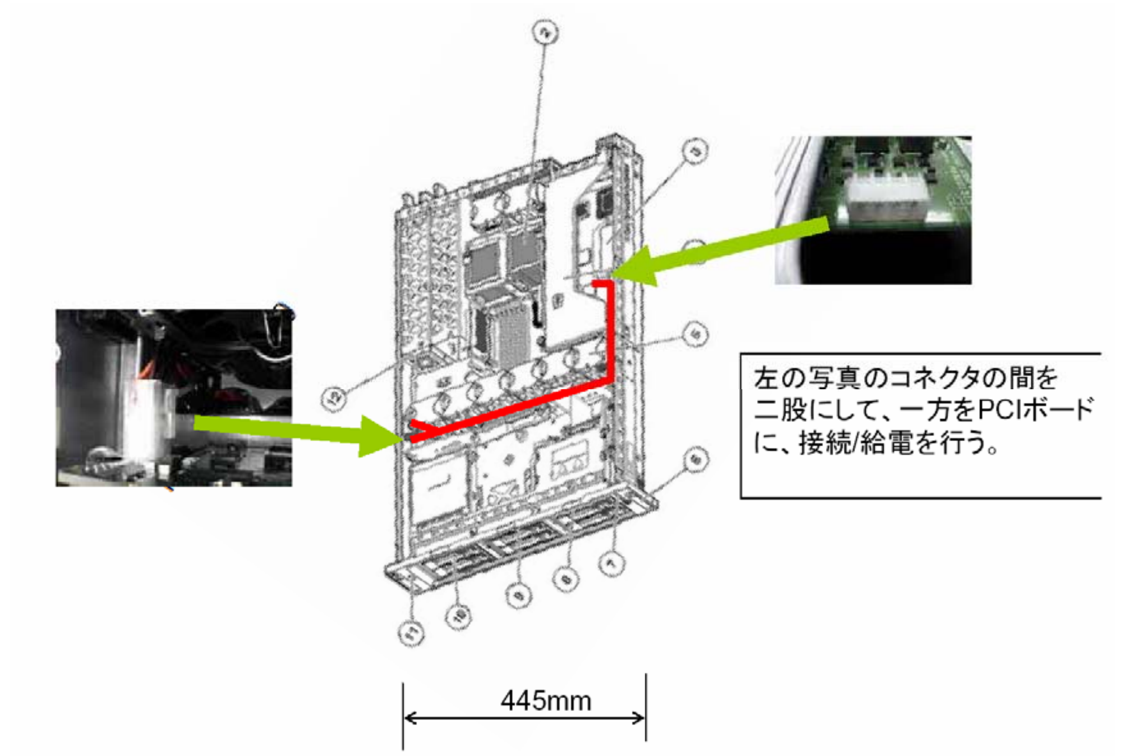
May 2005

16 nodes HP Cluster with Blade-GRAPE

Performance

Host 217 Gflops

Blade-GRAPE 2.2 Tflops



Cooperations

HP Co.

Best Systems Inc.

Sumi-Sho Computer Systems Co.

Blade-GRAPE X64

（Newly developed in 2006）

64 bit PCI-X version with FPGA

<u>Cooperation</u>

Hamamatsu Metrics Co.

K&F Computing Research Co.

"FIRST" Simulator

Completed in March, 2007

Blade-GRAPE X64

256（16×16）nodes

496 CPU ＋

16 Blade-GRAPE

224 Blade-GRAPE X64

Total Performance = 36.1 Tflops

Host 3.1 Tflops

Blade-GRAPE 33 Tflops

Total Memory = 1.6TB

Total storage = 22TB (Gfarm)

Gfarm File System

Gfarm file system = Scalable virtual file system federating local file systems of cluster nodes

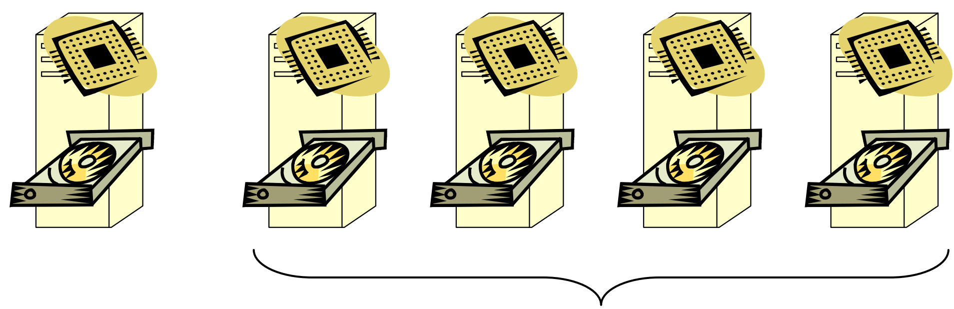
SC06 Storage Challenge
Winner in Large-Systems
by attaining 52GB/s for 1112 node system in KEK, Japan

Tatebe et al. (SC06)

Gfarm on FIRST

- **1 Meta-data server (first-fs2)**
- **256 filesystem nodes**

(22TB)

