Computational Astrophysics

Lecture 1: The role of simulation in astrophysics

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Urbana-Champaign Weather

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CURRENT CONDITIONS

23°F
1:53AM

Cloudy Skies
Temperature: 23°F
Wind Chill: 9°F
Dew Point: 18°F
Rel. Humidity: 80%
Winds: S at 18 mph
Visibility: 10 miles
Pressure: 1024.9 mb (30.23 in)
Sunrise: 7:08AM
Sunset: 5:03PM

Overnight

Partly cloudy. Lows 12 to 17. South winds 10 to 15 mph.

NEXT FEW DAYS

OVERNIGHT:

PARTLY CLOUDY

Partly cloudy. Lows 12 to 17. South winds 10 to 15 mph.

MONDAY:

PARTLY SUNNY

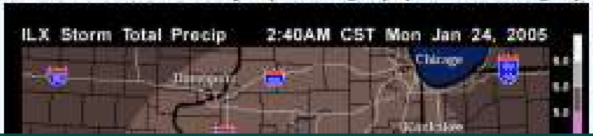
Partly sunny. Highs in the upper 30s. Southwest winds 10 to 15 mph.

MONDAY NIGHT:

North Quad Live: (Enlarge)

Latest Radar: (Enlarge) (Quick Image)

Storm Total Precip: (Enlarge) (Quick Image)



Research interests

- Astrophysics
  - Clusters of galaxies
  - Large-scale structure
  - Globular clusters
  - Supernovae and gamma-ray bursts
- Numerical
  - Adaptive mesh refinement
  - Frameworks and cyberinfrastructure
  - Co-developer, COSMOS and FLASH codes

Overview

Lecture 1: The role of simulation in astrophysics

Lecture 2: Gasdynamics

Lecture 3: Magnetic fields

Lecture 4: Particles and gravity

Lecture 5: Radiation

Lecture 6: Software development and testing

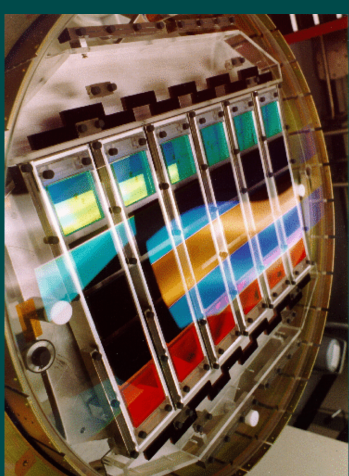
http://www.astro.uiuc.edu/classes/archive/astr496/s03_cac

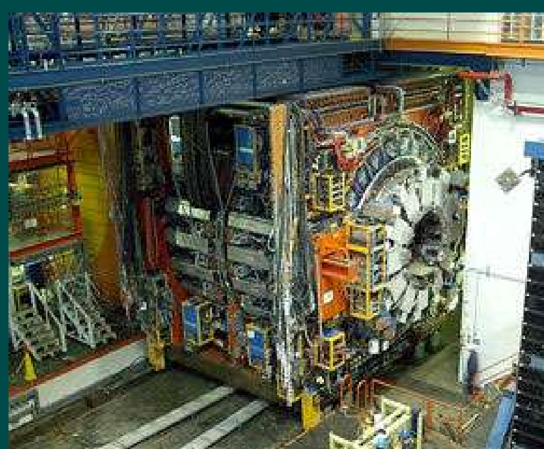
Governing Analogies

Telescopes
Accelerators
Apparatus

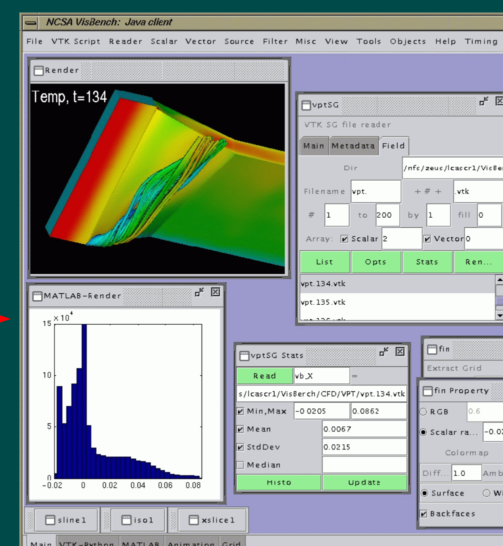
Fast computers +
Simulation codes

```
subroutine rieman (nzn, ei, rhoav, uav, utav, uttav, &
    pav, urell, ugrdl, game, gameav, xnav)

  implicit none

  integer :: nzn

  real, DIMENSION(q) :: ei, rhoav, uav, utav, uttav, pav, &
      &   urell, ugrdl, game, gameav

  real, DIMENSION(q) :: wlft, wrght, pstar, ustar, vstar, cestar, &
      rhostr, westar, ps, us, uts, utts, vs, rhos, ces, ws, wes, &
      gmstar, games, gamcs

  real, DIMENSION(q,qn) :: xnav

  real, DIMENSION(q) :: pstar1, pstar2, gmstrl, gmstrr, &
      &   wlft1, wrght1, gmin, gmax, &
      &   gamfac, aux

  real  ::  ge, gc, ustrl1, ustrr1, ustrl2, ustrr2, &
      & delu1, delu2, pres_err
```





