SPH simulations of galaxy formation

Looking under the hood of GADGET-2

Volker Springel

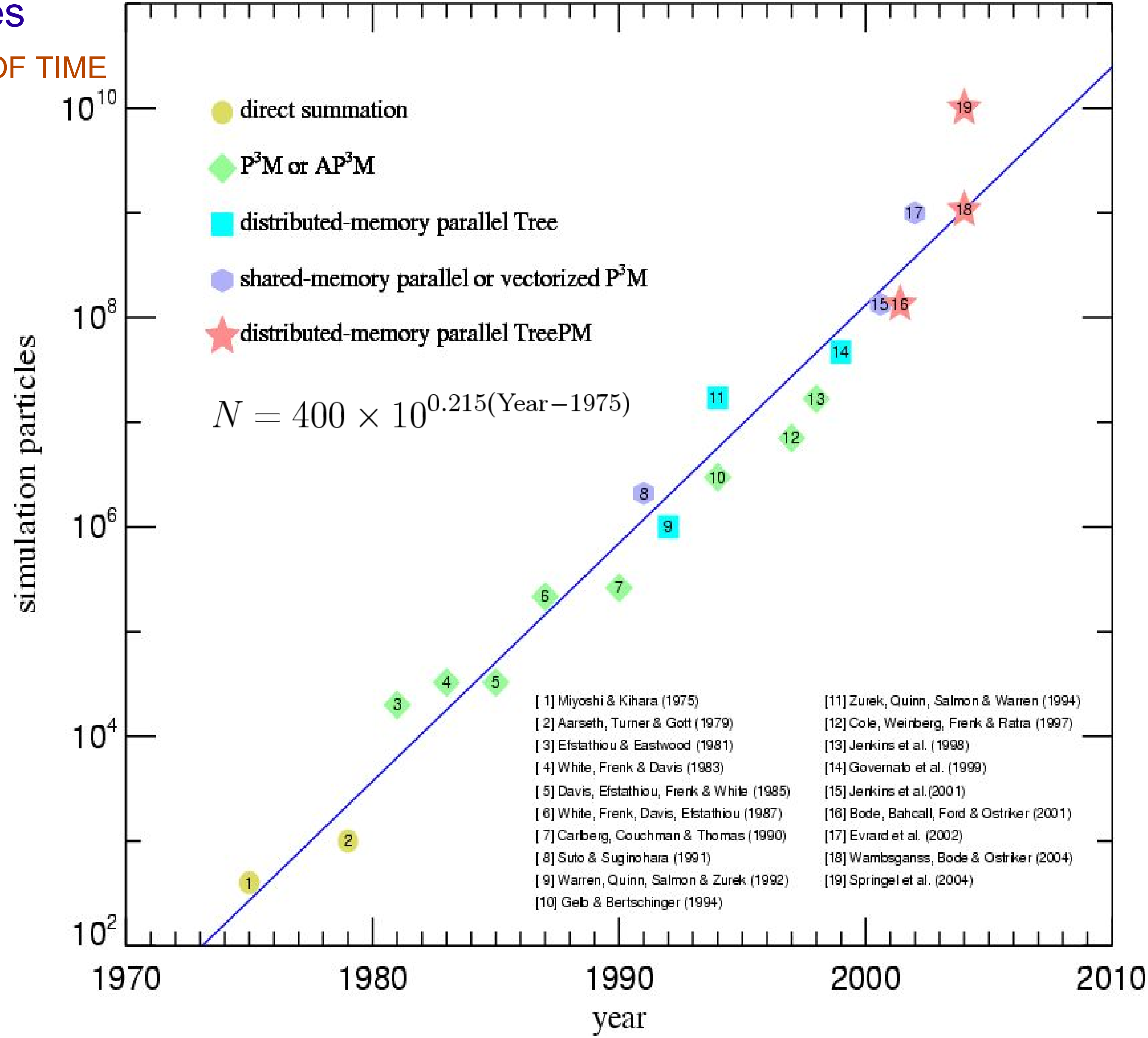
- **Large N-body runs**
- **Algorithmic aspects of a new simulation code: GADGET- II**
- **Non-standard physics in simulations of galaxy formation**
  - **sub-resolution multiphase-model for star formation, feedback & galactic winds**
  - **accretion on SMBH and feedback**

Max-Planck-Institut
für Astrophysik

Cosmological N-body simulations have grown rapidly in size over the last three decades

"**N**" AS A FUNCTION OF TIME

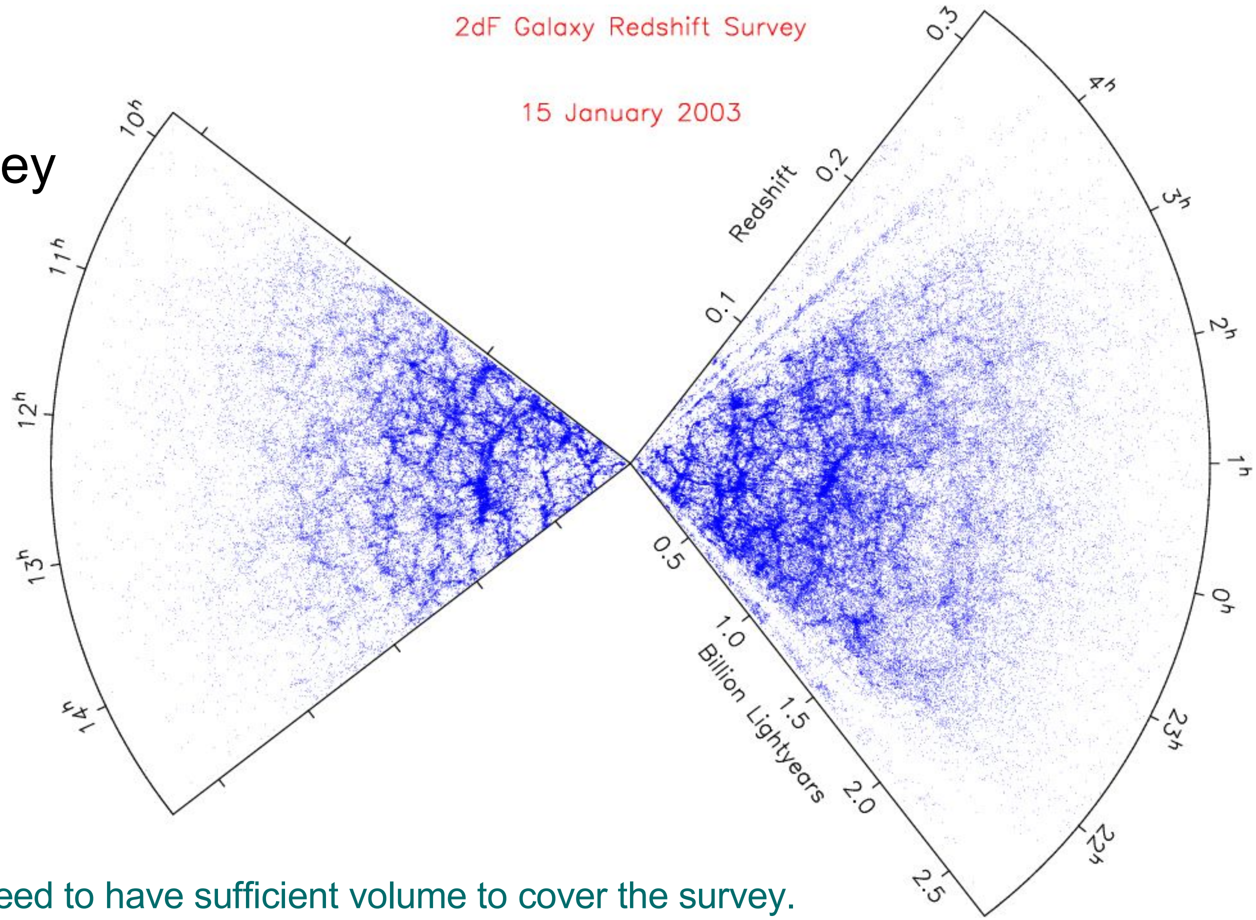
- Computers double their speed every 18 months (Moore's law)
- N-body simulations have doubled their size every 16-17 months
- Recently, growth has accelerated further.
  The Millennium Run should have become possible in 2010 – we have done it in 2004 !



Full exploitation of large observational galaxy surveys relies on theoretical mock catalogues of adequate size

EXAMPLES OF CURRENT OBSERVATIONAL SURVEYS

- Sloan Digital Sky Survey
- 2dF Galaxy Redshift Survey



Simulations and mock catalogues are needed for:

- Investigating systematic effects of the survey (selection effects, biases, etc.)
- Interpreting the observations in terms of the physics of galaxies
- Constraining the theory of galaxy formation

But:
- Theoretical mock catalogues need to have sufficient volume to cover the survey.
- Simultaneously, the particle mass must be small enough to resolve even the faintest galaxies that enter the survey.

Thanks to its extremely large dynamic range, the Millennium Run meets the opposing requirements of large volume and small particle mass like no other simulation before.

The maximum size of a TreePM simulation with *Lean*-GADGET-II is essentially memory bound

A HIGHLY MEMORY EFFICIENT VERSION OF GADGET-II

Particle Data	Tree storage	FFT workspace
44 bytes / particle	40 bytes / particle	24 bytes / mesh-cell

Not needed concurently!

Special code version *Lean*-GADGET-II needs: **84 bytes / particle** (Assuming 1.5 mesh-cells/particle)

Simulation Set-up:

- Particle number: 2160^3 = 10.077.696.000 = ~ 10^{10} particles
- Boxsize: L = 500 h^{-1} Mpc
- Particle mass: $m_p = 8.6 \times 10^8\ h^{-1}\ M_\odot$
- Spatial resolution: 5 h^{-1} kpc
- Size of FFT: 2560^3 = 16.777.216.000 = ~ 17 billion cells

Minimum memory requirement of simulation code

~840 GByte

Compared to Hubble-Volume simulation:

- > 2000 times better mass resolution
- 10 times larger particle number
- 13 better spatial resolution

The simulation was run on the *Regatta* supercomputer of the RZG

REQUIRED RESSOURCES

1 TByte RAM needed

16 x
32-way Regatta Node
64 GByte RAM
512 CPU total

CPU time consumed

350.000 processor hours

- 28 days on 512 CPUs/16 nodes
- 38 years in serial
- ~ 6% of annual time on total Regatta system
- sustained average code performance (hardware counters) 400 Mflops/cpu
- 5 x 10^{17} floating point ops
- 11000 (adaptive) timesteps

The simulation produced a multi-TByte data set

RAW SIMULATION OUTPUTS

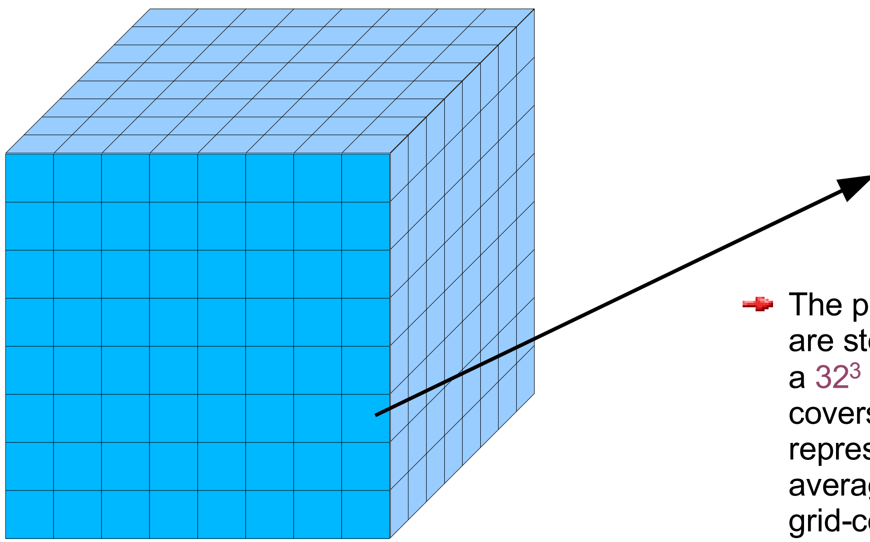
Data size

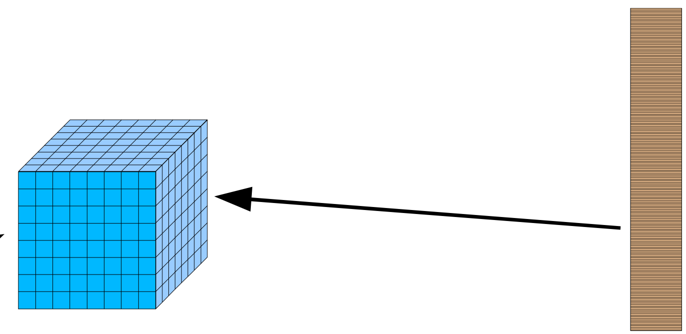
One simulation timeslice
360 GByte

we have stored
64 outputs

Raw data volume
23 TByte

Design for structure of snapshot files





- The particles of each subfile are stored in the sequence of a 32^3 Peano-Hilbert grid that covers the volume represented by the file. On average, 600 particles per grid-cell.

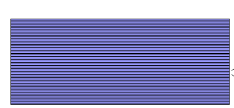
- A hash-table is produced for each file of a snapshot. Each entry gives the offset to the first particle in corresponding cell of the 32^3 grid, relative to the beginning of the file.
Size of tables:
512 x 128 Kb = 64 MB

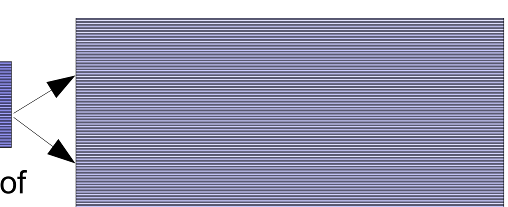
- Store simulation data in 8^3 = 512 files which map to subcubes in the simulation volume.
- Each file has ~ 20 million particles, 600 MB.

- Allows random access to particle data of subvolumes.