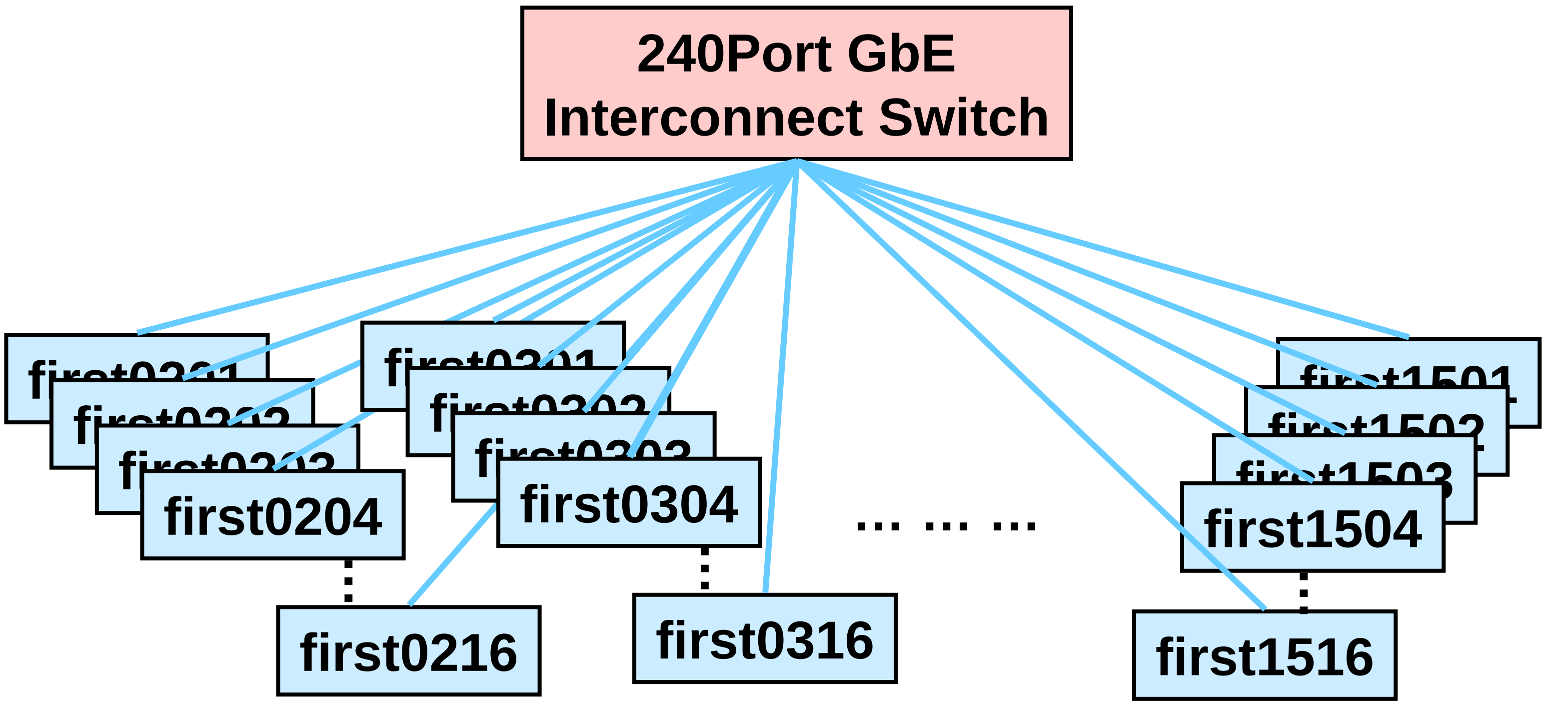


Meta-data server

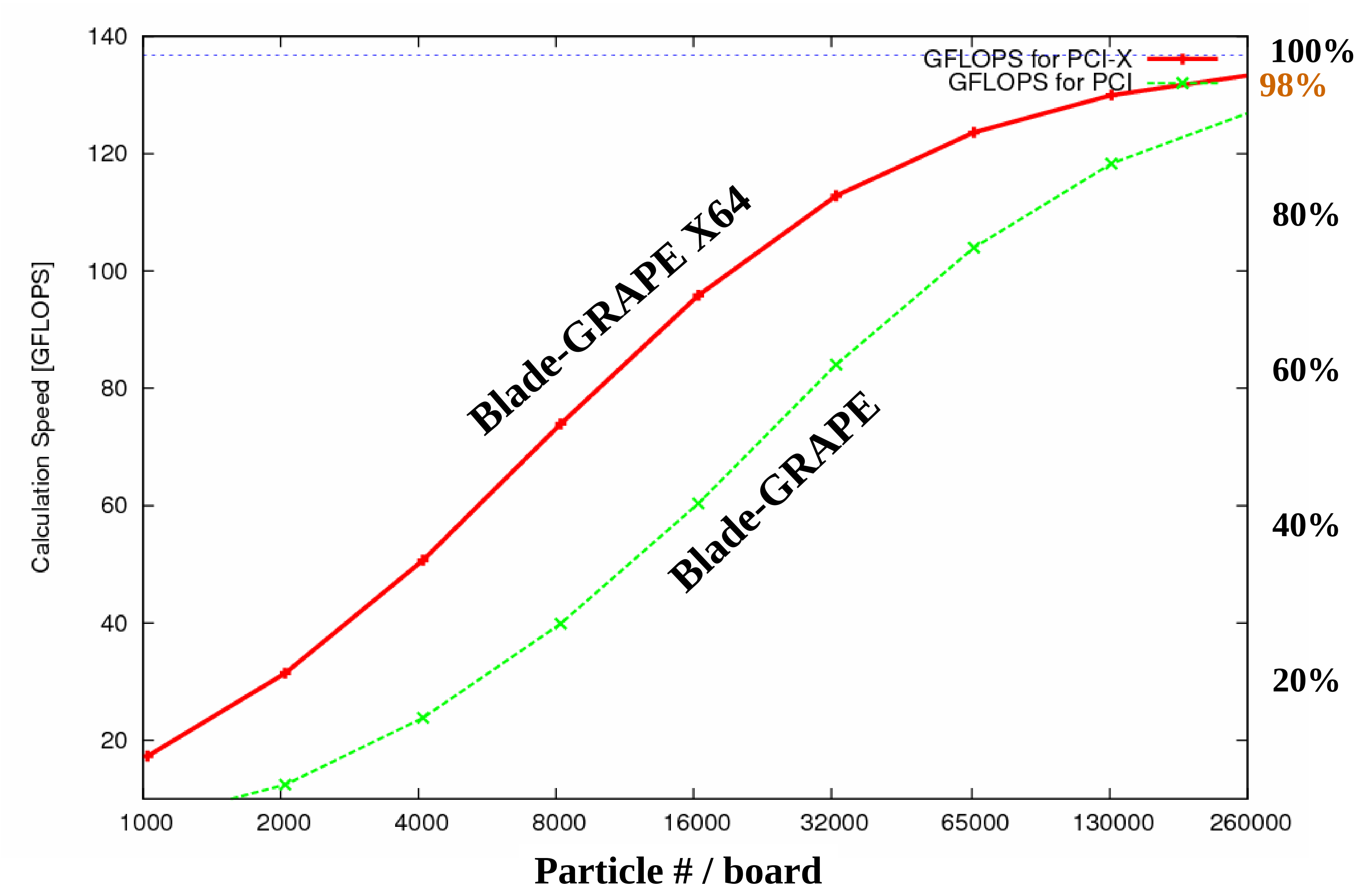
first 256 nodes

Network

Uniform Connection to 240 Port Gbit Ether Switch for first0101-1516



Blade-GRAPE Performance

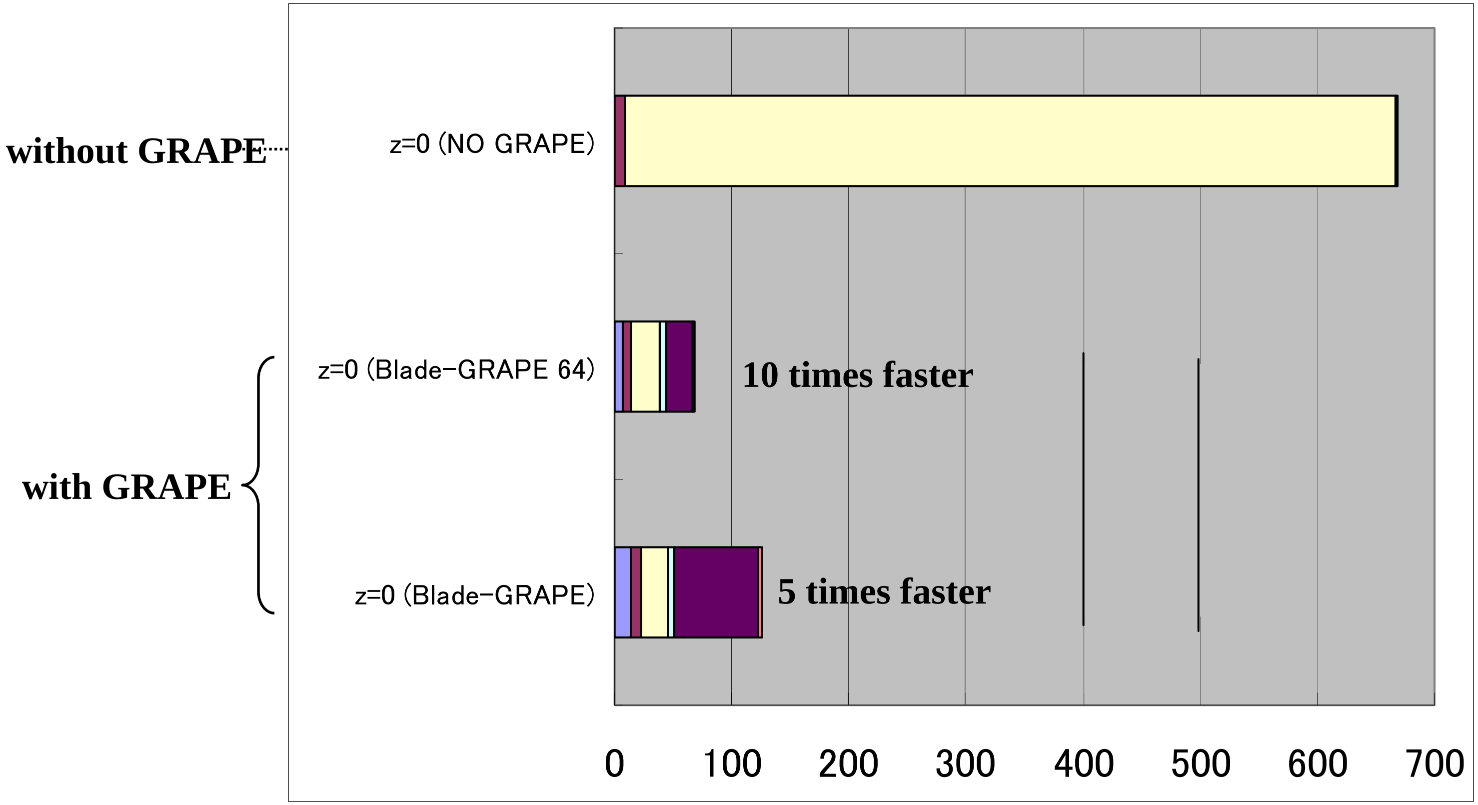


Performance of “FIRST” Simulator

- **PC Cluster +Blade-GRAPE**

  Peak speed=33.3Tflops

  Effective speed=32.3Tflops (*N*=260,000)



Press, News, Exhibitions

<Press Release>

First model of FIRST Simulator
March 13, 2005

<TV News & Newspapers>

<u>TV News</u>

NHK(Mito)　March 13, 2005
NHK(Capital Area) March 17, 2005

<u>News & Net</u>

Yomiuri, Asahi, Ibaraki, Tokyo, Jyoyo, Nikkan-Kogyo, Nikkei-Sangyo, Kyoto

<TV Interview>

NHK(Mito) May 17, 2005

<Exhibitions>

SC05 (Seattle)
SC06 (Tampa)
SC07 (Reno) *coming soon*

SC05

Press Release

Press Release

Radiation-SPH(RSPH) Scheme with FIRST simulator

TREE-GRAPE-SPH +Radiative transfer
+ Non-equilibrium Chemistry + Thermal processes