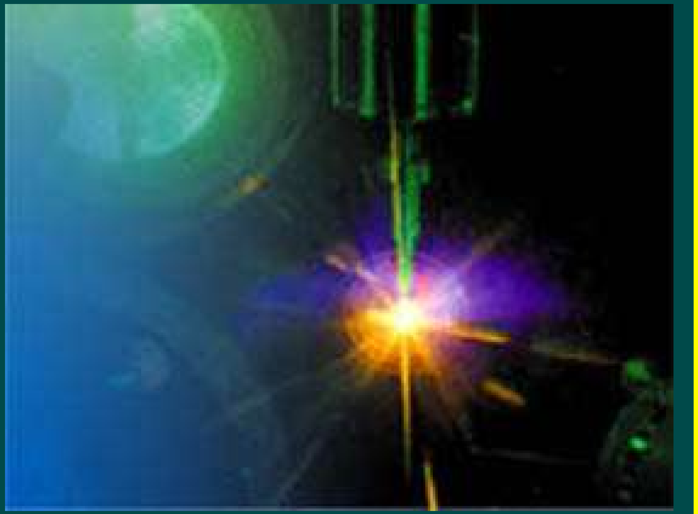
Cameras
Detectors

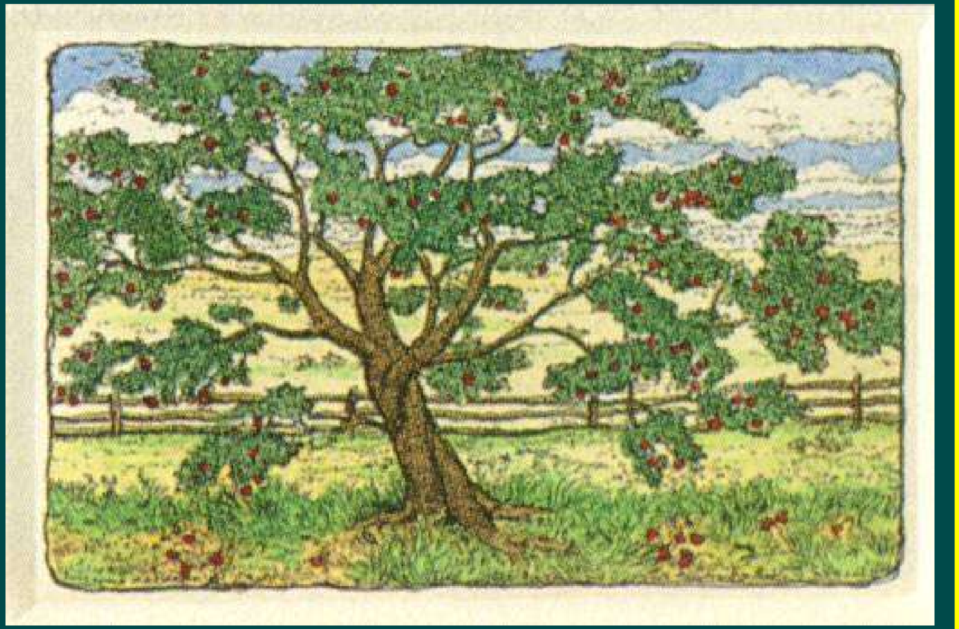


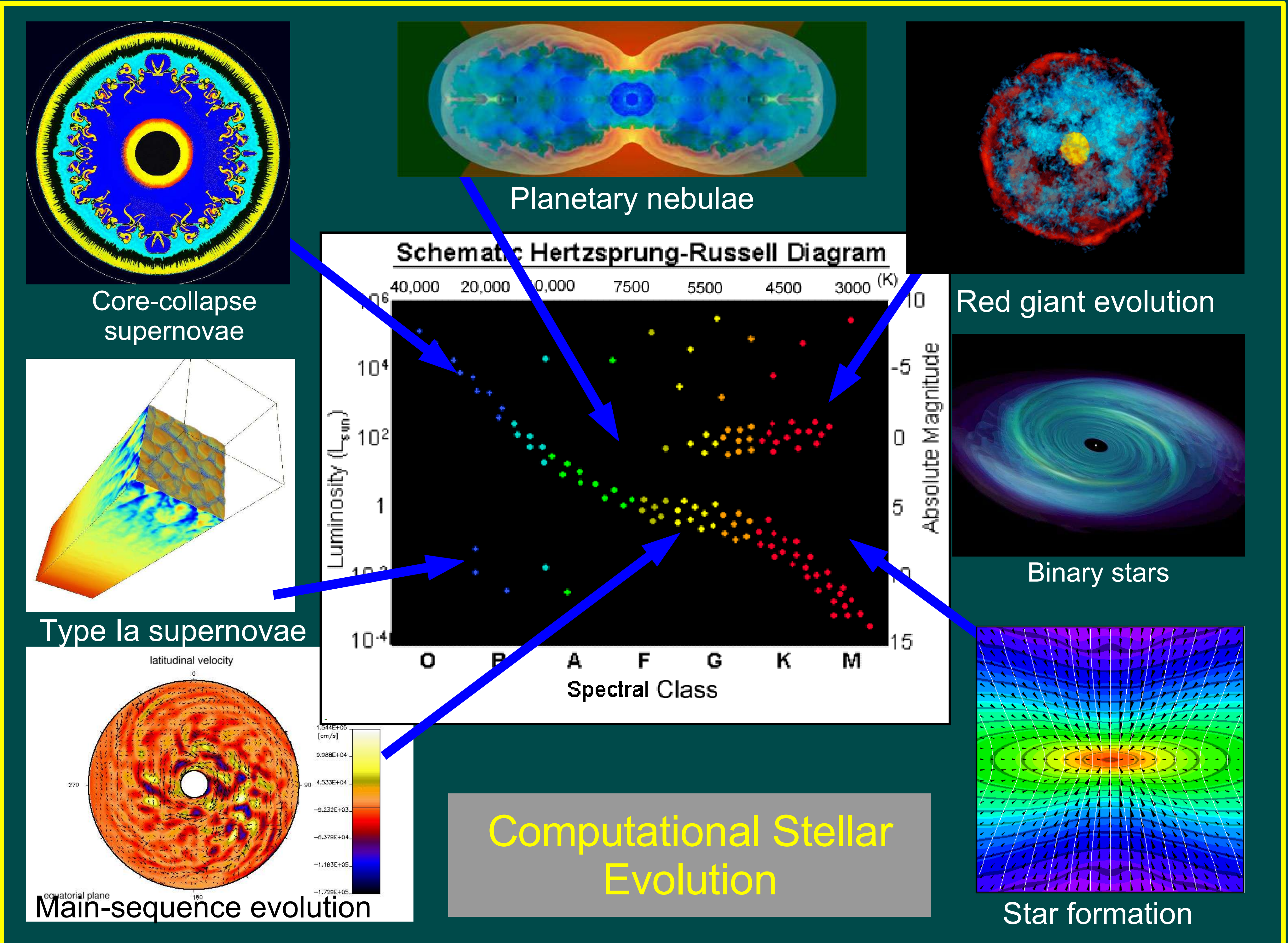
Analysis software

The Fundamental Issues

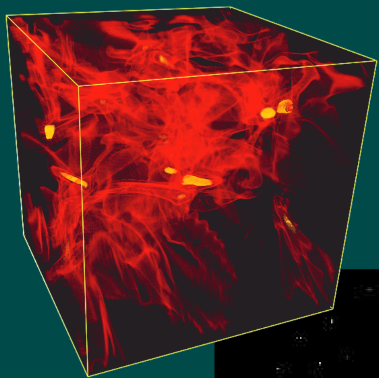
- We cannot visit/manipulate the objects of study; too distant
- Astrophysics involves extreme conditions that cannot be replicated in lab (mostly)
- Timescales are $\gg$ human lifespan; all we have are snapshots (mostly)