FoF group catalogues

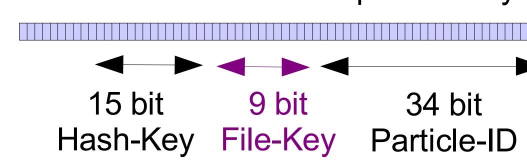
Are computed on the fly





- Group catalogue: Length of each group and offset into particle list
- Long list of particle keys (64 bit) that make up each group

- Structure of 64-bit particle key



- Allows fast selective access to all particles of a given group

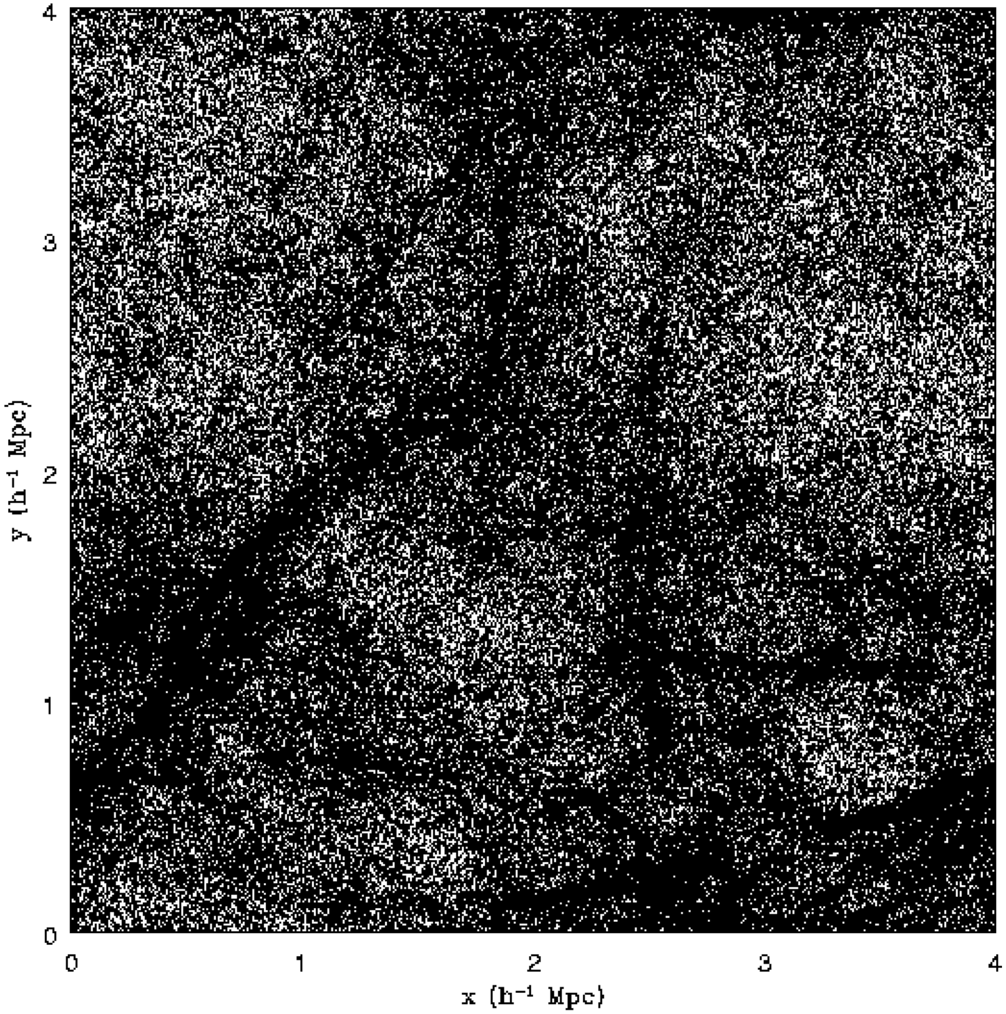
Visualization of large particle simulation data sets is challenging

THE TRADITIONAL DOT-PLOT IS STILL USED BY A NUMBER OF GROUPS

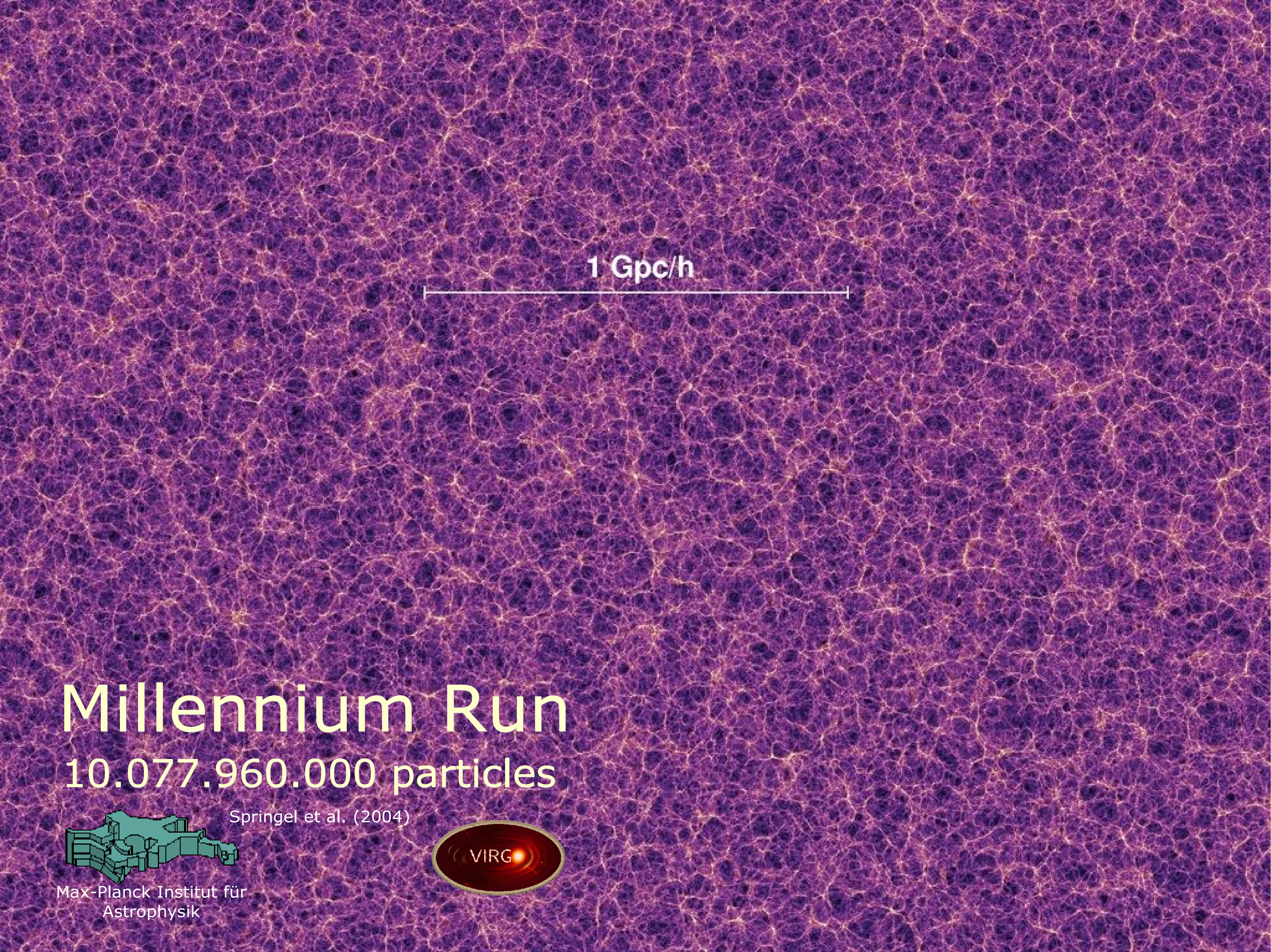
astro-ph (2004)

512^3 particles

4 h^{-1}Mpc boxsize



0.25% of particles projected onto xy-plane



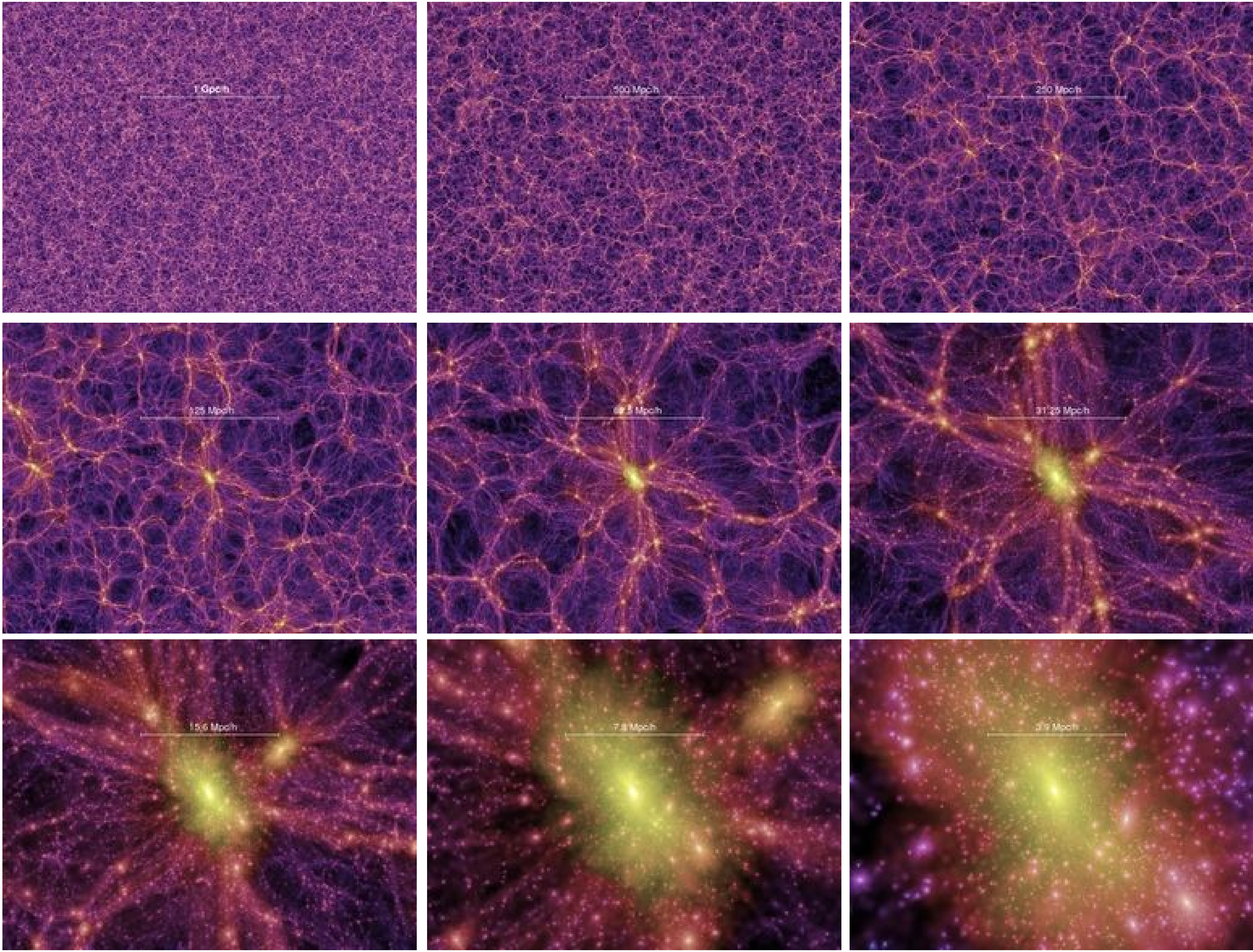
Millennium Run

10.077.960.000 particles

Springel et al. (2004)