1. Hydrodynamics
   SPH (Umemura 1993; Steinmetz & Muller 1993)

2. Self-gravity
   Parallel Tree-GRAPE code (Orthogonal Recursive Bisection)

3. Frequency-dependent Radiative Transfer (Ray-tracing)
   (Kessel-Deynet & Burkert 2000, Nakamoto et al. 2001)

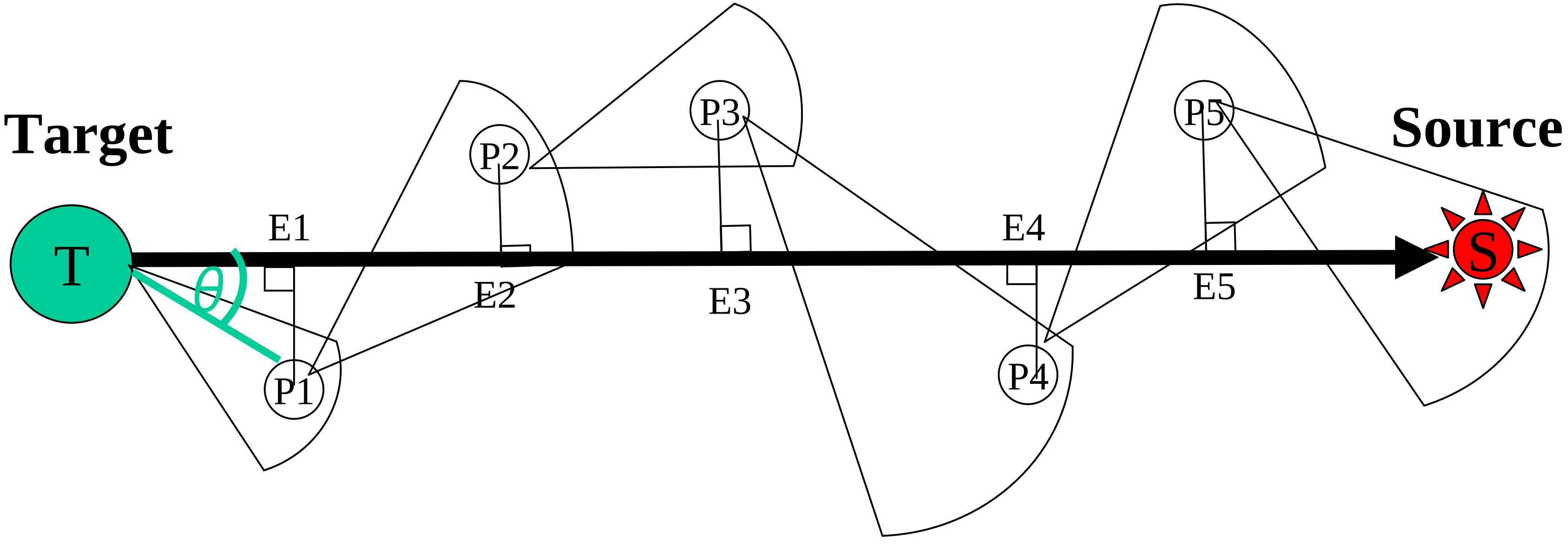
4. Non-equilibrium Chemistry & Thermal Processes
   (Susa & Kitayama 2000)

Radiation Transfer on SPH

Kessel-Deynet & Burkert (2000)

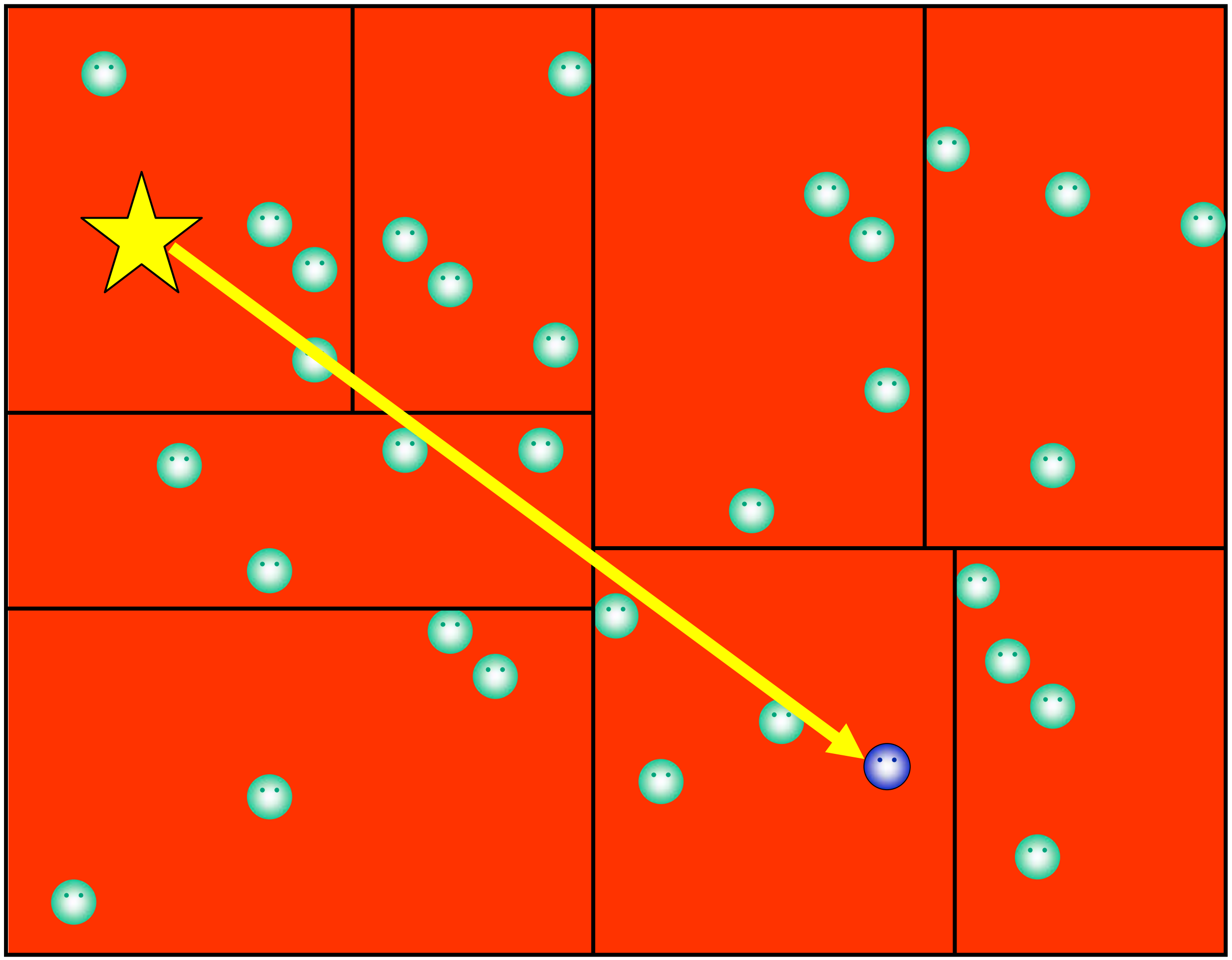
Optical depth calculations (Ray Tracing)

$$\tau_{TS} = \sum_i \frac{\sigma}{2}\left(n_{E_i} + n_{E_{i+1}}\right)\left(s_{E_{i+1}} - s_{E_i}\right)$$