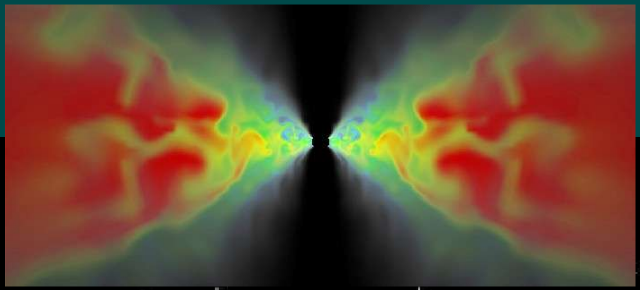




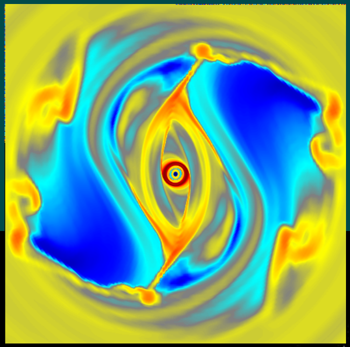
Core-collapse supernovae
Planetary nebulae
Red giant evolution
Schematic Hertzsprung-Russell Diagram
40,000
20,000
7500
5500
4500
3000
(K)
Luminosity (L_{sun})
10^4
10^2
1
10^{-4}
Absolute Magnitude
10
-5
0
5
15
O
A
F
G
K
M
Spectral Class
Binary stars
Type Ia supernovae
latitudinal velocity
equatorial plane
Main-sequence evolution
Star formation
Computational Stellar Evolution