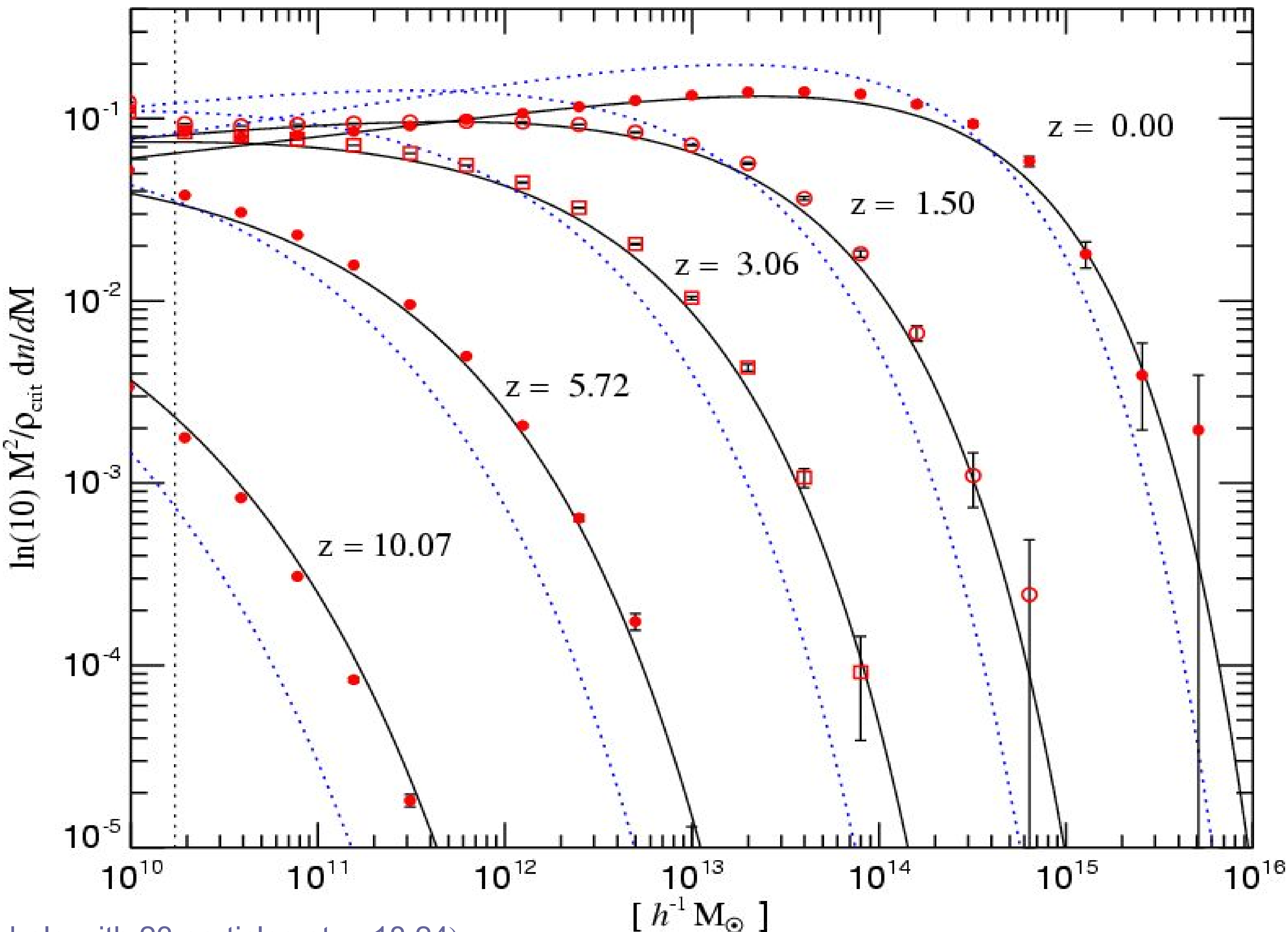
Max-Planck Institut für Astrophysik

VIRGO


1 Gpc/h
500 Mpc/h
250 Mpc/h
125 Mpc/h
62.5 Mpc/h
31.25 Mpc/h
15.6 Mpc/h
7.8 Mpc/h
3.9 Mpc/h

The halo mass function is very well fit by the model of Sheth & Tormen

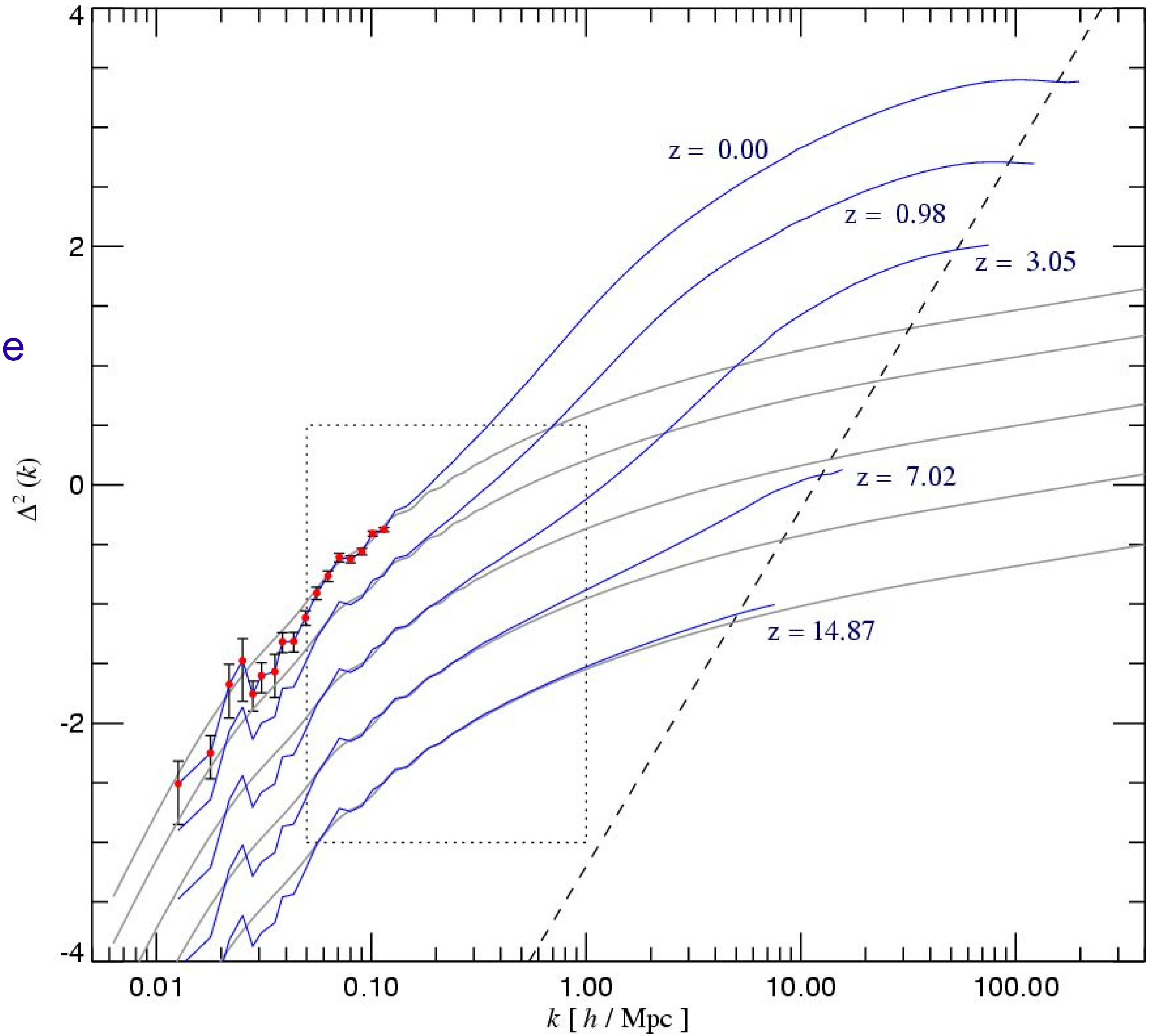
MASS MULTIPLICITY FUNCTION



(First halo with 23 particles at z=18.24)

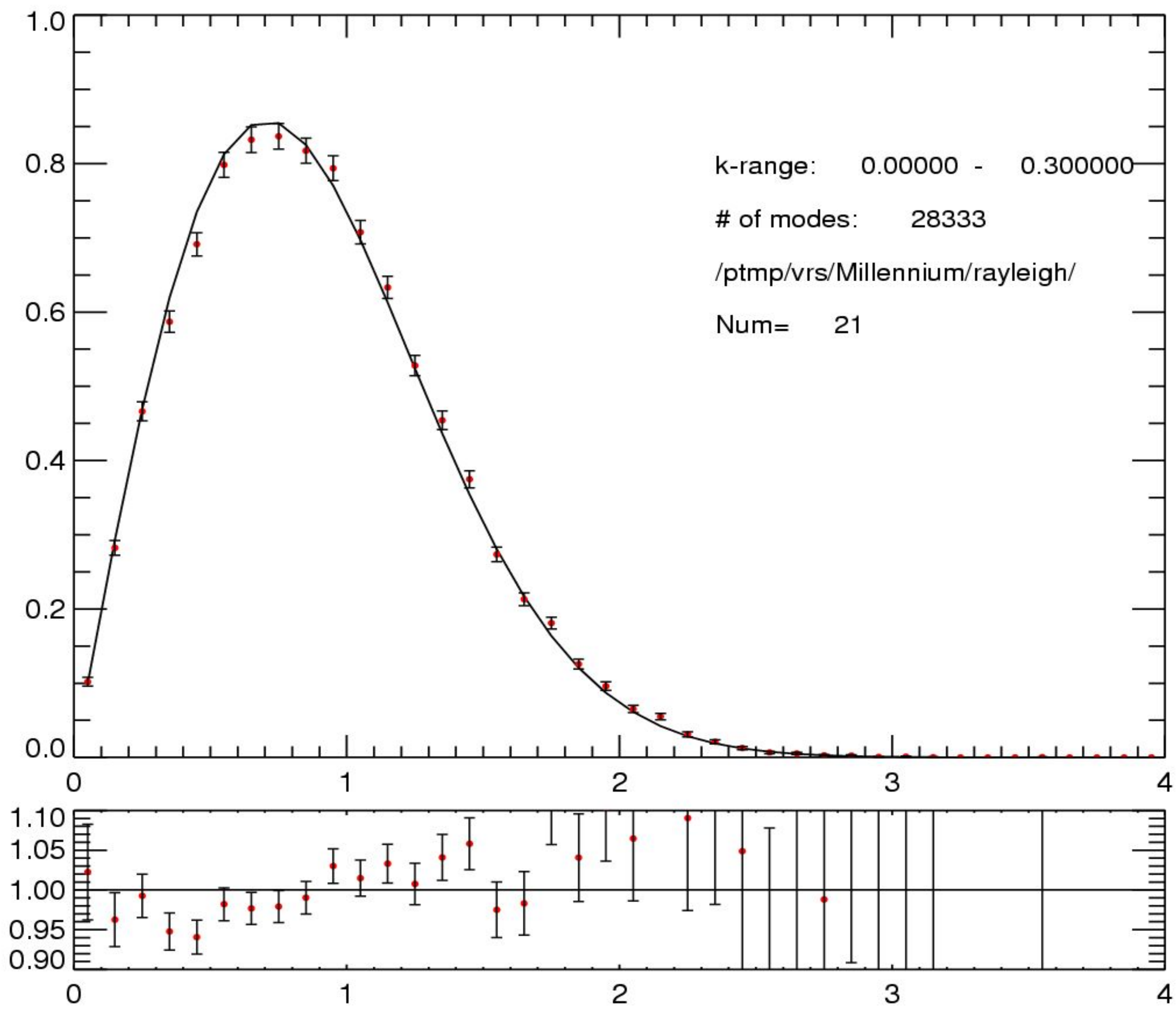
The non-linear evolution of the mass power spectrum is accurately determined by the Millennium Run over a large range of scales

MASS POWER SPECTRUM



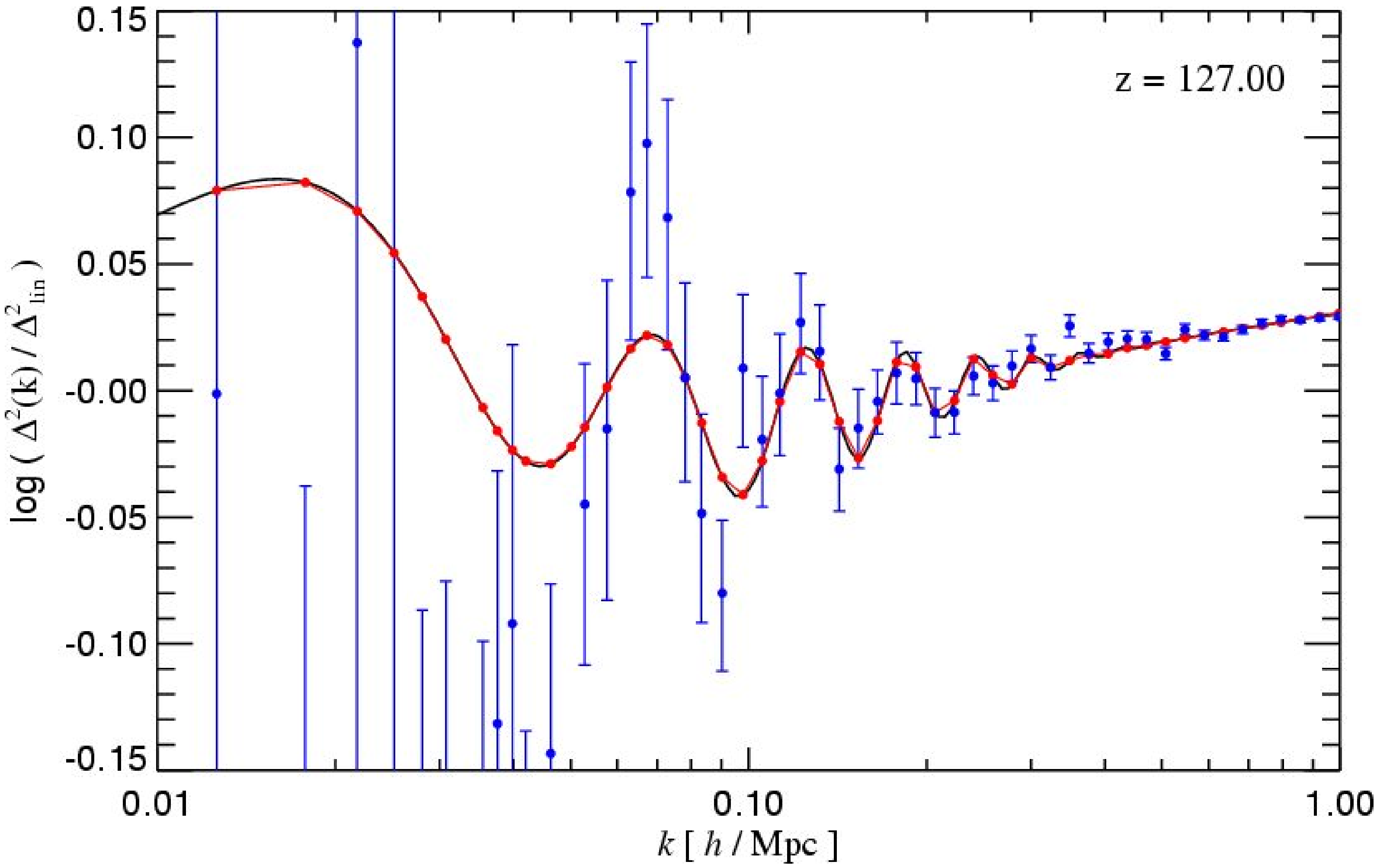
The power in individual modes is Rayleigh distributed around the mean

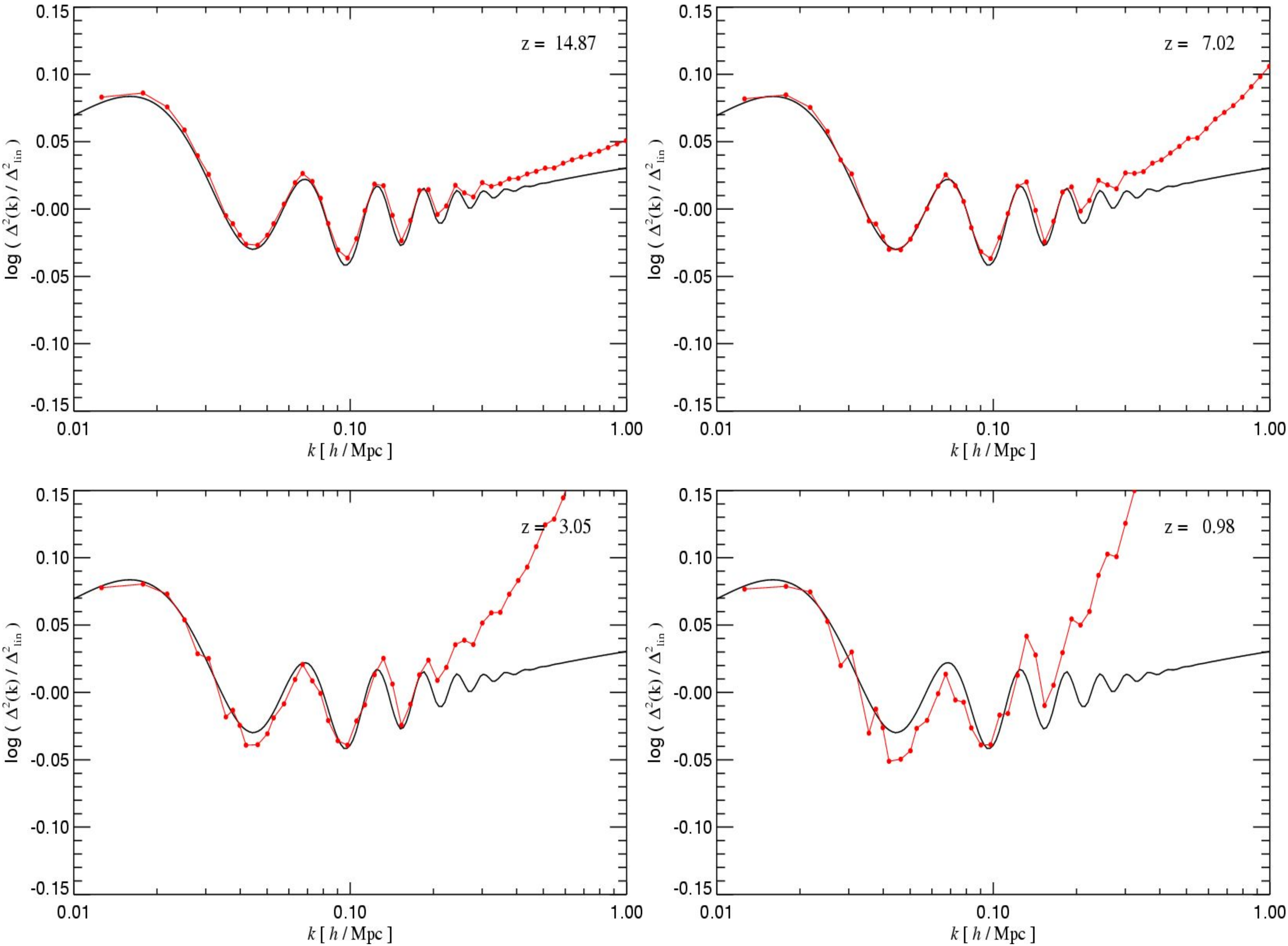
DISTRIBUTION OF MODE AMPLITUDES RELATIVE TO THE MEAN



The boxsize of the Millennium Run is large enough to resolve the baryonic wiggles in the matter power spectrum