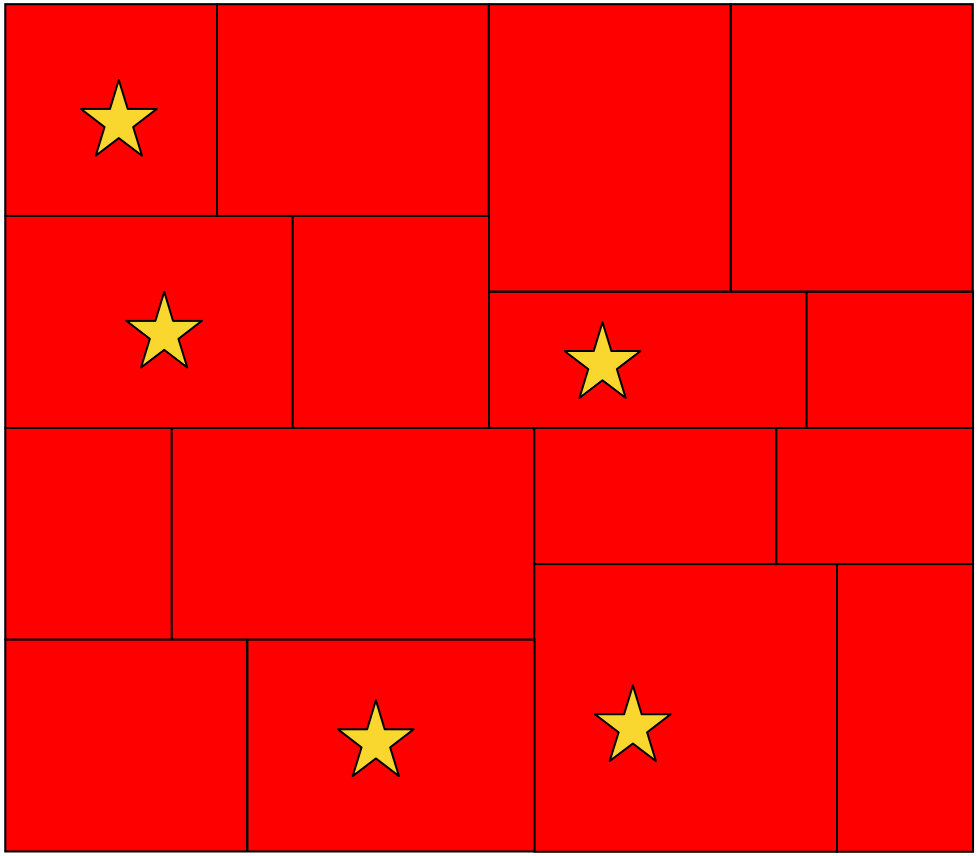
Parallelization of Radiative Transfer

Parallelization by Domain decomposition
ORB (Orthogonal Recursive Bisection)

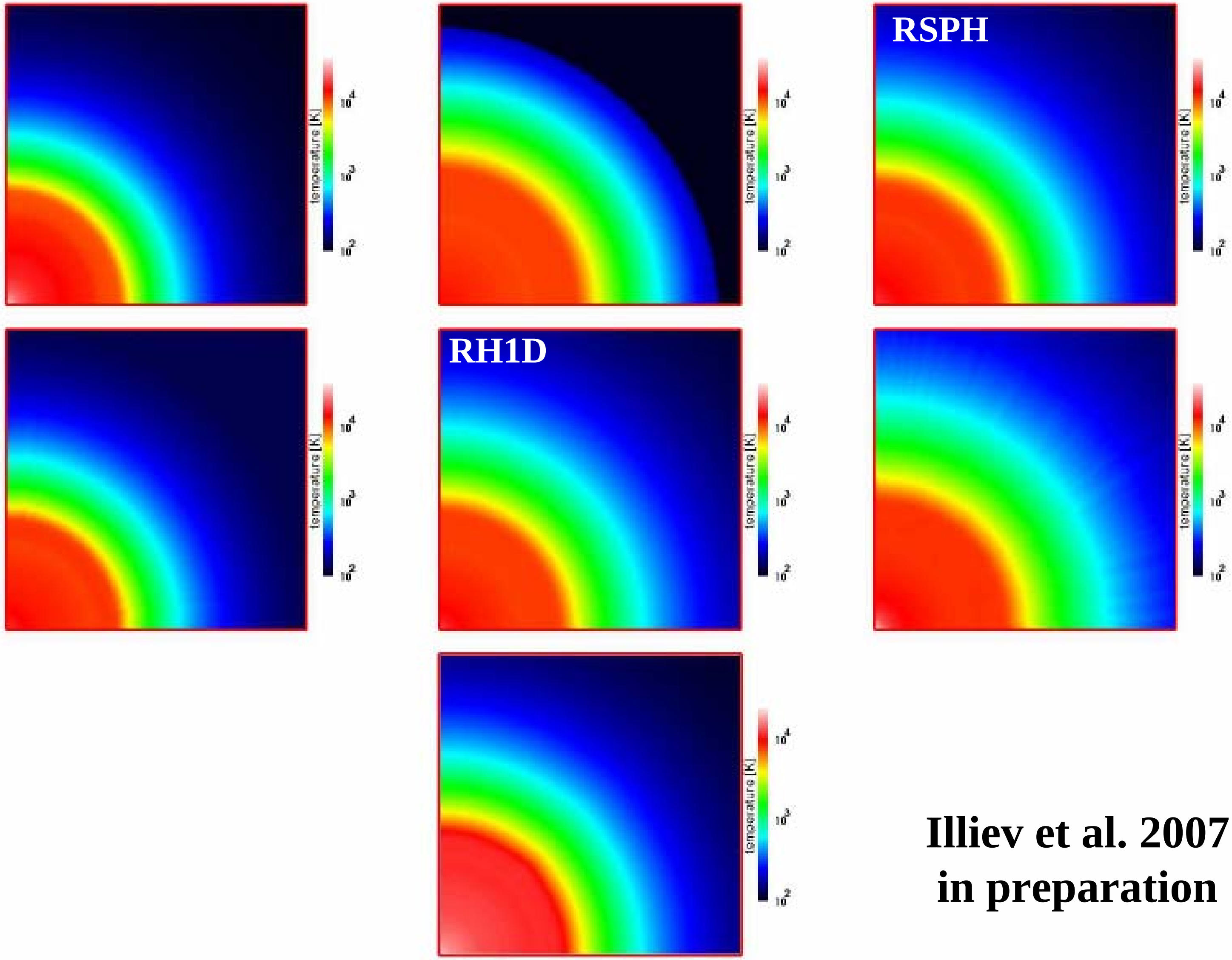


Paralellization for Multiple Sources

MWF(Node Wave Front) Parallelization



Cosmological Radiative Transfer Codes Comparison Project II: Radiative Hydrodynamic Tests



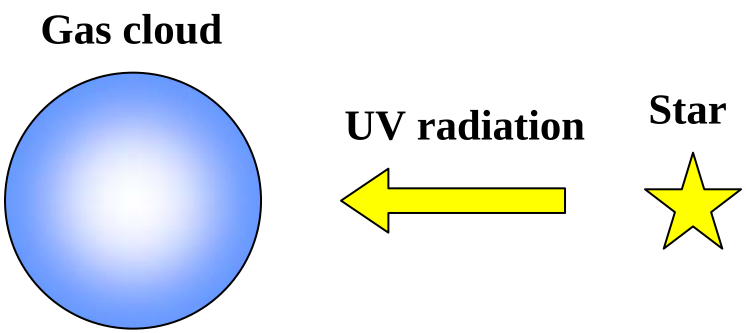
Illiev et al. 2007 in preparation

Figure 5. Test 5 (H II region expansion in an initially-uniform gas): Images of the temperature, cut through the simulation volume at coordinate $z = 0$ at time $t = 100$ Myr for (left to right and top to bottom) C^2-Ray, HART, RSPH, Zeus-MP, RH1D, LICORICE, and FLASH.

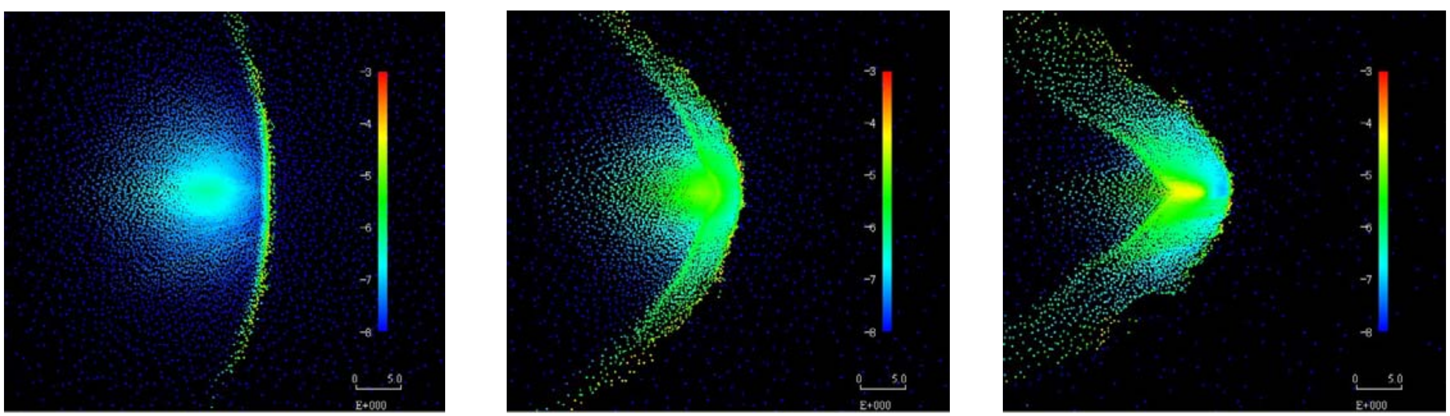
Radiation SPH Simulation on Radiative Feedback on First Star Formation