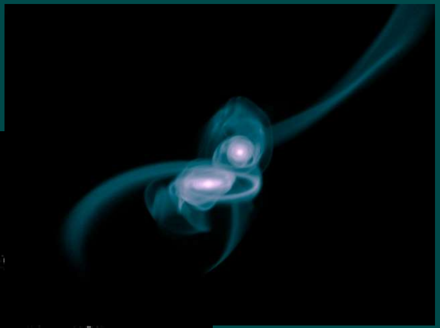
Molecular clouds



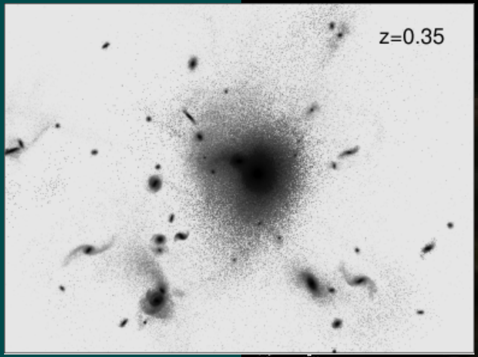
Supermassive black holes



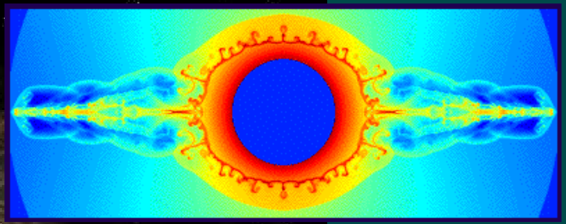
Evolution of disk structure



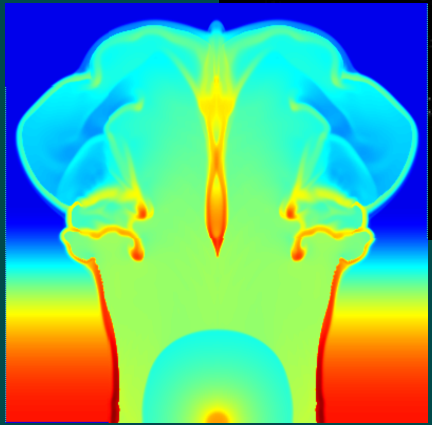
Galaxy mergers



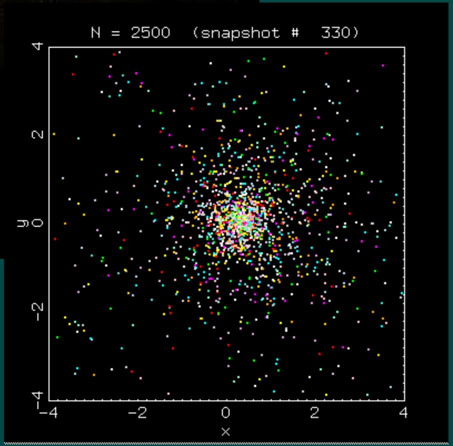
Galaxy evolution in clusters



Supernovae and the interstellar medium



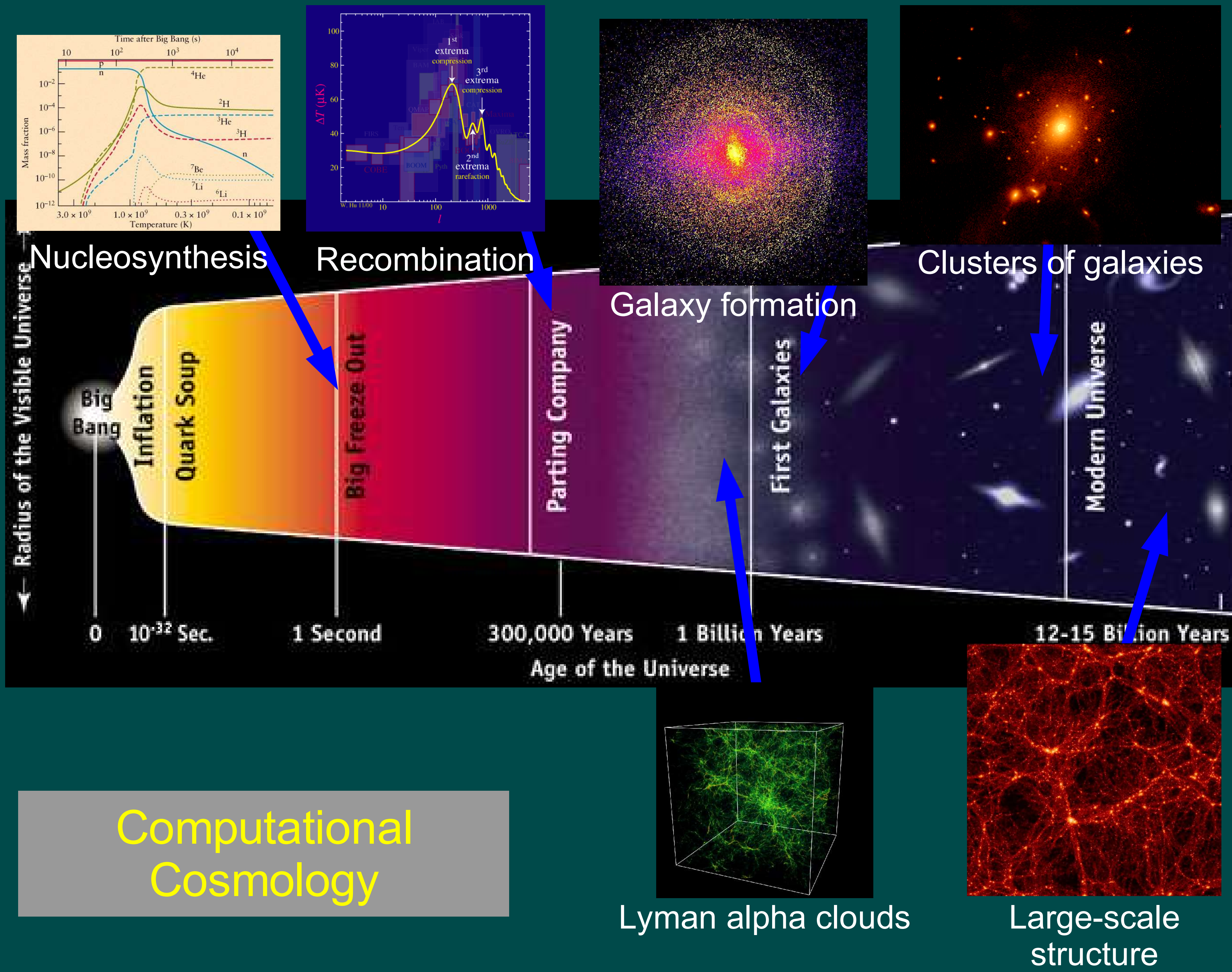
Superbubbles



Star clusters

Computational Galactic Evolution

Computational Cosmology



Elements of simulation

- Numerical experiment
  - *Ab initio* physics
  - Modelled physics
  - Initial conditions
  - Boundary conditions
- Analysis
  - Parameter determination
  - Simulated observations
  - Physical insight

Tools of simulation

- Initial conditions generator
- Simulation code (time evolution)
- Analysis tools (post-processing)
- Visualization tools
- Infrastructure

Steps in numerical experimentation

1. Choosing a problem
2. Choosing a numerical method
3. Choosing a code
4. Constructing initial and boundary conditions
5. Estimating requirements
6. Proposing for resources
7. Verifying calculations
8. Conducting calculations
9. Analyzing results
10. Refining the calculations

Choosing a problem

1. Back-of-the-envelope calculations

- Have a basic understanding of the problem and rough outlines of solution before you sit down at the computer!
- Estimate orders of magnitude (energies, timescales, etc.)
- Know the state of the art

2. Goals of numerical experimentation

- Theory testing – Can theory *X* produce effect *Y*?
- Parameter estimation – What is theoretical expectation for observed value of quantity *Q* (*and its errors*)?
- Sensitivity analysis – What input parameters are most important for determining outcome?
- Physical insight – What physical models/mechanisms must be included?
- Numerical insight – How do numerical issues (e.g. resolution) affect results?

Choosing a numerical method

1. Determining the classes of solvers needed

- What physics is needed?
- Can existing algorithms handle the necessary physics?
- Will new algorithms need to be developed?

2. Determining feasibility

- What parts of solution can be solved *ab initio* and what parts must be put in by hand?
- Do the available methods perform well on available machines?
- What were the requirements of the most similar published work?