LINEAR MASS POWER SPECTRUM AT HIGH REDSHIFT

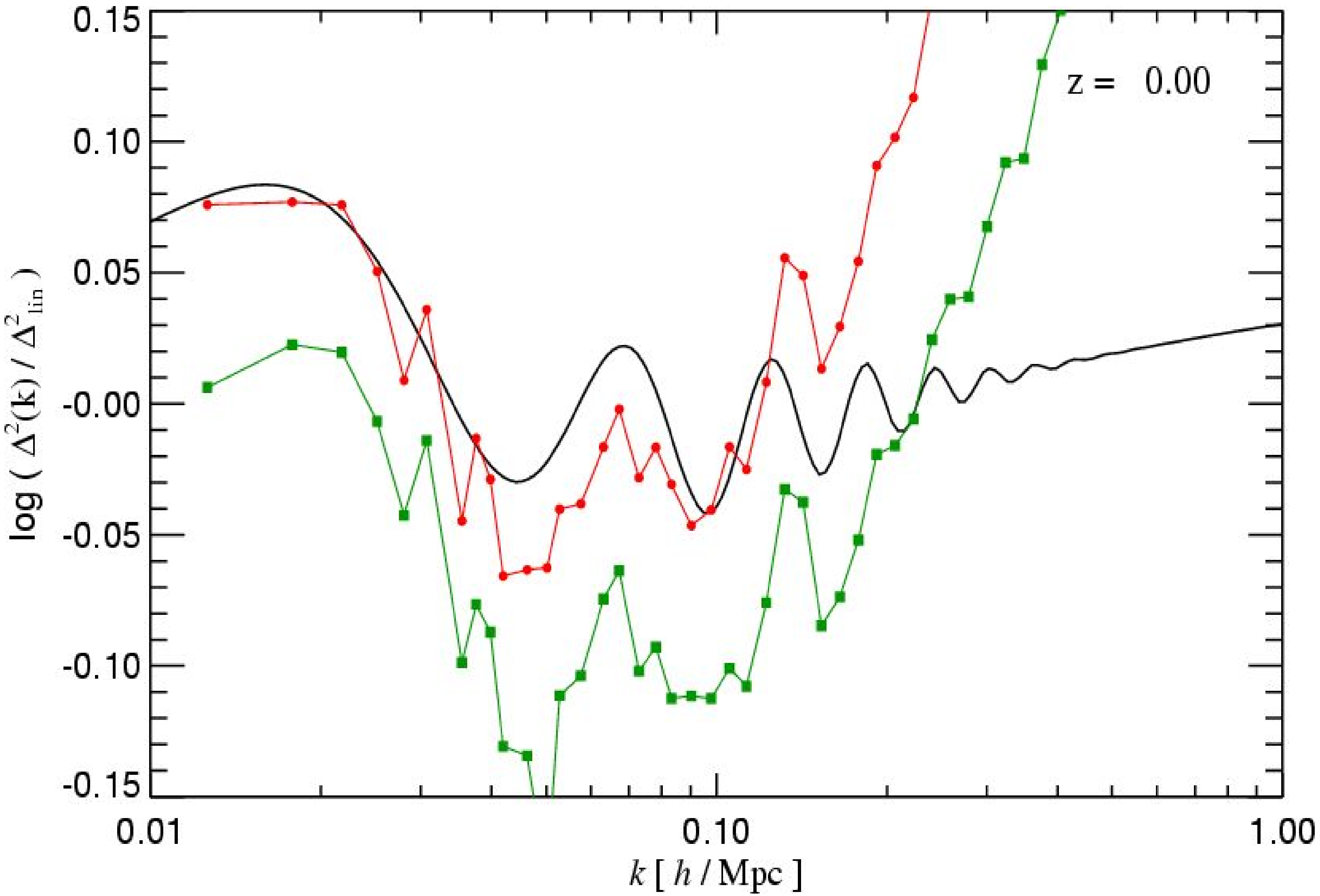




z = 14.87
z = 7.02
z = 3.05
z = 0.98
log ($\Delta^2(k) / \Delta^2_{lin}$)
k [h / Mpc]
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
0.01
0.10
1.00

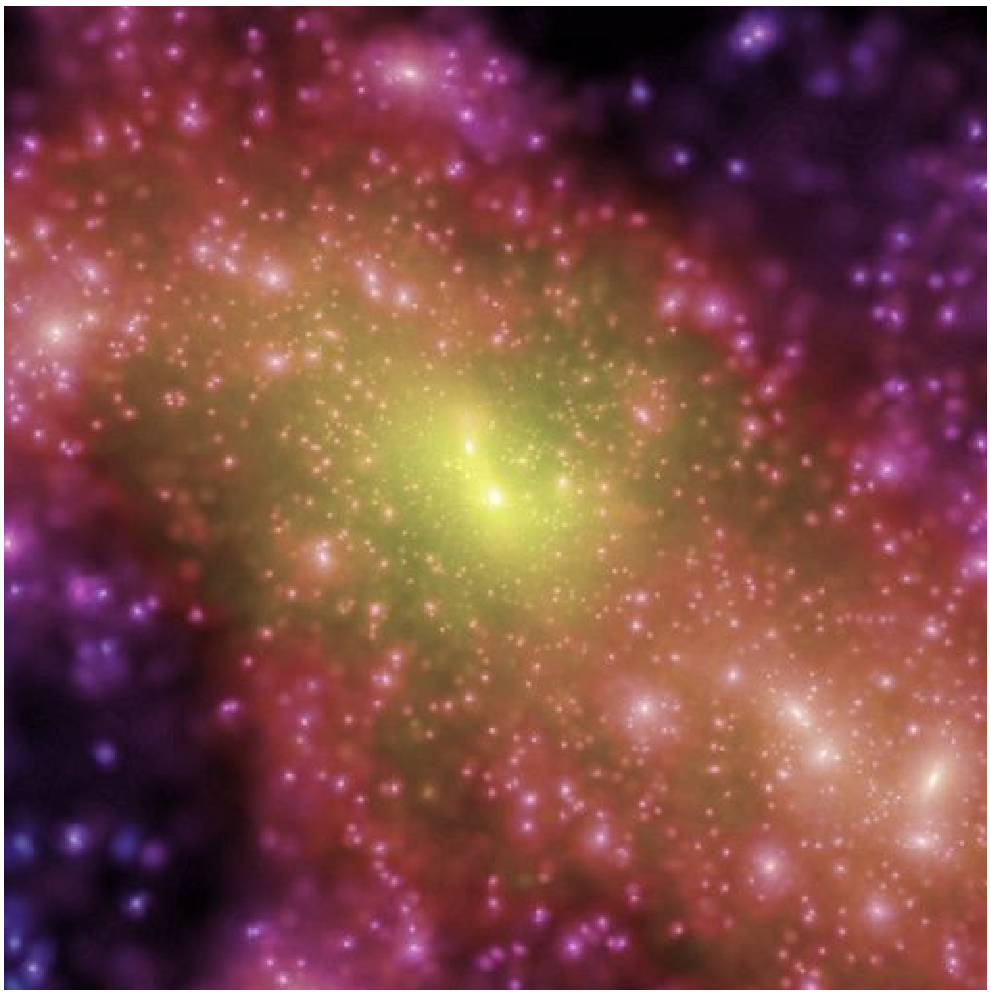
Non-linear evolution accelerates the growth of power and eliminates structure in the spectrum by mode-coupling

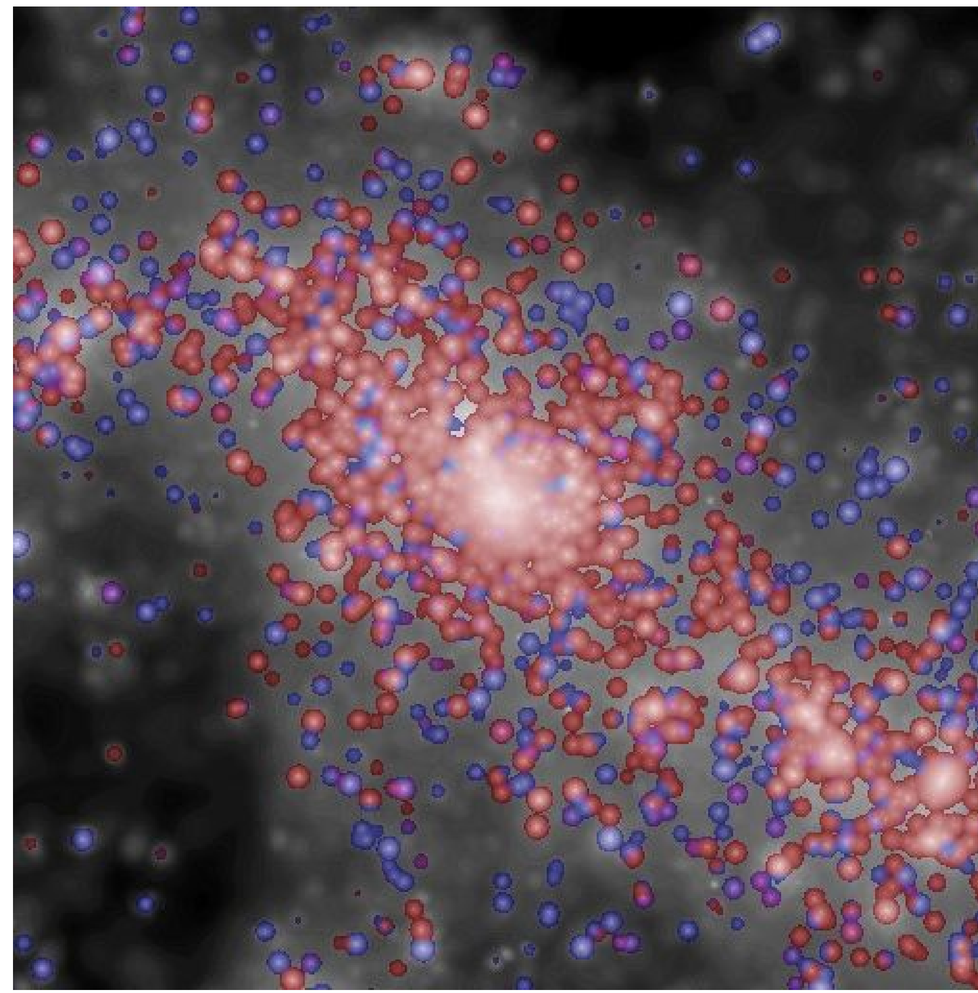
LINEAR MASS POWER SPECTRUM AT THE PRESENT EPOCH



A merger tree containing 800 million dark matter (sub)halos is used to compute semi-analytic models of galaxy formation

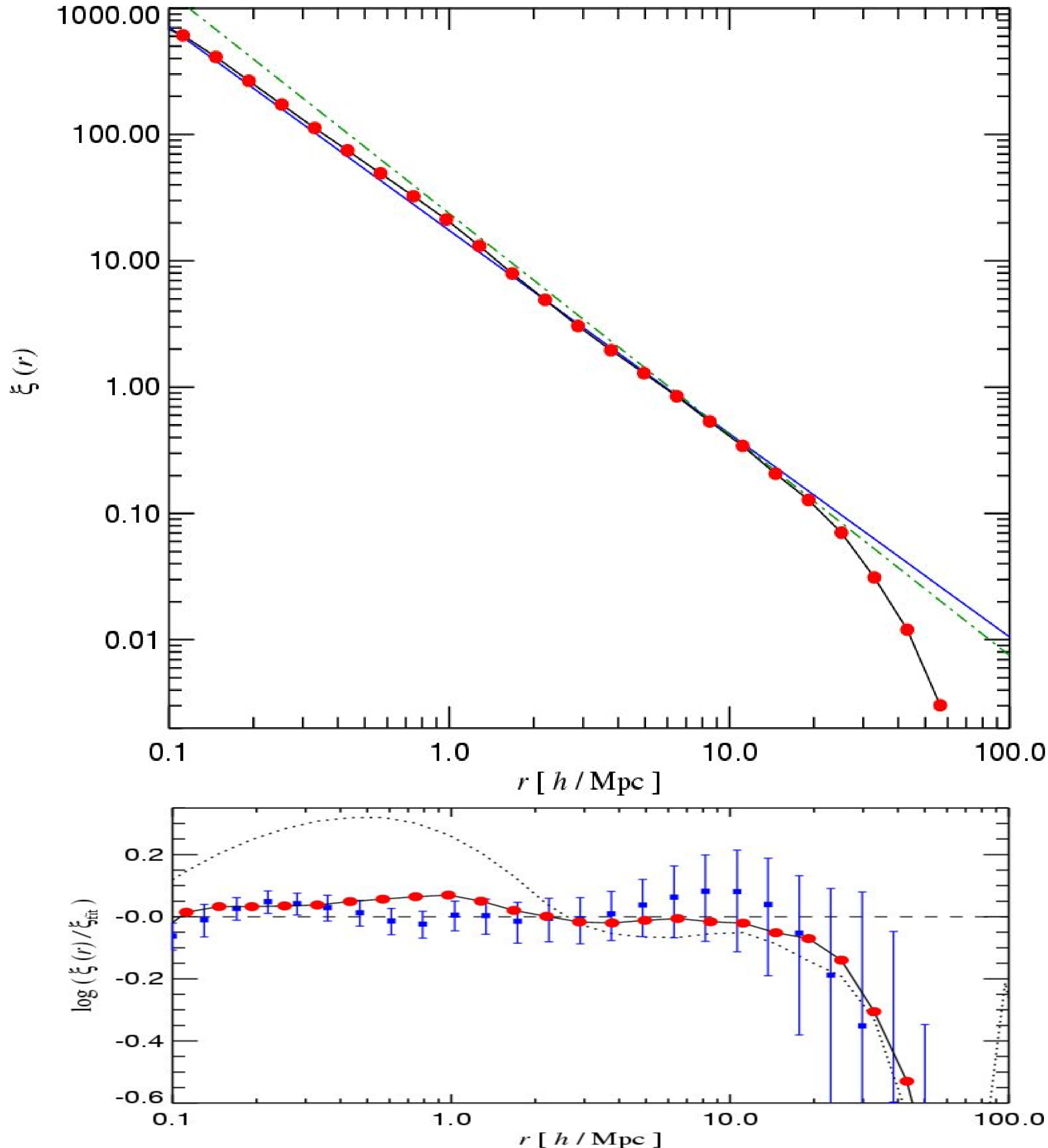
DARK MATTER AND GALAXY DISTRIBUTION IN A CLUSTER OF GALAXIES





The two-point correlation function of galaxies in the Millennium run is a very good power law

GALAXY TWO-POINT FUNCTION COMPARED WITH APM AND SDSS



Postprocessing of the simulation data requires effcient analysis codes

VARIOUS POSTPROCESSING-TASKS

Things done on the fly by the simulation code

- **FoF group finding**
- **Power spectrum and correlation function measurement**

Tasks carried out as true postprocessing

- **Substructure finding and halo/subhalo properties**
  - Done by L-SubFind in massiv parallel mode
  - With 32 CPU/256 GB (chubby queue) can process one clustered snapshot in ~4-5 hours
- **Construction of merger history trees**
  - Two step procedure. L-BaseTree finds halos descendants in future snapshots, thereby providing horizontal links in the merger tree. Serial/OpenMP-parallel, requires ~200 GB shared RAM, fast.
  - In a second step, L-HaloTrees builds up fully threaded vertical trees for each halo. These are the input objects for the semi-analytic code.
- **Semi-analytic galaxy formation**
  - New semi-analytic code L-Galaxies, can be run in massively parallel mode on the merger trees generated for the Millennium Run.
  - Interfacing with VO databases is in preparation.
- **Data visualization**
  - Challenging because of the data volume. L-HsmlFind (massively parallel) determines dark matter adaptive smoothing lengths, while L-Picture (serial) makes a picture for an arbitrarily inclinded and arbitrarily large slice through the periodic simulation.