(Susa & Umemura 2006, 2007)

1 million dark matter / gas particles



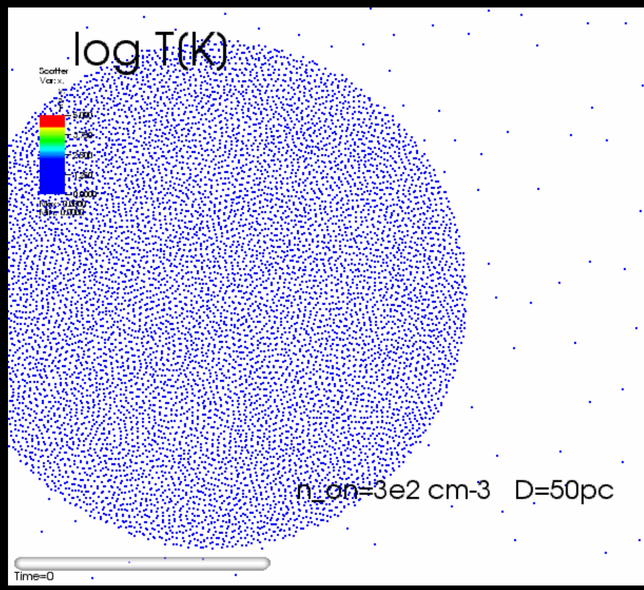
UV radiation from a star generates an ionized region accompanied by a shock, which collides with a gas cloud. If the cloud density is higher than a threshold value, it can collapse to form a new star.