Choosing a code

1. Does it already have the physics you need?

2. Does it run efficiently on a machine you have access to?

3. What is the learning curve like?

4. Is it well-tested?

5. Does it support standard data formats?

Some publicly available astrophysics codes

Code	**Type**	**Physics**	**Parallel**	**Reference**
Cactus	Eulerian/Nested	Gas, gravity (GR)	MPI	Allen et al 99
Enzo	AMR/PM	Gas, particles, gravity, cosmology	MPI	Norman & Bryan 98; O'Shea et al 04
FLASH	AMR/PM	Gas, particles, gravity, cosmology, nuclear, MHD	MPI	Fryxell et al 00; Ricker et al 05
GADGET	P3M; TPM (v.2); SPH	Gas, particles, gravity, cosmology	MPI	Springel et al 01
Hydra	AP3M/SPH	Gas, particles, gravity, cosmology	No	Couchman 91
MLAPM	AMR/PM	Particles, gravity	No	Knebe et al 01
PMcode	PM	Particles, gravity	No	Klypin & Holtzmann 97
TITAN	1D AMR	Gas, radiation	No	Gehmeyr & Mihalas
VH-1	Eulerian	Gas	No	Blondin et al 91
Zeus-MP	Eulerian	Gas, gravity, MHD	MPI	Stone & Norman 92

http://www.cactuscode.org
http://cosmos.ucsd.edu
http://flash.uchicago.edu
http://www.mpa-garching.mpg.de/gadget
http://hydra.mcmaster.ca/hydra
http://www.aip.de/People/AKnebe/MLAPM
http://astro.nmsu.edu/~aklypin/pm.htm
http://wonka.physics.ncsu.edu/pub/VH-1

Issues in constructing initial conditions

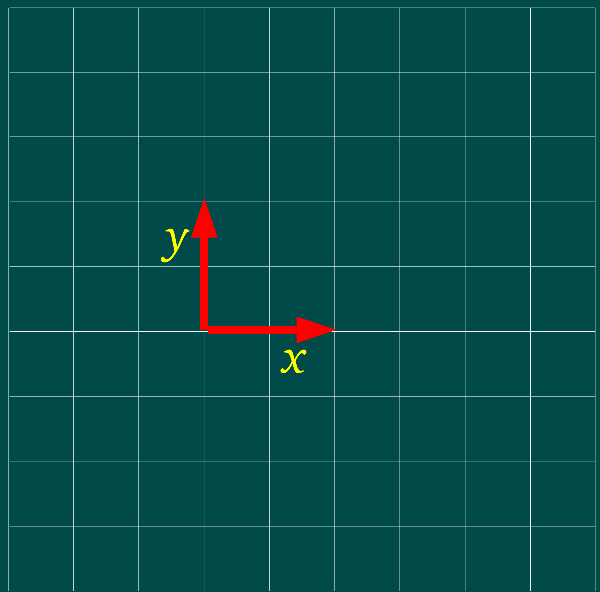
- Mapping 1D profiles onto 2D/3D grids
  - Appropriate averaging/interpolation of models
  - Artificially damping hydrostatic models
  - Allowing initial transients to dissipate
- Sharp features/gradients
  - Artificial smoothing to eliminate startup errors
  - Adequate resolution
- Gaussian random fields
  - Fourier transform normalization
  - Adequate resolution for power spectrum
- Perturbations
  - Numerical noise can seed instabilities, physical or numerical
  - Better to control spectrum and amplitude of perturbations

Issues in constructing boundary conditions

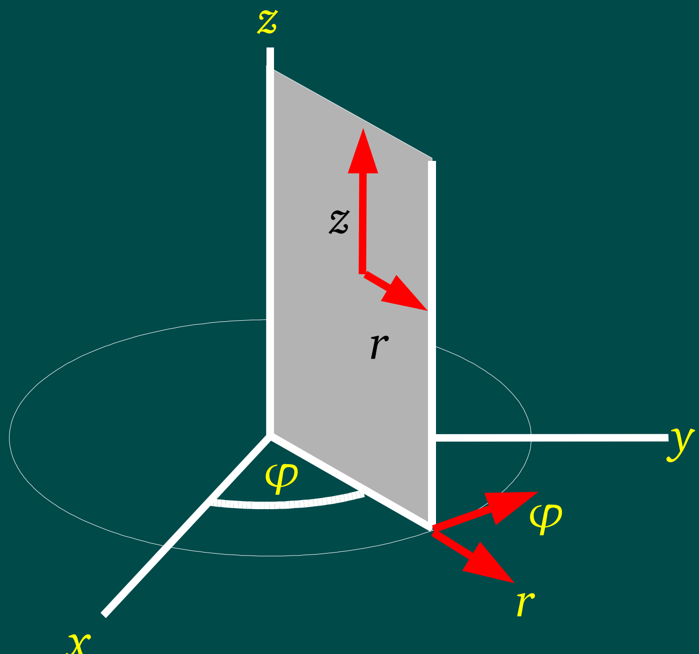
- Gasdynamics
  - Avoiding unphysical inflows and outflows
  - Avoiding reflected waves
- Gravity
  - Loss of potential due to outflowing matter
  - Neglected external tidal fields
  - In collapse problems, nonlinearity of fundamental mode
- General
  - Consistency among physics solvers
  - Geometric consistency
  - Enforced symmetries

Common geometries

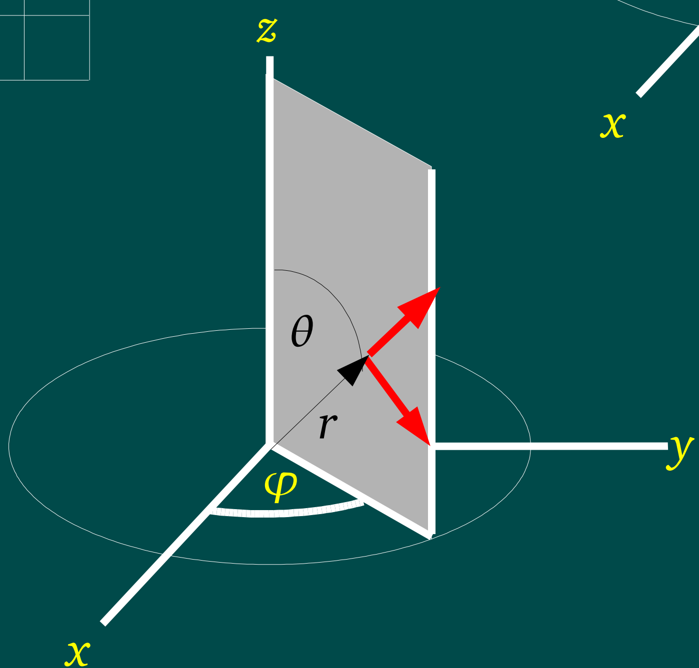
Cartesian



Cylindrical
(axisymmetric or polar)