	Lines of C-Code
L-GenIC	1900
L-Gadget2	12000
L-SubFind	3000
L-BaseTree	700
L-HaloTrees	900
L-Galaxies	2600
L-HsmlFind	1800
L-Picture	1600
Lines	24500
Characters	580000

We recently developed a largely new cosmological code: GADGET-II

NEW FEATURES OF GADGET-II

- New symplectic integration method
- Higher speed of the tree algorithm
- Less memory consumption for tree and particle storage (~100% saving)

Key feature for Millenium Run

- **Code may be run optionally as a TreePM hybrid code**
- SPH neighbour search faster
- Conservative SPH formulation
- Fully consistent dynamic tree updates
- Additional types of runs possible (e.g. 2D, hydrodynamics-only, long periodic boxes)
- Efficient and clean formation of star particles
- More physics
- More output options, including HDF5
- Still fully standard C & standard MPI. The FFTW and GSL libraries are needed.
- Reduced communication overhead, better scalability, arbitrary number of cpus
- Built in parallel group finder

The new code is quite a bit better than the old version...

Physics in GADGET-II for simulations of galaxy formation

- Radiative cooling, UV background (homogeneous)
- Subresolution multiphase model for the ISM: Star formation and feedback
- Phenomenological model for galactic winds
- Detailed chemical enrichment
- Thermal conduction
- MHD (with caveats)
- Non-thermal relativistic component (cosmic rays)
- Growth of supermassive black holes and AGN feedback

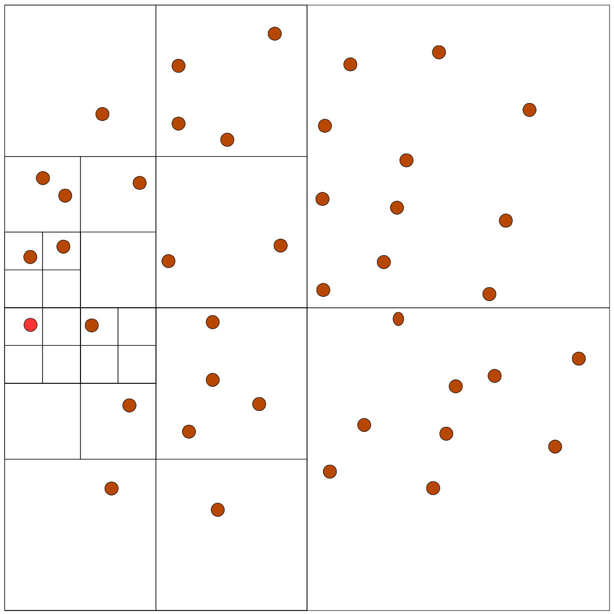
The new code is quite a bit better than the old version...

Gravity is the driving force for structure formation in the universe

HIERARCHICAL TREE ALGORITHMS

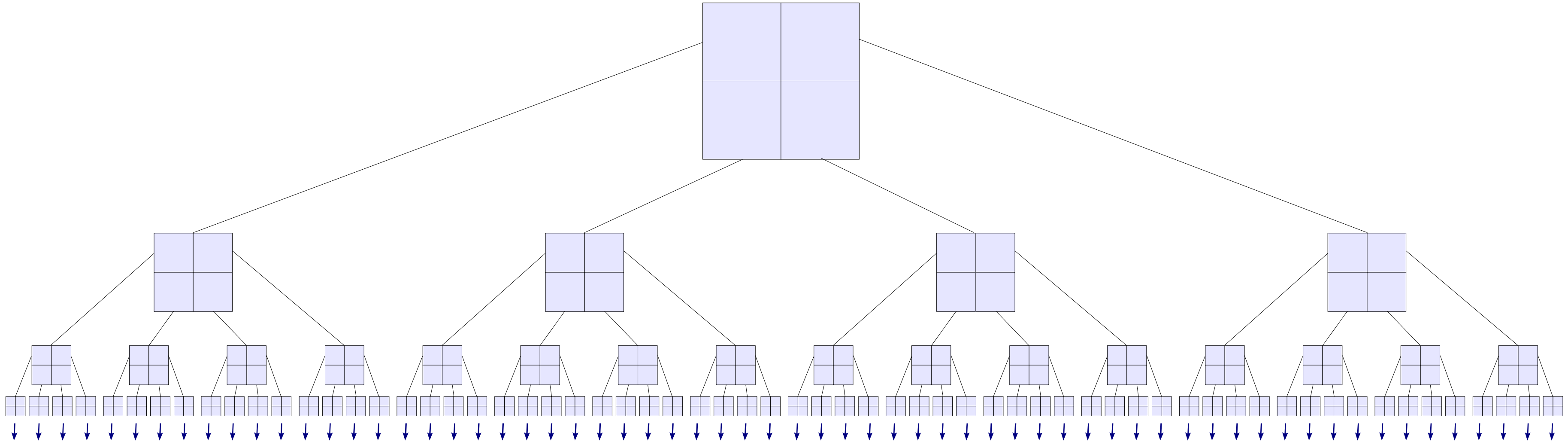
The N^2 - scaling of direct summation puts serious limitations on N...

But we want $N \sim 10^6$-10^{10} for collisionless dynamics of dark matter !



Idea: Group distant particles together, and use their multipole expansion.

→ Only ~ log(N) force terms per particle.

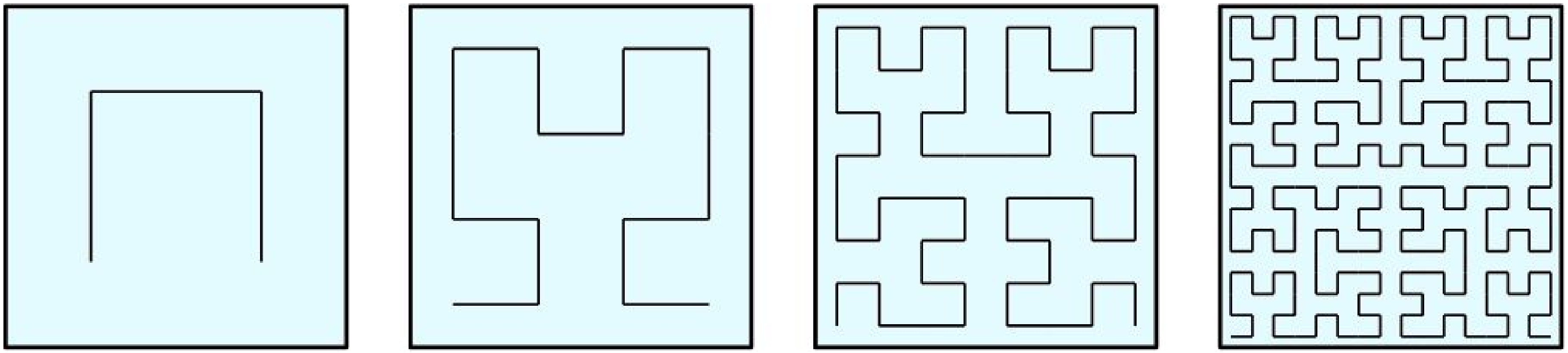


The tree-algorithm of Gadget-2 has been optimized for providing better memory locality

REDUCTION OF CACHE MISSES AND DOMAIN DECOMPOSITION

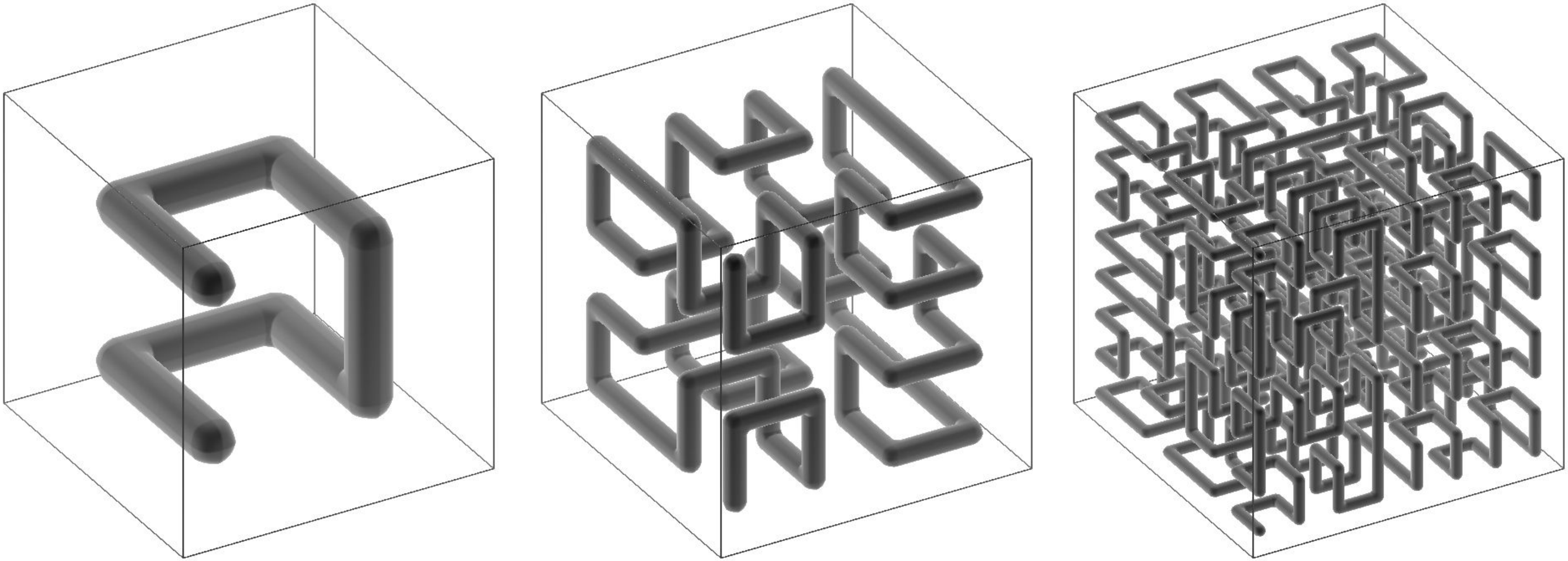
Idea: Order the particles along a space-filling curve

Hilbert's curve: A fractal that fills the square



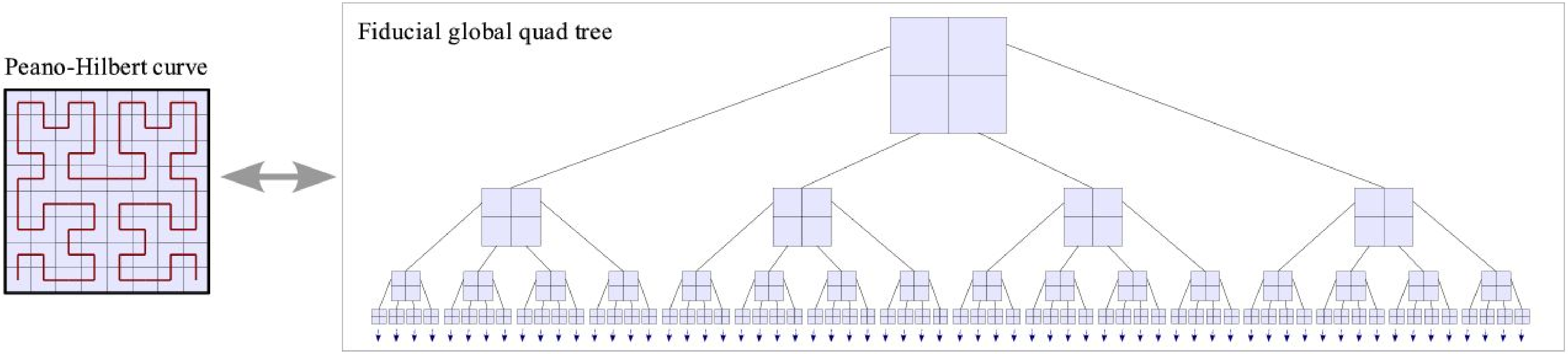
The space-filling Hilbert curve can be readily generalized to 3D

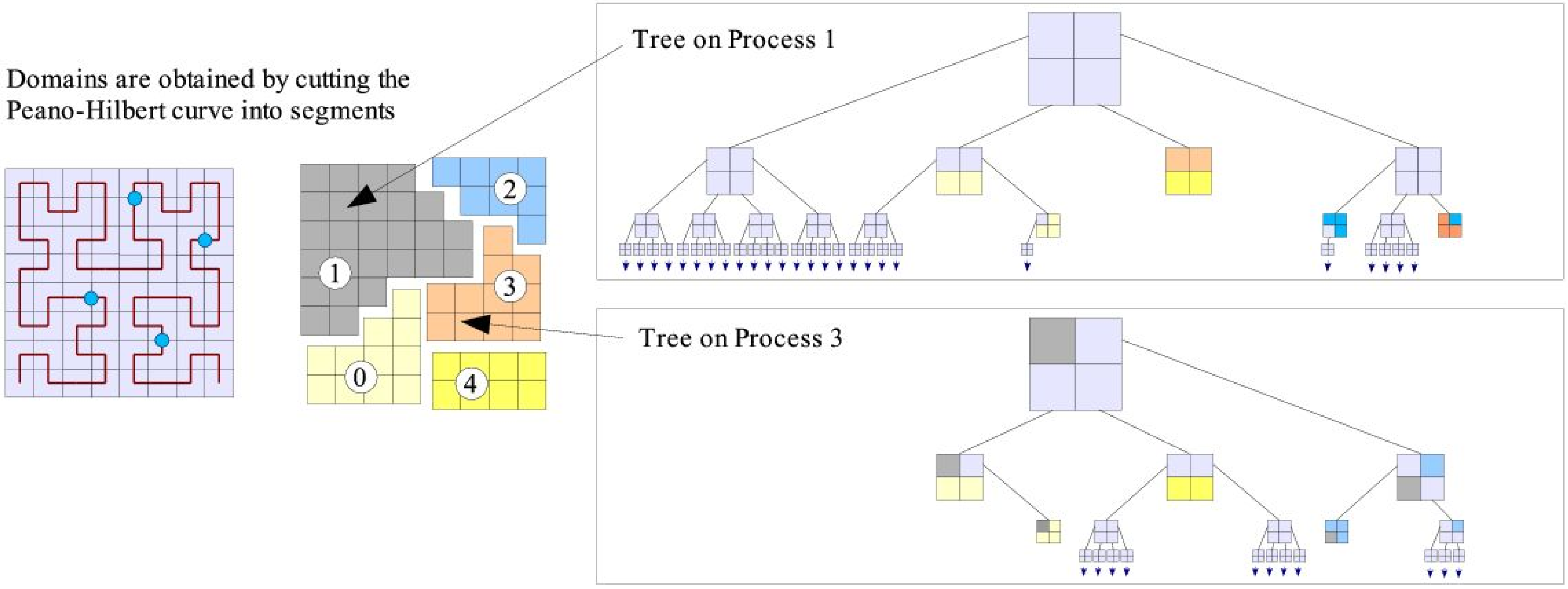
THE PEANO-HILBERT CURVE



A space-filling Peano-Hilbert curve is used in GADGET-2 for a novel domain-decomposition concept

HIERARCHICAL TREE ALGORITHMS





The TreePM technique combines the advantages of PM-method and Tree-algorithm

THE TREE-PM FORCE SPLIT

Periodic peculiar potential

$$\nabla^2\phi(\mathbf{x}) = 4\pi G[\rho(\mathbf{x}) - \overline{\rho}] = 4\pi G \sum_{\mathbf{n}} \sum_i m_i \left[\tilde{\delta}(\mathbf{x} - \mathbf{x}_i - \mathbf{n}L) - \frac{1}{L^3}\right]$$

Idea: Compute the long-range force with the PM algorithm, and only a **local** short-range force with the tree.