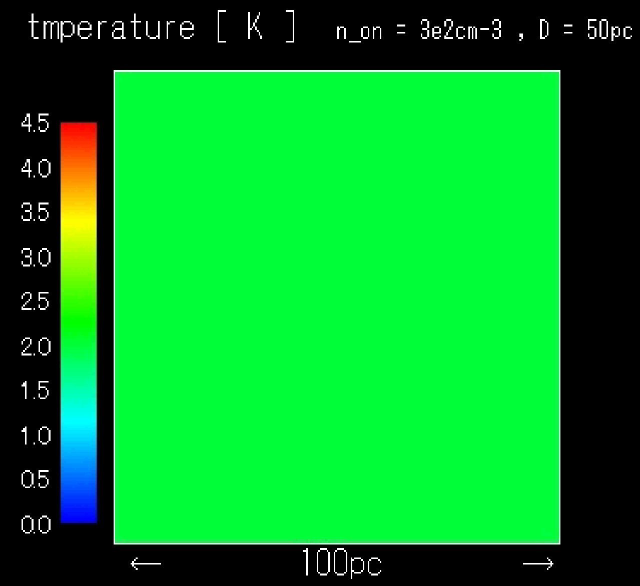


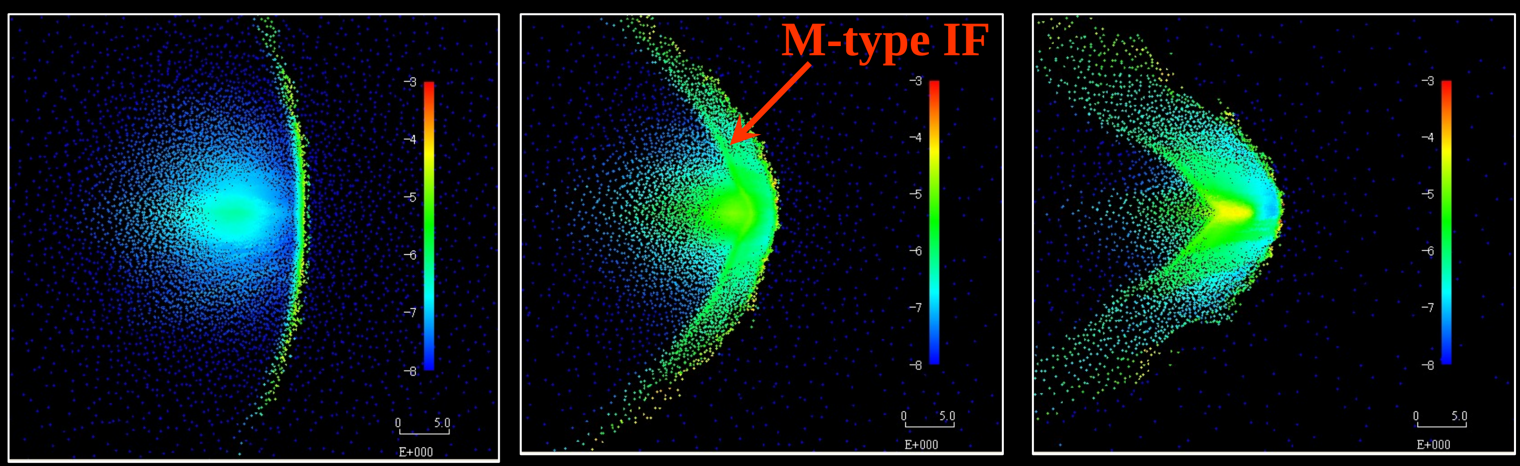
H_2 Shielded Collapse

$n_{on} = 3 \times 10^{3}\,cm^{-3}$

Susa & Umemura 2006

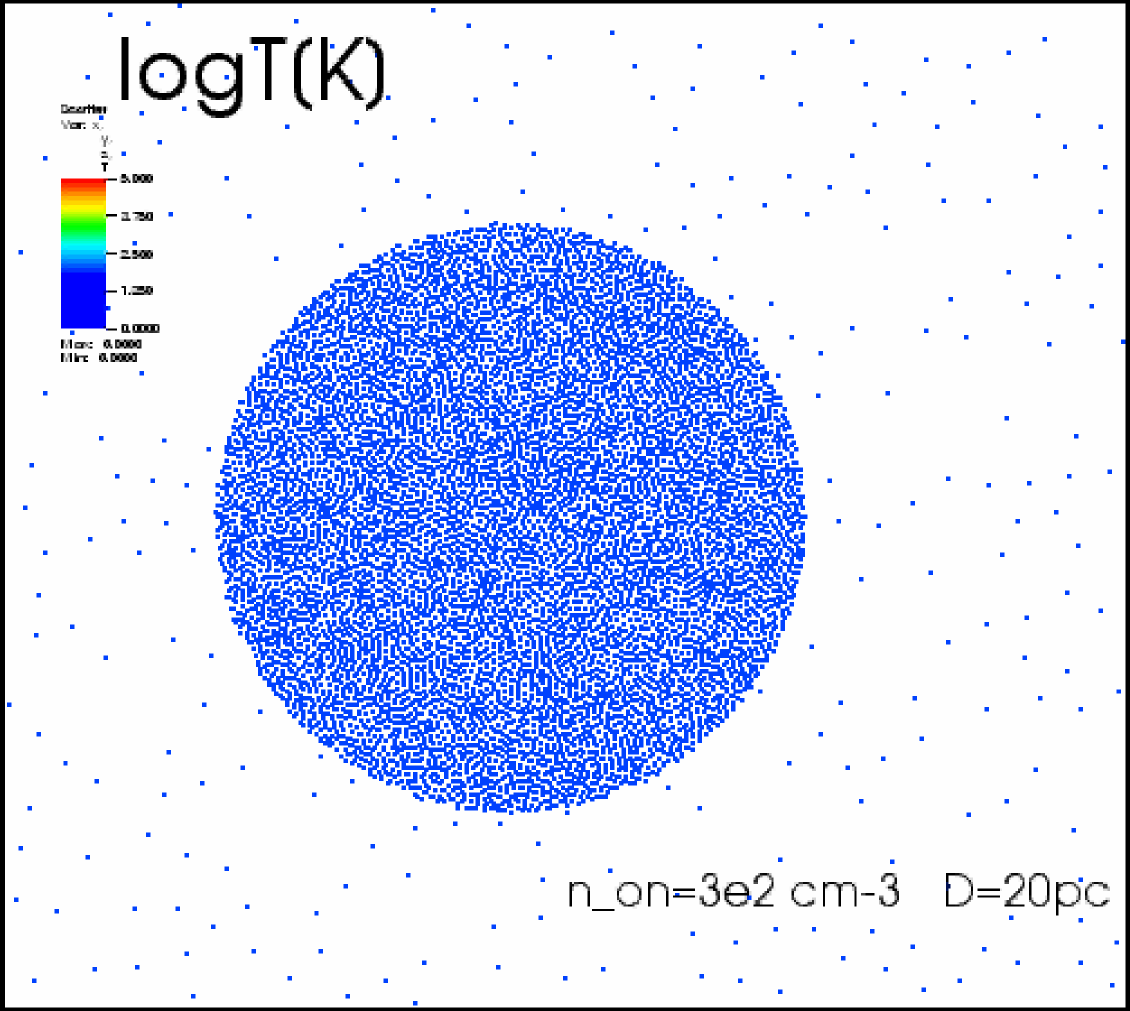






Shock-driven Evaporation

$$n_{on} = 3 \times 10^{2}\,\mathrm{cm}^{-3}$$



- **shock is raised by M-type IF**
- **shock blows the collapsing core**

P³M-GRAPE Simulation on Formation of First Stars

(Suwa et al. 2007 ⇒ this afternoon)

WMAP 3 year ΛCDM cosmology

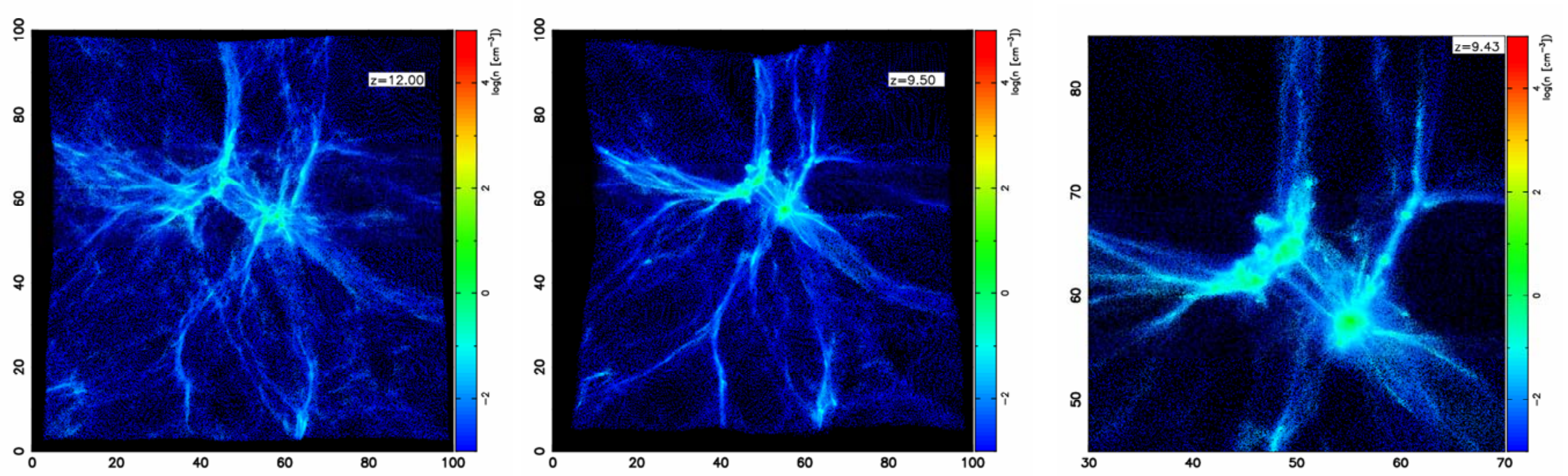
z_{in}=15, 100kpc [comoving]^3

Baryon mass: $6\times10^6 M_\odot$
Dark matter mass: $3\times10^7 M_\odot$

6 x 10^7 particles for baryon + dark matter

Mass resolution: $0.3 M_\odot$ in baryon
$1.5 M_\odot$ in DM

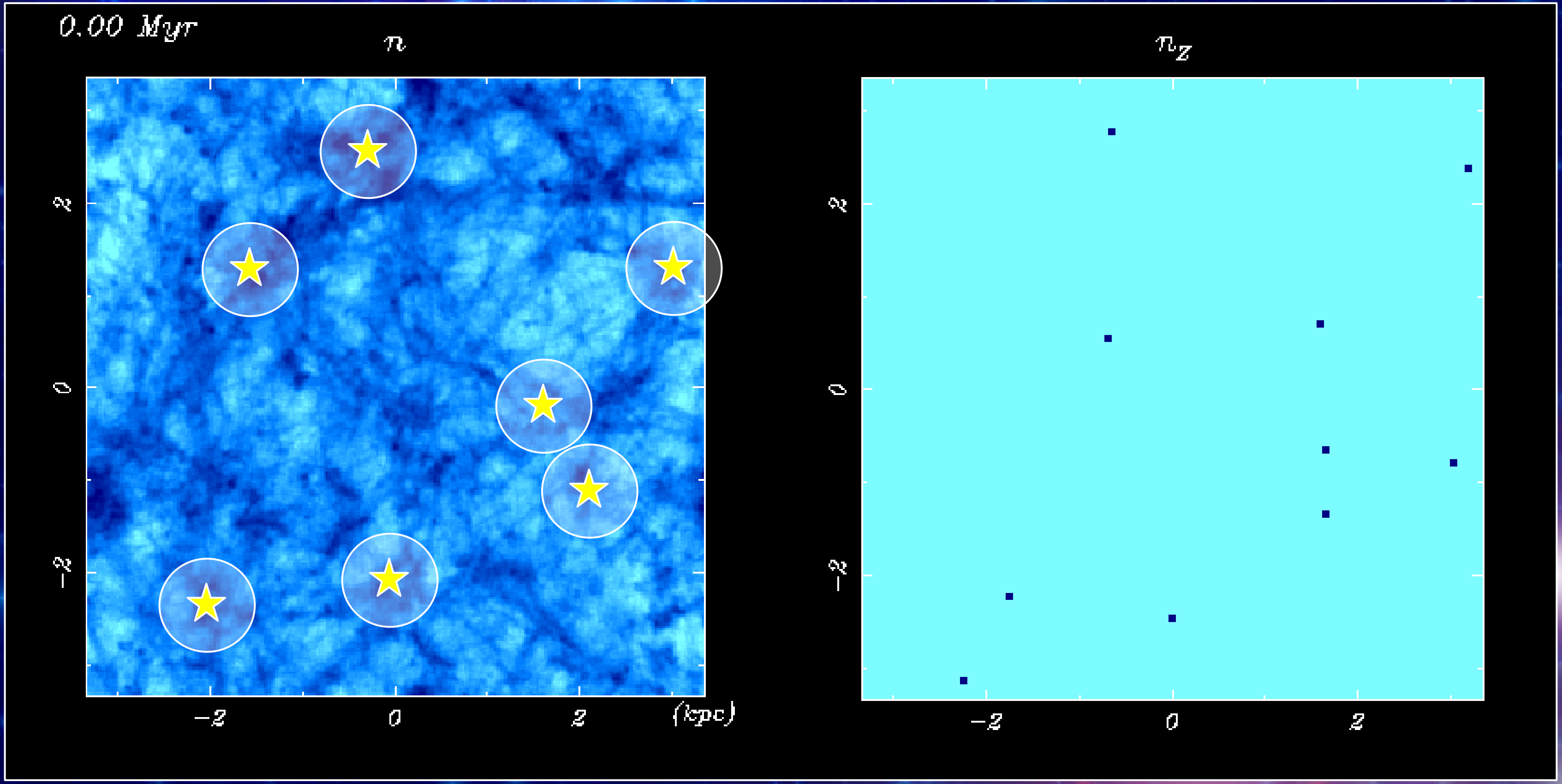
No change of mass resolution throughout the simulation