Spherical

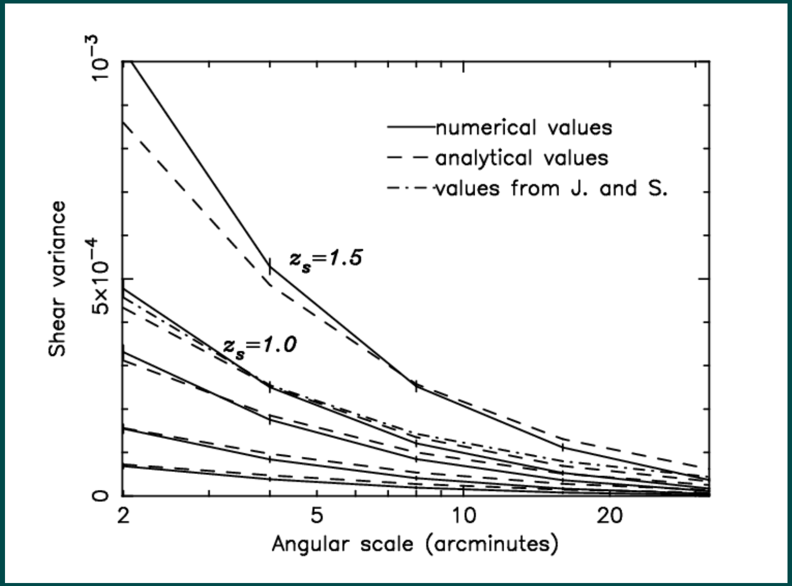


Conducting experiments

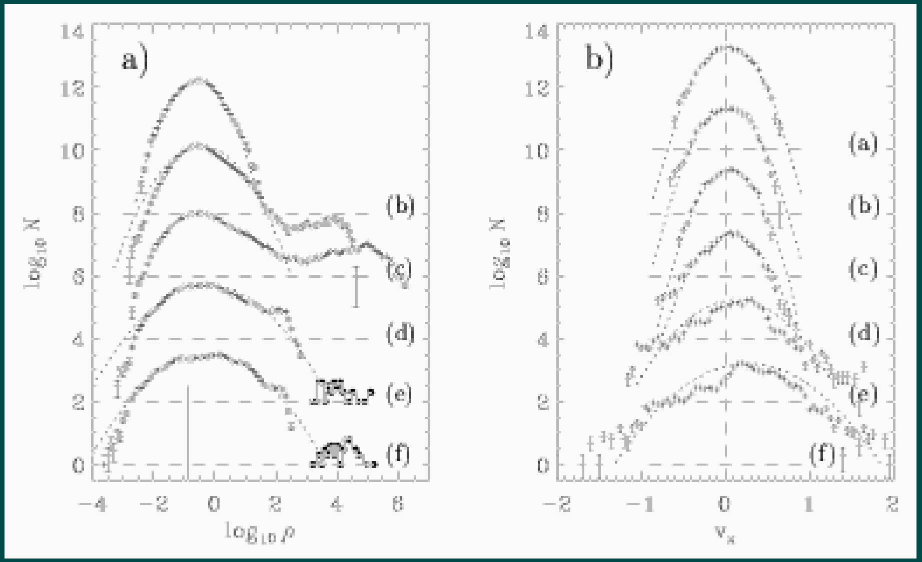
1. Work up from smaller calculations
   - Don't start with a 1024^3 run!!!
2. Employ controls
   - Verify the calculation as well as the code
   - Utilize cross-checks for consistency
3. Ensure repeatability
   - Keep raw data, intermediate data, plots, and code organized
   - Every plot and number should have a source file from which it can be regenerated
4. Document reasoning process
   - Why did you perform this calculation?
   - Did you expect this result?
   - You will forget everything in six months
5. Keep track of usage
   - Will you be able to complete your project?

Analyzing results

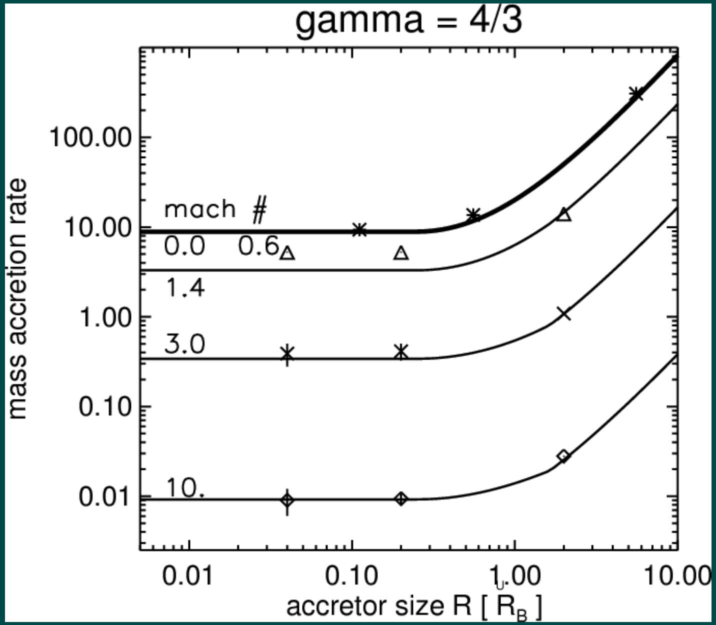
- Power spectra
- Distributions
- Integral quantities
- Profiles
- Slices
- Projections
- Isosurfaces
- Simulated observations
- Volume visualizations
- Scatter plots