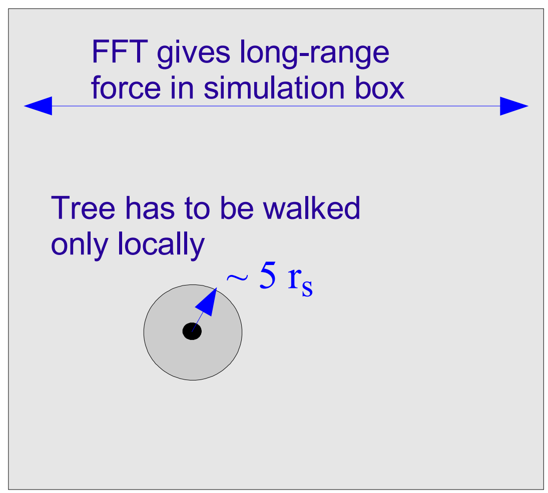
Let's split the potential in Fourier space into a long-range and a short-range part:

$$\phi_{\mathbf{k}}^{\text{long}} = \phi_{\mathbf{k}} \exp(-\mathbf{k}^2 r_s^2)$$

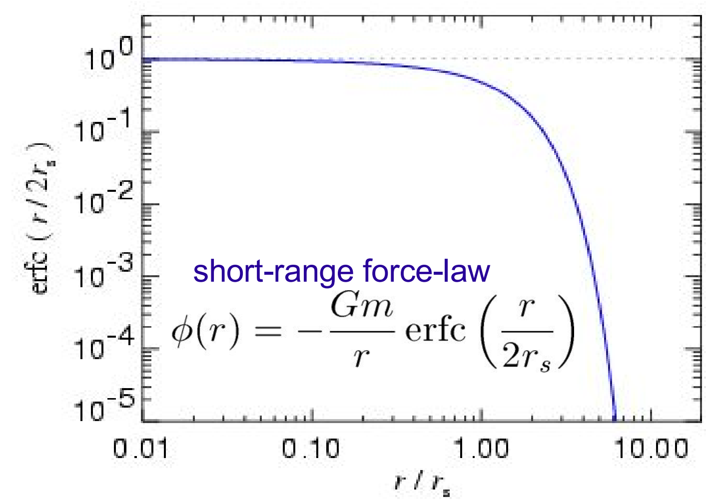
$$\phi_{\mathbf{k}}^{\text{short}} = \phi_{\mathbf{k}} \left[1 - \exp(-\mathbf{k}^2 r_s^2)\right]$$

Solve with PM-method

- CIC mass assignment
- **FFT**
- multiply with kernel
- **FFT backwards**
- Compute force with 4-point finite difference operator
- Interpolate forces to particle positions



Solve in real space with TREE



Advantages of this algorithm include:

- Accurate and fast long-range force
- No force anisotropy
- Speed is insensitive to clustering (as for tree algorithm)
- No Ewald correction necessary for periodic boundary conditions

Symplectic integration schemes can be generated by applying the idea of operating splitting to the Hamiltonian

THE LEAPFROG AS A SYMPLECTIC INTEGRATOR

Separable Hamiltonian

$$H = H_{\rm kin} + H_{\rm pot}$$

Drift- and Kick-Operators

$$\mathbf{D}(\Delta t) \equiv \exp\left(\int_t^{t+\Delta t} {\rm d}t\, \mathbf{H}_{\rm kin}\right) = \begin{cases} \mathbf{p}_i & \mapsto & \mathbf{p}_i \\ \mathbf{x}_i & \mapsto & \mathbf{x}_i + \frac{\mathbf{p}_i}{m_i}\Delta t \end{cases}$$

$$\mathbf{K}(\Delta t) = \exp\left(\int_t^{t+\Delta t} {\rm d}t\, \mathbf{H}_{\rm pot}\right) = \begin{cases} \mathbf{x}_i & \mapsto & \mathbf{x}_i \\ \mathbf{p}_i & \mapsto & \mathbf{p}_i - \sum_j m_i m_j \frac{\partial\phi(\mathbf{x}_{ij})}{\partial \mathbf{x}_i}\Delta t \end{cases}$$

The drift and kick operators are symplectic transformations of phase-space !

The Leapfrog

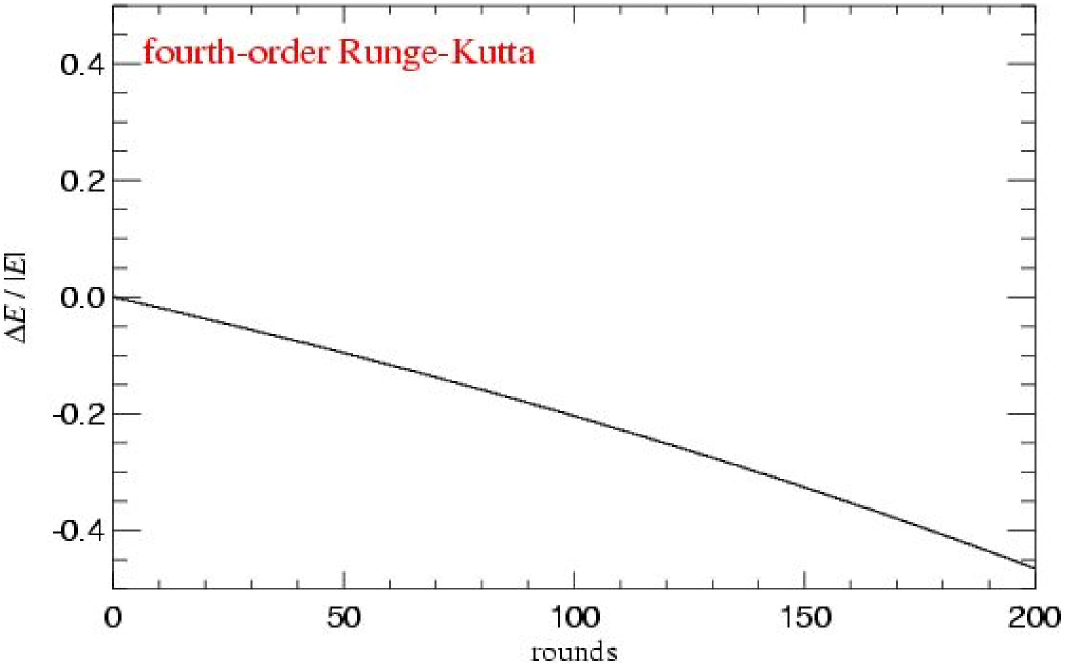
Drift-Kick-Drift:
$$\tilde{\mathbf{U}}(\Delta t) = \mathbf{D}\left(\frac{\Delta t}{2}\right)\,\mathbf{K}(\Delta t)\,\mathbf{D}\left(\frac{\Delta t}{2}\right)$$

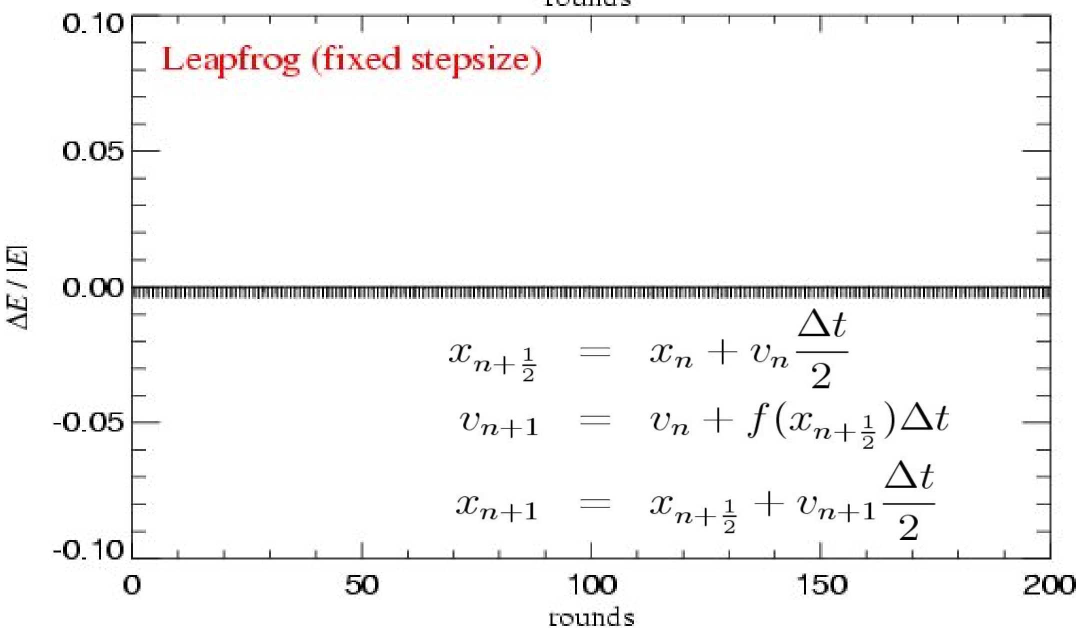
Kick-Drift-Kick:
$$\tilde{\mathbf{U}}(\Delta t) = \mathbf{K}\left(\frac{\Delta t}{2}\right)\,\mathbf{D}(\Delta t)\,\mathbf{K}\left(\frac{\Delta t}{2}\right)$$

Hamiltonian of the numerical system:
$$\tilde{H} = H + H_{\rm err} \qquad H_{\rm err} = \frac{\Delta t^2}{12}\left\{\{H_{\rm kin}, H_{\rm pot}\}, H_{\rm kin} + \frac{1}{2}H_{\rm pot}\right\} + \mathcal{O}(\Delta t^3)$$

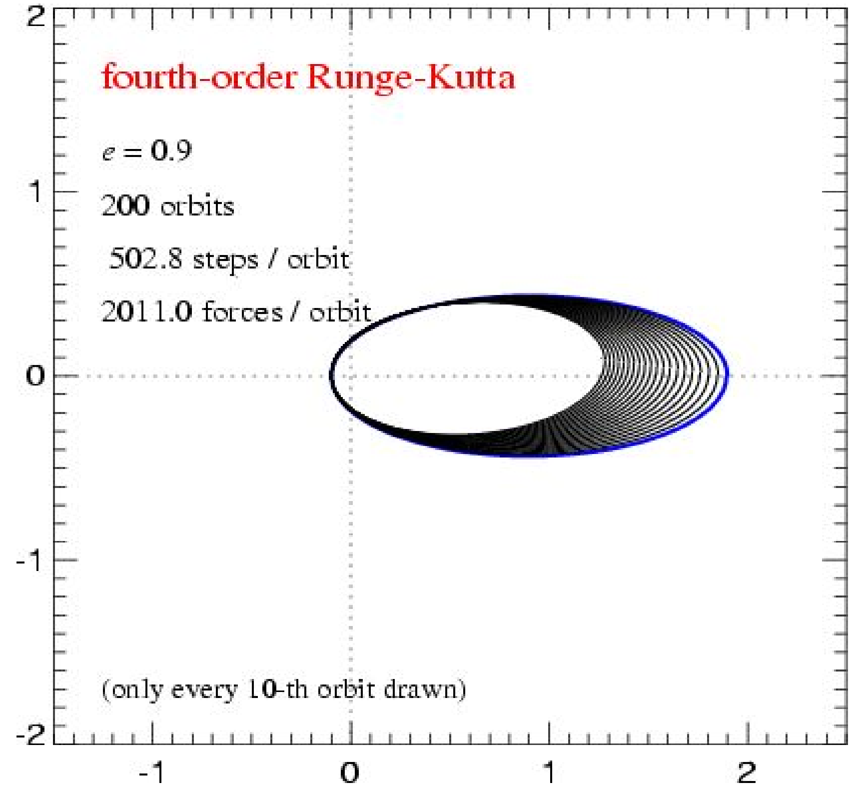
The leapfrog is behaving much better than one might expect...

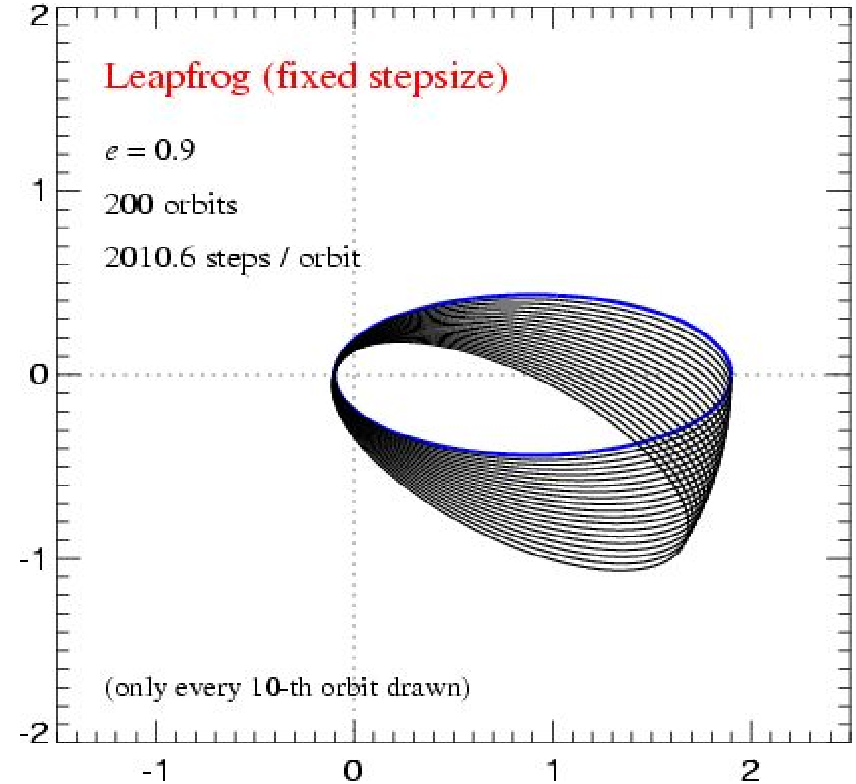
INTEGRATING THE KEPLER PROBLEM





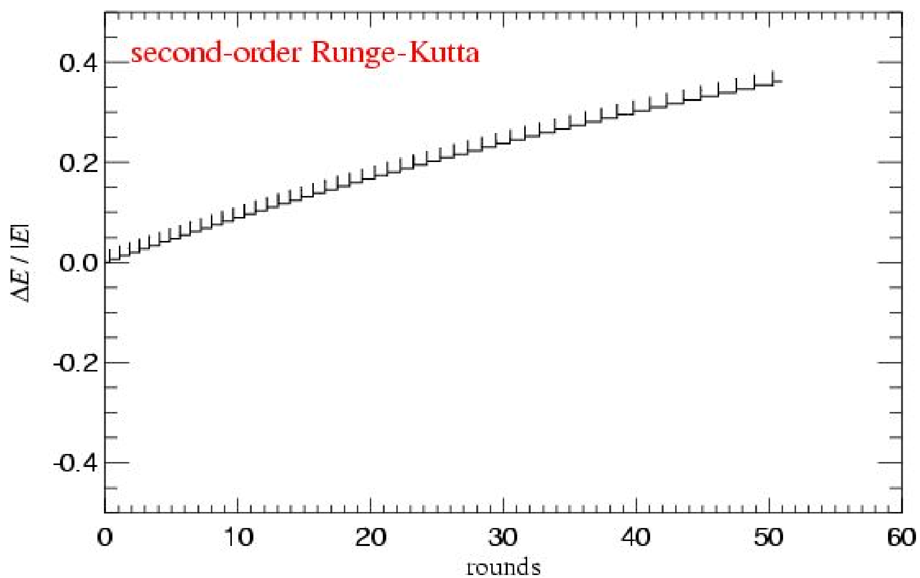
$$x_{n+\frac{1}{2}} = x_n + v_n \frac{\Delta t}{2}$$
$$v_{n+1} = v_n + f(x_{n+\frac{1}{2}}) \Delta t$$
$$x_{n+1} = x_{n+\frac{1}{2}} + v_{n+1} \frac{\Delta t}{2}$$