First Metal Enrichment in the Universe

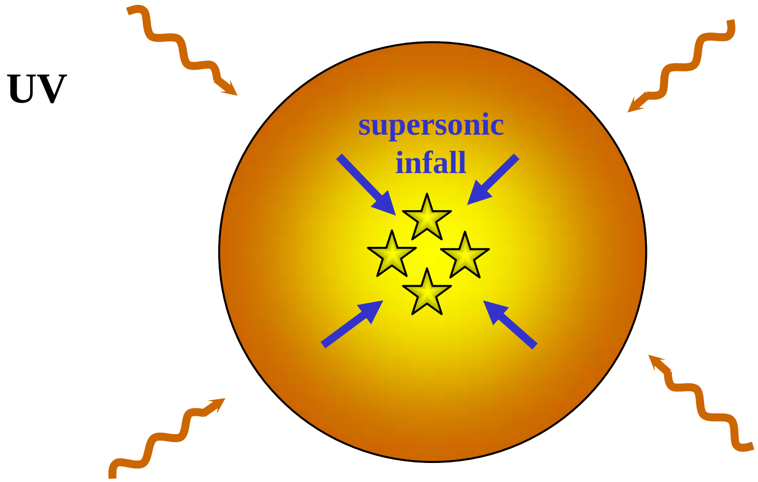
Mori & Umemura 2007

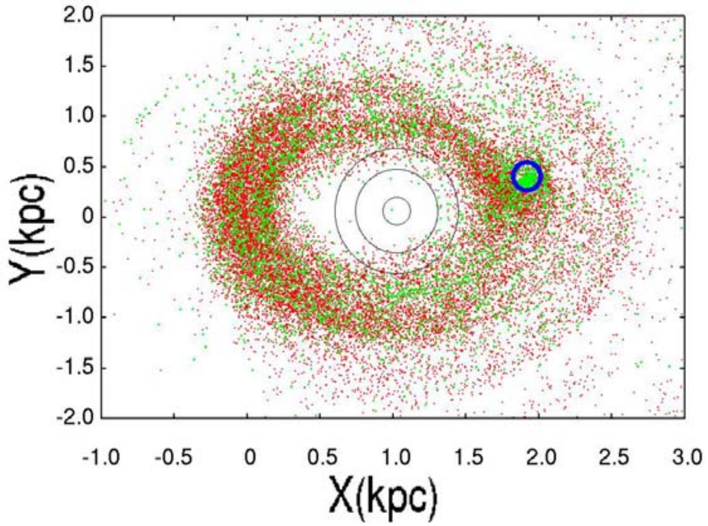
Total mass $10^8\ M_\odot$, Baryon mass: $1.75 \times 10^7\ M_\odot$, z=20
256^3 mesh

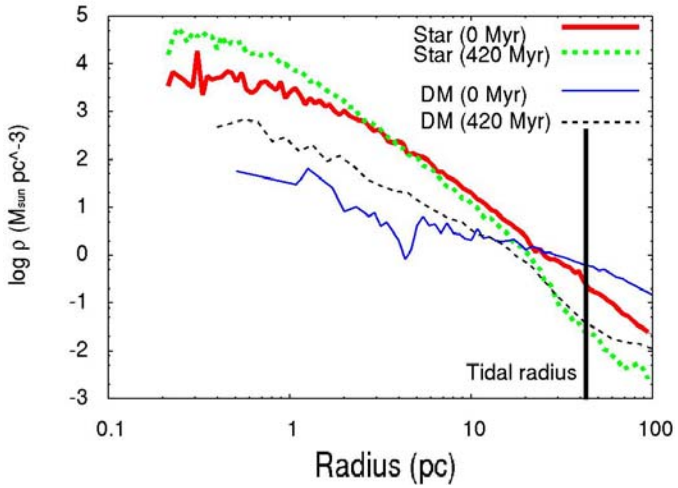


Globular Cluster Formation in UV Background

(Hasegawa & Umemura, 2007 ⇒ next afternoon)





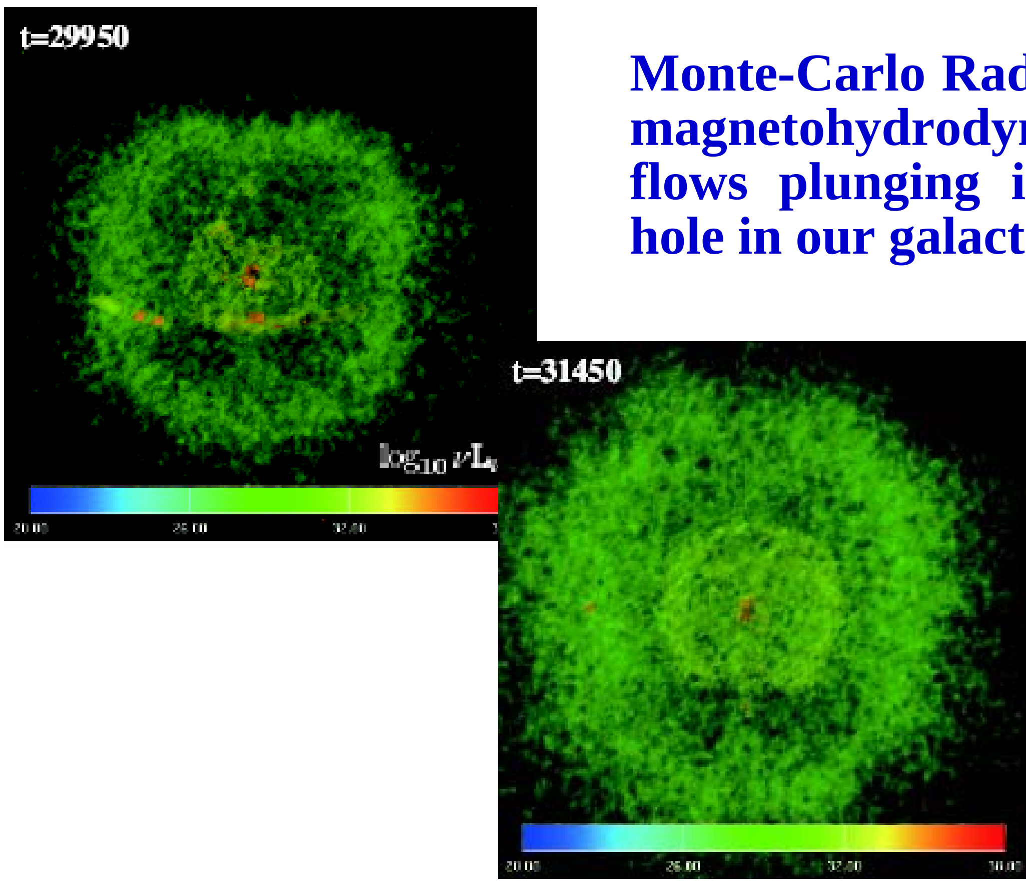


Radiative Transfer in Magneto-hydrodynamic Accretion Flows

(Kato et al. 2007 ⇒ next afternoon)

Emergent spectrum of the Galactic center

Monte-Carlo Radiative Transfer is solved in magnetohydrodynamic (MHD) accretion flows plunging into a supermassive black hole in our galactic center.



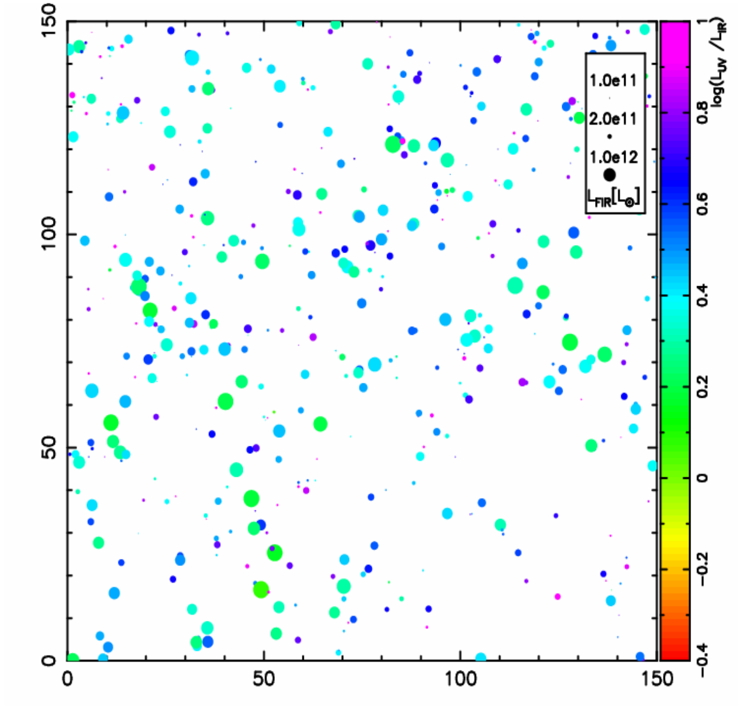
P³M-GRAPE Simulation on Early Structure Formation in the Universe

(Hirashita et al. 2007, in prep)

High-Redshift Galaxies

1.6 x 10^7 dark matter particles

We simulate distributions and luminosities of high-z galaxies with cosmological N-body scheme on 16 nodes of FIRST.