Angular scale dependence of cosmic shear – A. Barber

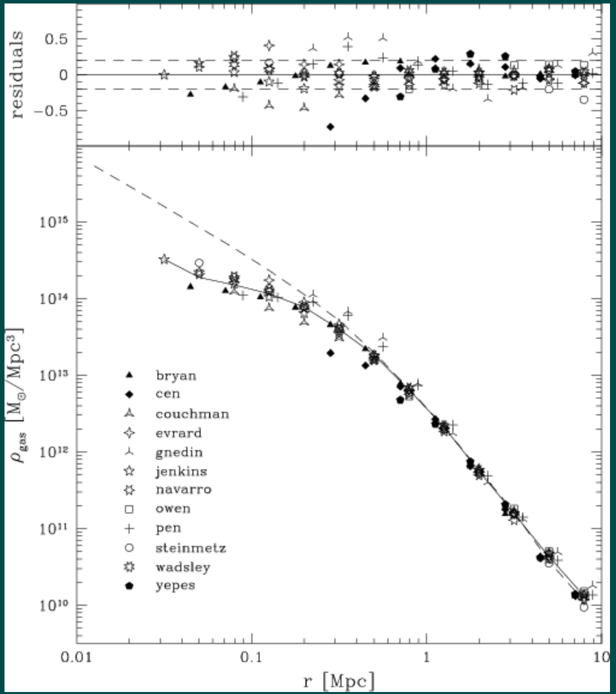


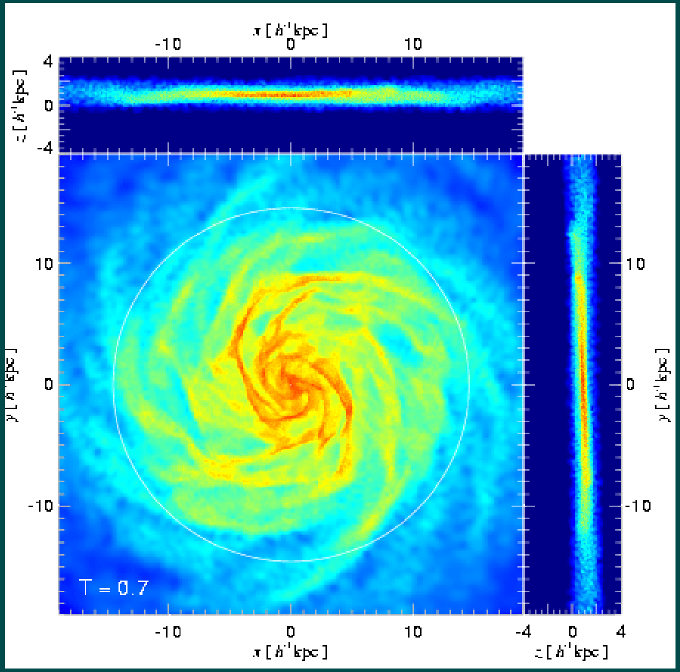
One-point probability density functions of gas density in supersonic, self-gravitating turbulence – R. Klessen



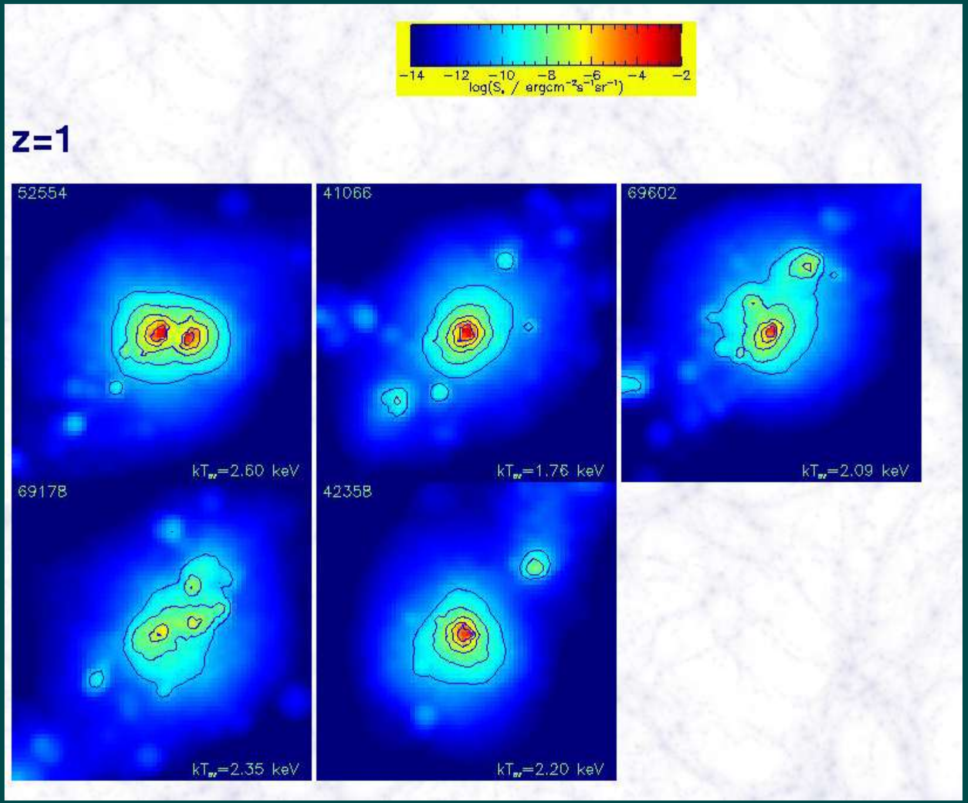
Mass accretion rate in 3D Bondi-Hoyle accretion vs. accretor size – M. Ruffert

Gas density profile in a simulated cluster of galaxies – Frenk et al. (1999)