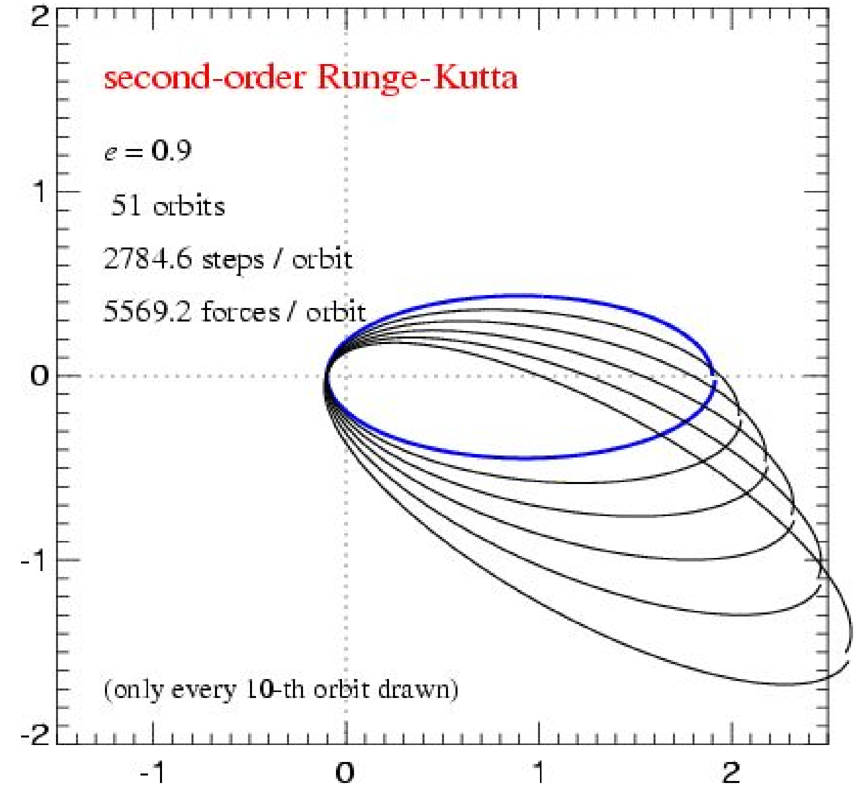


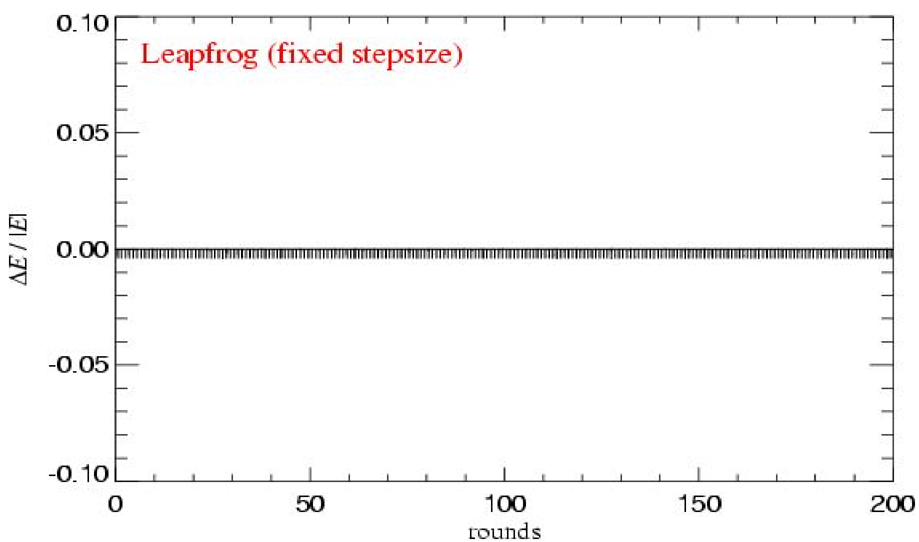


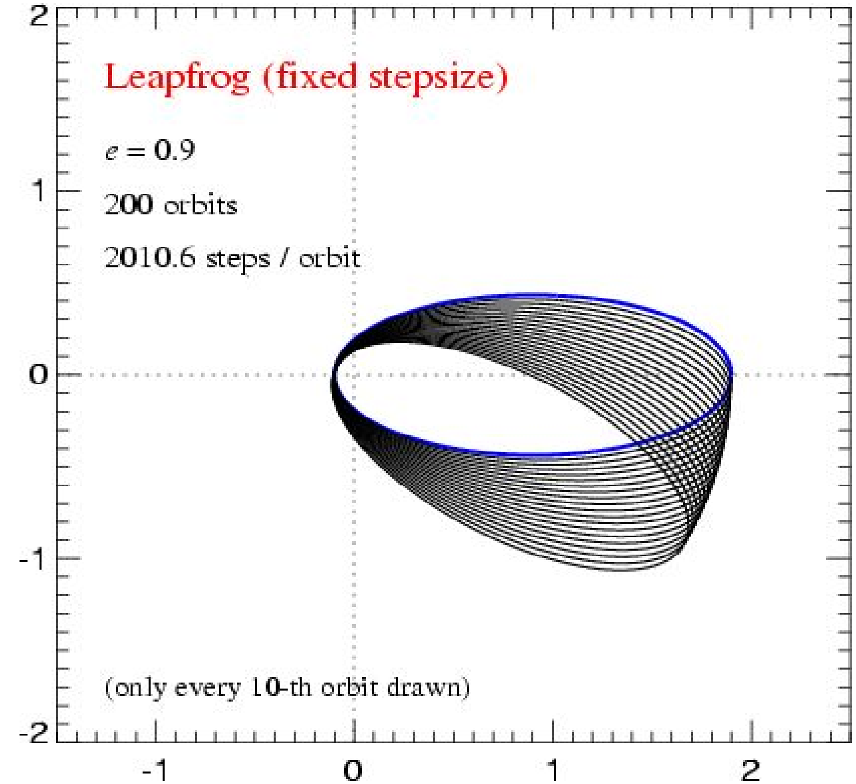
When compared with an integrator of the same order, the leapfrog is highly superior

INTEGRATING THE KEPLER PROBLEM









The force-split can be used to construct a symplectic integrator where long- and short-range forces are treated independently

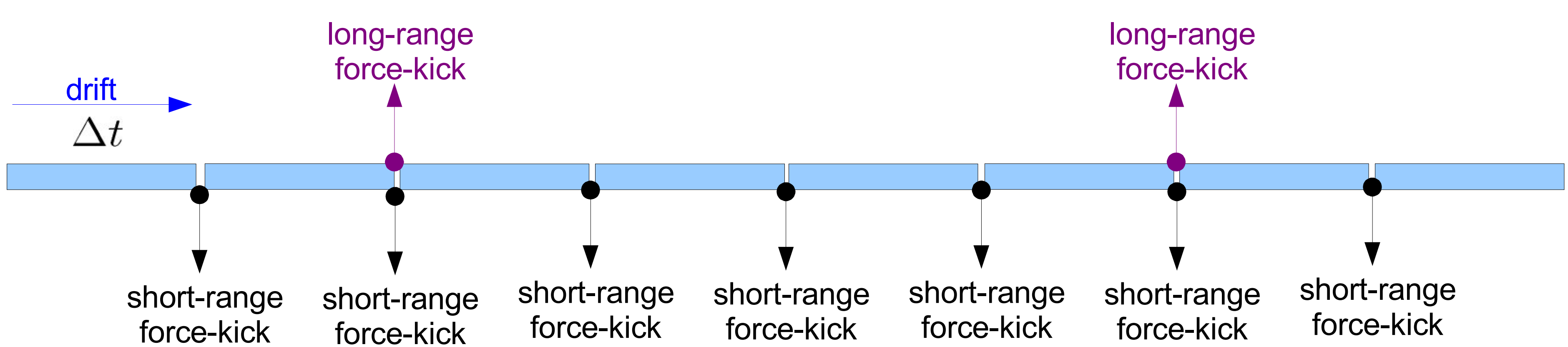
TIME INTEGRATION FOR LONG AND SHORT-RANGE FORCES

Separate the potential into a long-range and a short-range part:

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m_i a(t)^2} + \frac{1}{2}\sum_{ij} \frac{m_i m_j\, \varphi_{\rm sr}(\mathbf{x}_i - \mathbf{x}_j)}{a(t)} + \frac{1}{2}\sum_{ij} \frac{m_i m_j\, \varphi_{\rm lr}(\mathbf{x}_j - \mathbf{x}_j)}{a(t)}$$

The short-range force can then be evolved in a symplectic way on a smaller timestep than the long range force:

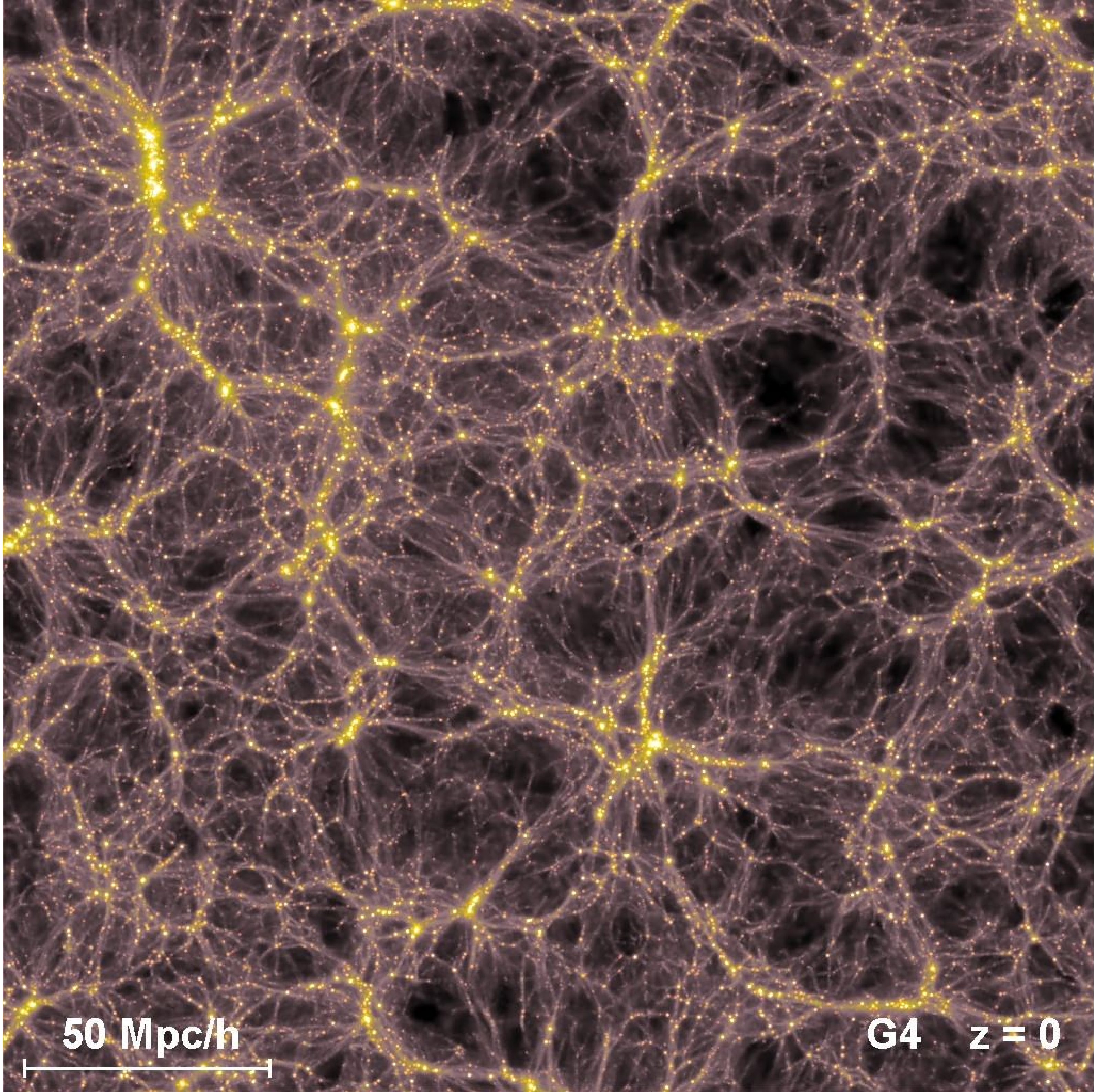
$$\tilde{\mathbf{U}}(\Delta t) = \mathbf{K}_{\rm lr}\left(\frac{\Delta t}{2}\right)\left[\mathbf{K}_{\rm sr}\left(\frac{\Delta t}{2m}\right)\mathbf{D}\left(\frac{\Delta t}{m}\right)\mathbf{K}_{\rm sr}\left(\frac{\Delta t}{2m}\right)\right]^m \mathbf{K}_{\rm lr}\left(\frac{\Delta t}{2}\right)$$



A faithful representation of cosmic structure formation requires large simulation volumes

BARYONIC DENSITY IN SIMULATIONS WITH RADIATIVE COOLING, STAR FORMATION AND FEEDBACK

Springel & Hernquist (2003)



Modeling a true multi-phase ISM in cosmological volumes is currently not feasible

THE COMPUTATIONAL CHALLENGE

<u>Giant molecular clouds</u>

$$\begin{aligned} M_{\rm cl} &\sim 5\times 10^5\ {\rm M}_\odot \\ R_{\rm cl} &\sim 30\ {\rm pc} \\ \overline{n} &\sim 200\ {\rm cm}^{-3} \\ \delta &\sim 10^9 \\ t_{\rm cl} &\sim 4\times 10^6\ {\rm yr} \end{aligned}$$

<u>Currently achievable resolution</u>

for $L \geq 50\,h^{-1}{\rm Mpc}$:

$$\begin{aligned} M_{\rm sph} &\sim 10^7\ {\rm M}_\odot \\ \epsilon &\sim 1\ {\rm kpc} \\ \delta &\sim 10^7 \end{aligned}$$

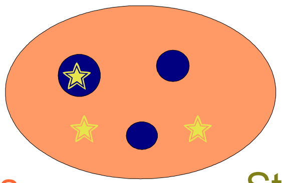
huge dynamic range + difficult/unclear physics !