These galaxies are expected to be found by next generation telescopes, e.g. ALMA.

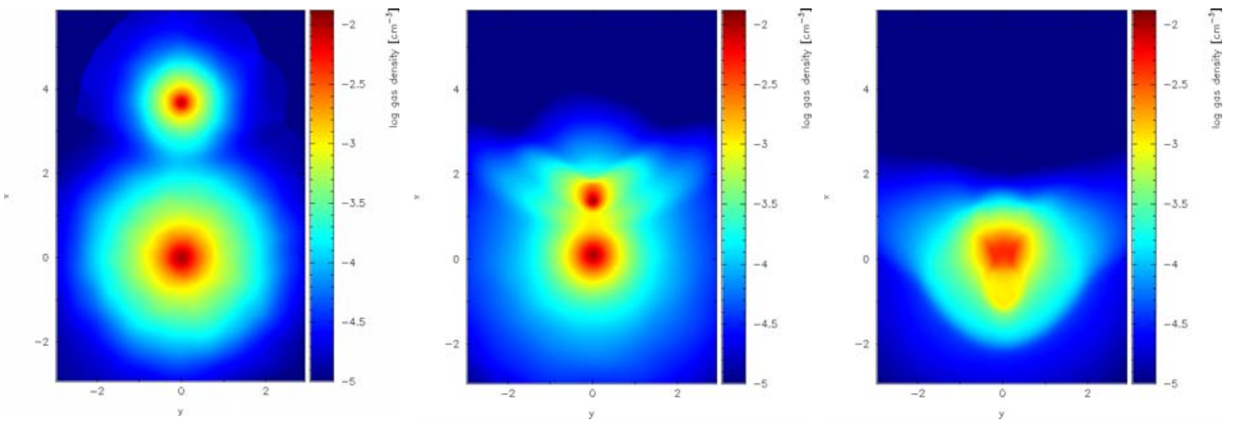
Luminous infrared galaxies at z=6

SPH Simulation on Merger of Galaxy Clusters

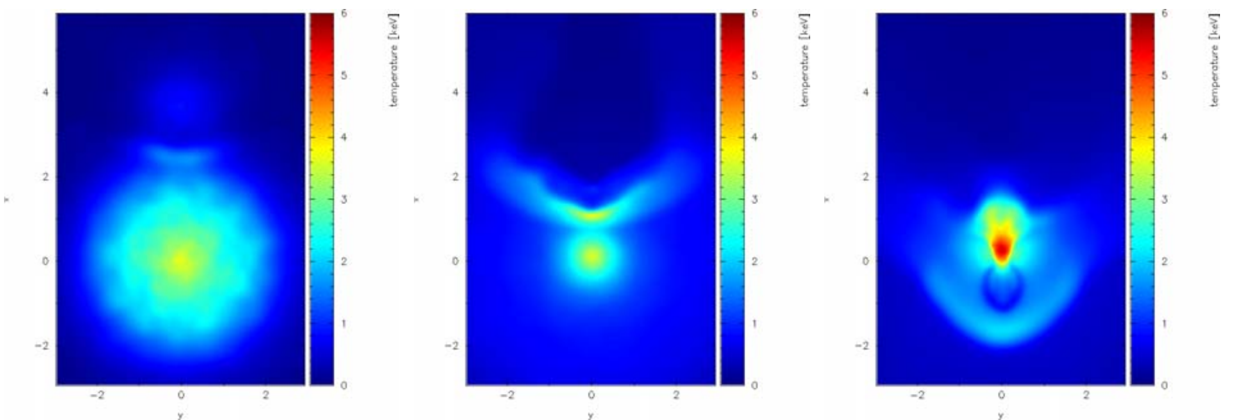
(Akahori et al. 2007 ⇒ next afternoon)

Non-equilibrium states of intracluster plasma

Density



Temperature



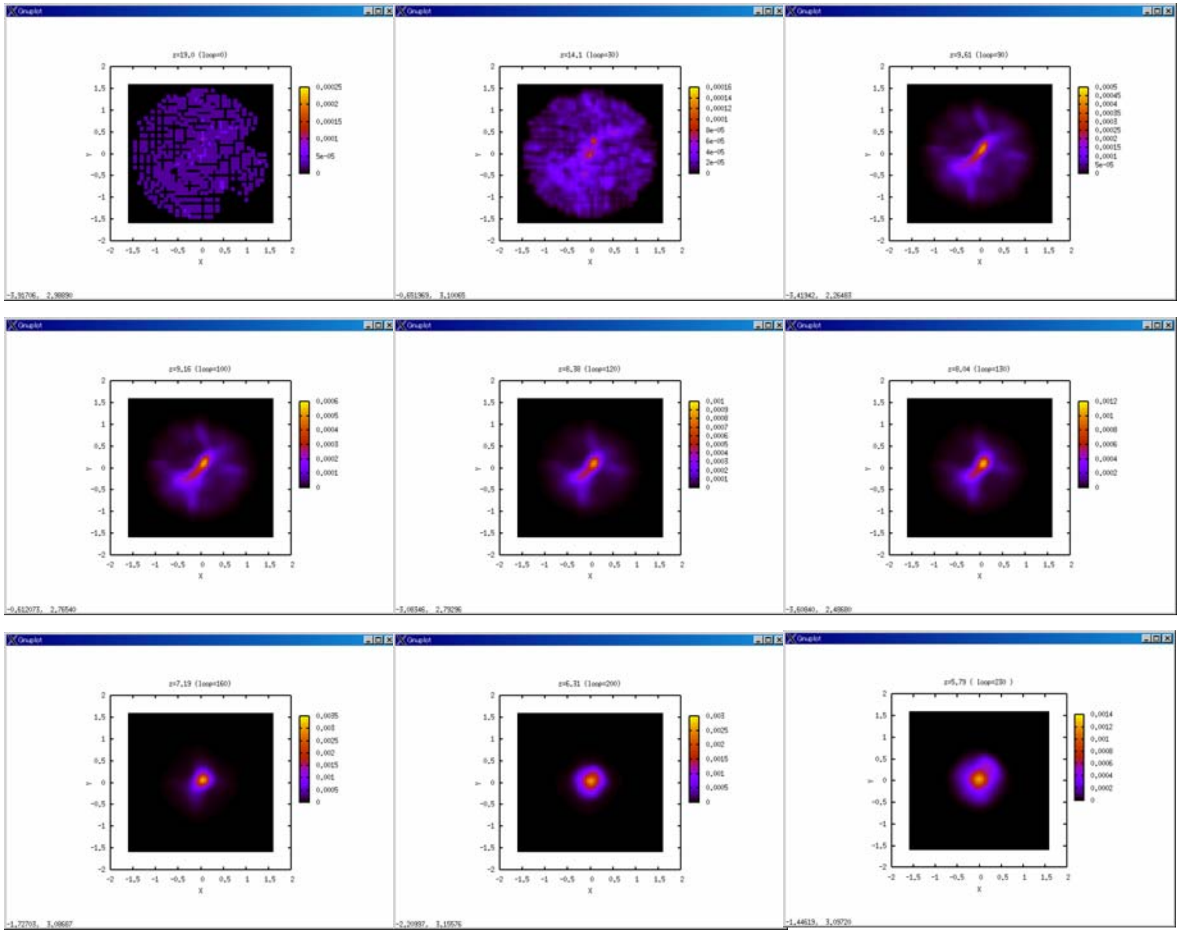
Non-equilibrium states of intracluster plasma are good probes for understanding merging clusters, in parallel with calculations for dozens of electron non-equilibrium states of oxygen, iron, and other heavy elements in the plasma.

6D Collisionless Boltzmann for Dark Matter

(Sato & Umemura, in prep.)

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} + \left(-2\frac{\dot{a}}{a}v - \frac{1}{a^3}\sum_j \frac{Gm_j\left(x_i - x_j\right)}{\left|x_i - x_j\right|^3} \right)\frac{\partial f}{\partial v} = 0$$

6D collisionless Boltzmann equation is solved in phase space with CIP scheme.



Summary

- "FIRST" simulator has been build up to realize radiation hydrodynamic simulations in astrophysics.

- It possesses accelerator for gravity calculations, Blade-GRAPE, and the total peak speed is 36.1 Tflops.

- Intensive simulations have started with FIRST simulator on

1) Formation of First Stars
2) Formation of Globular Clusters
3) Formation of First Galaxies
4) BH Accretion Flows
5) Clusters & Large-scale Structure
6) Collisionless Boltzmann