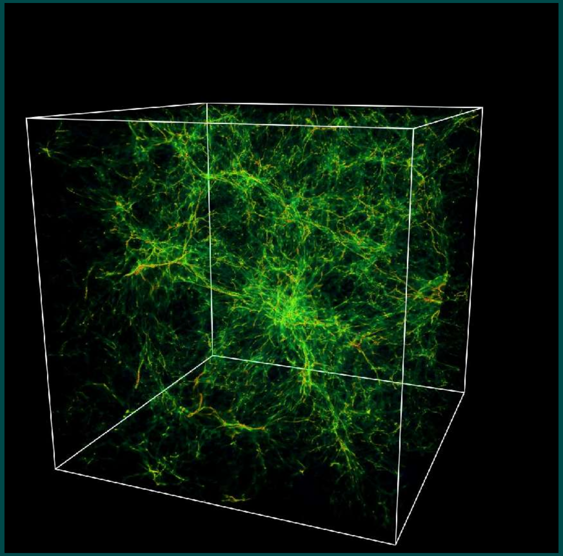




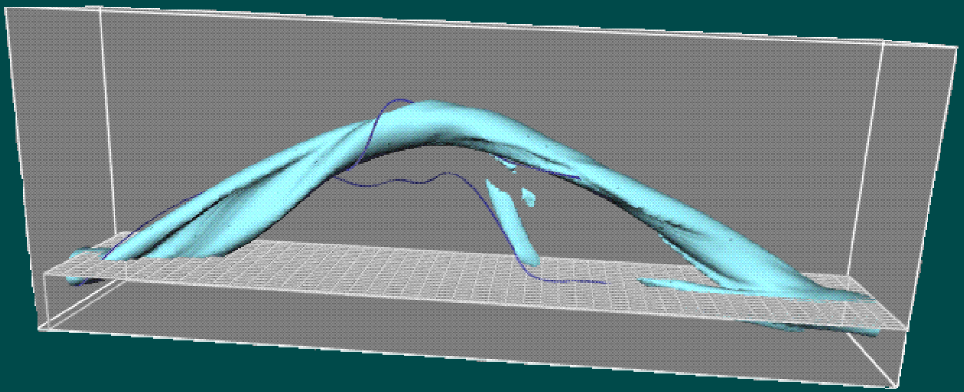
Projections of star formation rate in spiral galaxies – V. Springel



Simulated X-ray observations of clusters in a large-scale structure simulation – Hydra Consortium

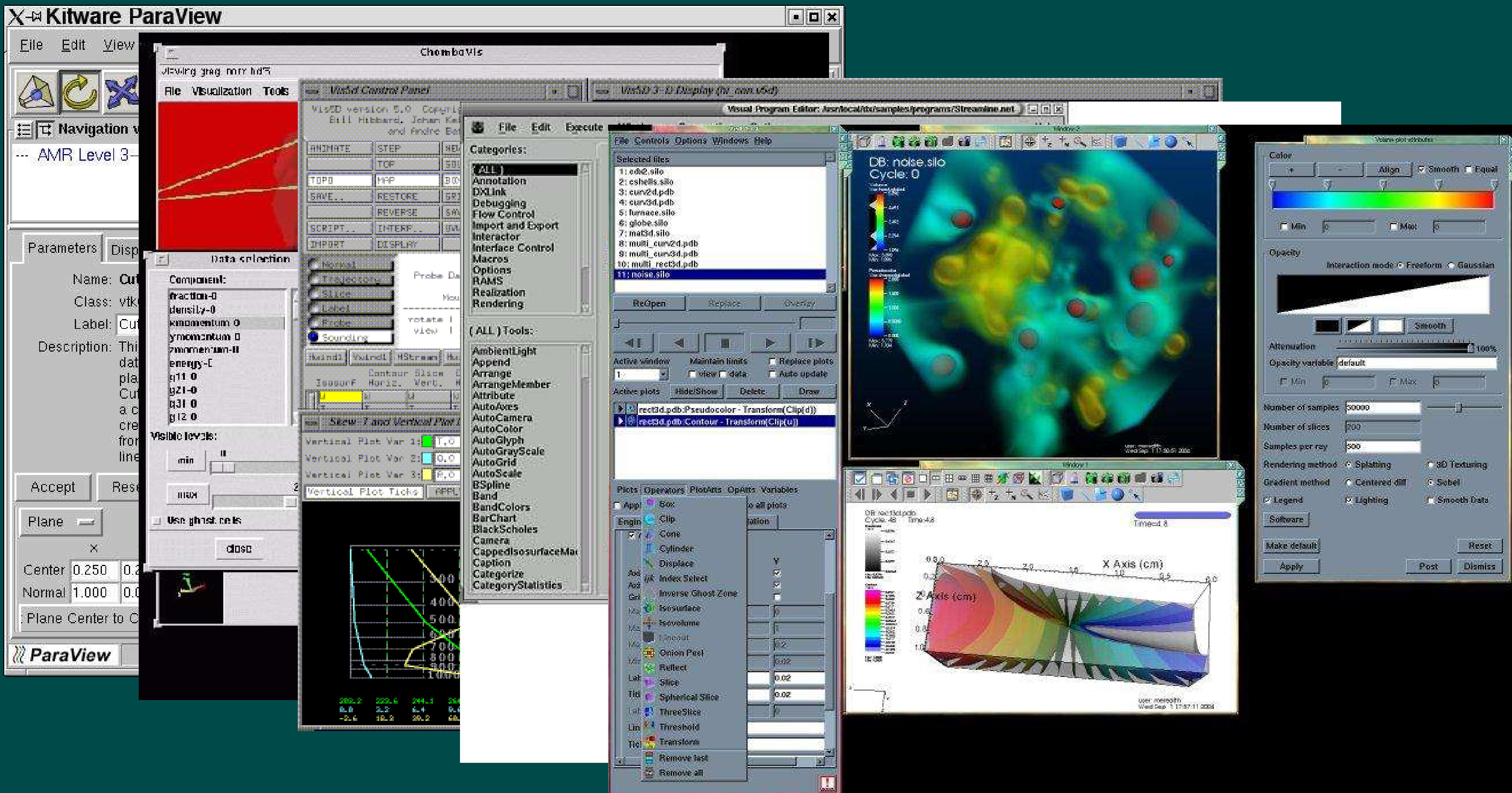


Gas density volume visualization of the Ly α forest – R. Cen



Isosurface of a buoyant magnetic flux tube – A. Nordlund

Some publicly available visualization packages



ParaView (http://www.paraview.org)
ChomboVis (http://seesar.lbl.gov/anag/chombo/chombovis.html)
Vis5D+ (http://vis5d.sourceforge.net)
OpenDX (http://www.opendx.org)
VisIt (http://www.llnl.gov/visit)