→ *Need to develop effective subgrid-models that are motivated by physical models of the ISM*

A simple multi-phase model for cosmological simulations

MODEL EQUATIONS

Subresolution phases of the ISM:



Yepes, Kates, Khokhlov & Klypin (1997)
Hultman & Pharasyn (1999)

supernova mass fraction

Star formation:

$$\frac{\mathrm{d}\rho_\star}{\mathrm{d}t} = (1-\beta)\frac{\rho_c}{t_\star}$$

star formation timescale

Cloud evaporation:

$$\left.\frac{\mathrm{d}\rho_h}{\mathrm{d}t}\right|_{\mathrm{evap}} = A\beta\frac{\rho_c}{t_\star}$$

cloud evaporation paramater

Growth of clouds:

$$\left.\frac{\mathrm{d}\rho_c}{\mathrm{d}t}\right|_{\mathrm{TI}} = -\left.\frac{\mathrm{d}\rho_h}{\mathrm{d}t}\right|_{\mathrm{TI}} = \frac{\Lambda_{\mathrm{net}}(\rho_h, u_h)}{u_h - u_c}$$

radiative losses cool material from the hot phase to the cold clouds

Thermal energy budget:

supernova `temperature' ~ 10^8 K

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\rho_h u_h + \rho_c u_c\right) = -\Lambda_{\mathrm{net}}(\rho_h, u_h) + \beta\frac{\rho_c}{t_\star}u_{\mathrm{SN}} - (1-\beta)\frac{\rho_c}{t_\star}u_c,$$

Total energy | Cooling | Feedback | Loss to stars

cold clouds:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\rho_c u_c\right) = -\frac{\rho_c}{t_\star}u_c - A\beta\frac{\rho_c}{t_\star}u_c + \frac{(1-f)u_c}{u_h - u_c}\Lambda_{\mathrm{net}}$$

$$f = \begin{cases} 1 & \text{normal cooling} \\ 0 & \text{thermal instability} \end{cases}$$

hot phase:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\rho_h u_h\right) = \beta\frac{\rho_c}{t_\star}(u_{\mathrm{SN}} + u_c) + A\beta\frac{\rho_c}{t_\star}u_c - \frac{u_h - f u_c}{u_h - u_c}\Lambda_{\mathrm{net}}$$

Mass transfer budget:

Star formation

cold clouds:

$$\frac{\mathrm{d}\rho_c}{\mathrm{d}t} = -\frac{\rho_c}{t_\star} - A\beta\frac{\rho_c}{t_\star} + \frac{(1-f)}{u_h - u_c}\Lambda_{\mathrm{net}}$$

Evaporation | Cloud Growth

hot phase:

$$\frac{\mathrm{d}\rho_h}{\mathrm{d}t} = \beta\frac{\rho_c}{t_\star} + A\beta\frac{\rho_c}{t_\star} - \frac{(1-f)}{u_h - u_c}\Lambda_{\mathrm{net}}$$

Supernovas

Temperature evolution:

hot phase:

$$\rho_h \frac{\mathrm{d}u_h}{\mathrm{d}t} = \left[u_{\rm SN} - (A+1)(u_h - u_c)\right] \beta \frac{\rho_c}{t_\star} - f \Lambda_{\rm net}$$

cold clouds: temperature assumed to be constant at ~ 10^4 K

equilibirum temperature for star formation + thermal instability $\longrightarrow$

$$u_h = \frac{u_{\rm SN}}{A+1} + u_c$$

Evaporation efficiency:

$$A(\rho) = A_0 \left(\frac{\rho}{\rho_{\rm th}}\right)^{-4/5}$$

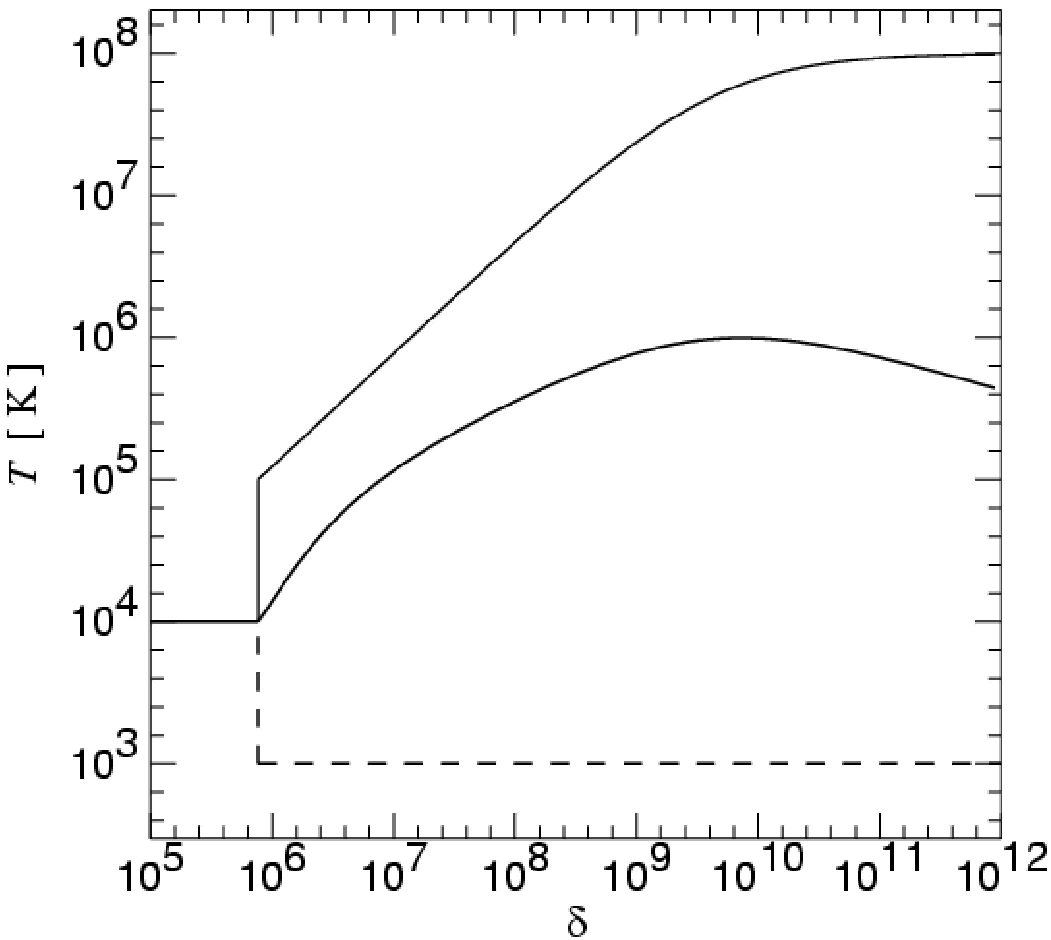
Star formation timescale:

$$t_\star(\rho) = t_\star^0 \left(\frac{\rho}{\rho_{\rm th}}\right)^{-1/2}$$

$\rho_{\rm th}$ and A_0 are constraint by plausible temperature range of the ISM $\longrightarrow$ star formation timescale $t_\star^0$ is adjustable parameter of model

The ISM is pressurized by star formation in the region of coexistence between a hot medium and embedded cold clouds

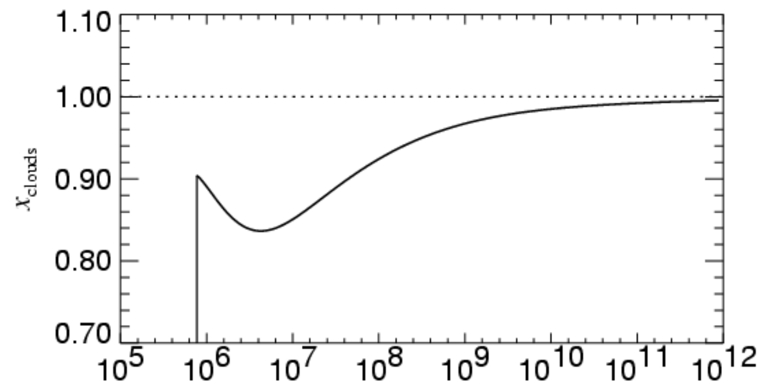
EFFECTIVE EQUATION OF STATE

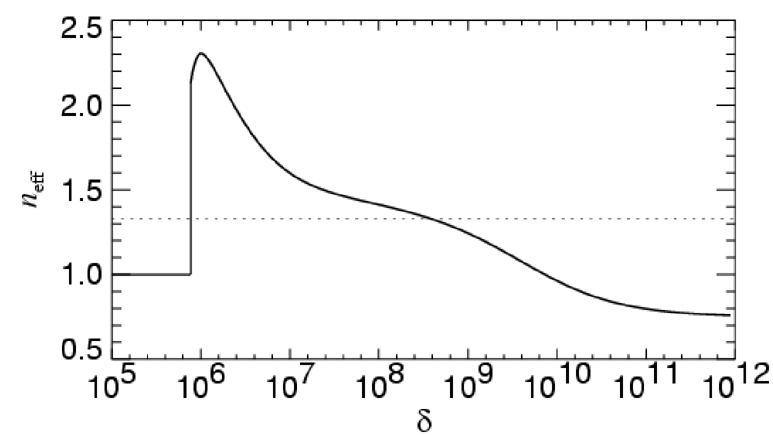


Effective Pressure:

$$P_{\text{eff}} \equiv (\gamma - 1)(\rho_h u_h + \rho_c u_c)$$

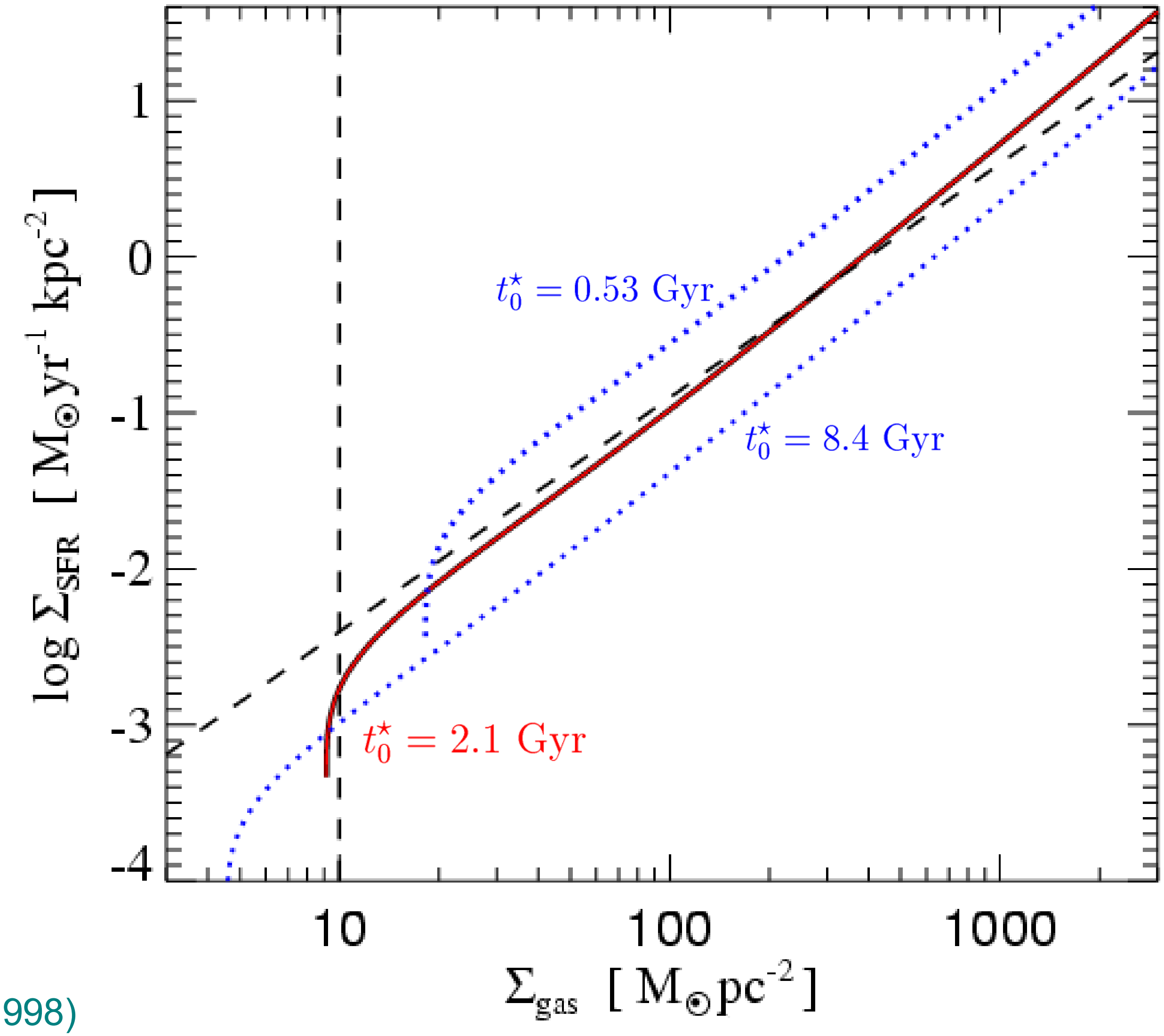
$$T_{\text{eff}} \equiv \frac{\mu}{k}\frac{P_{\text{eff}}}{\rho}$$





Self-gravitating sheets of gas are used to normalize the multi-phase model

KENNICUTT LAW

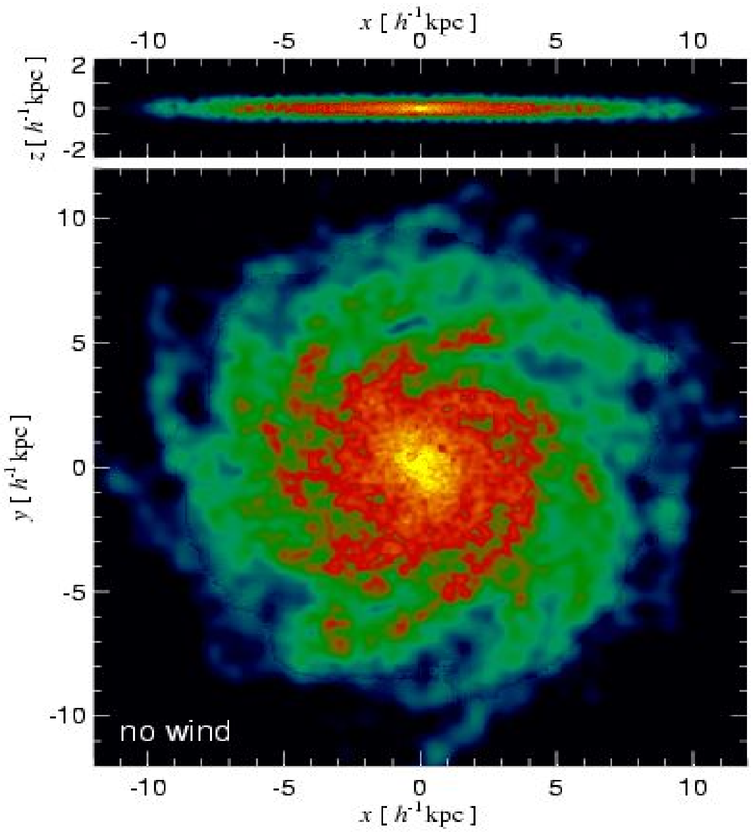


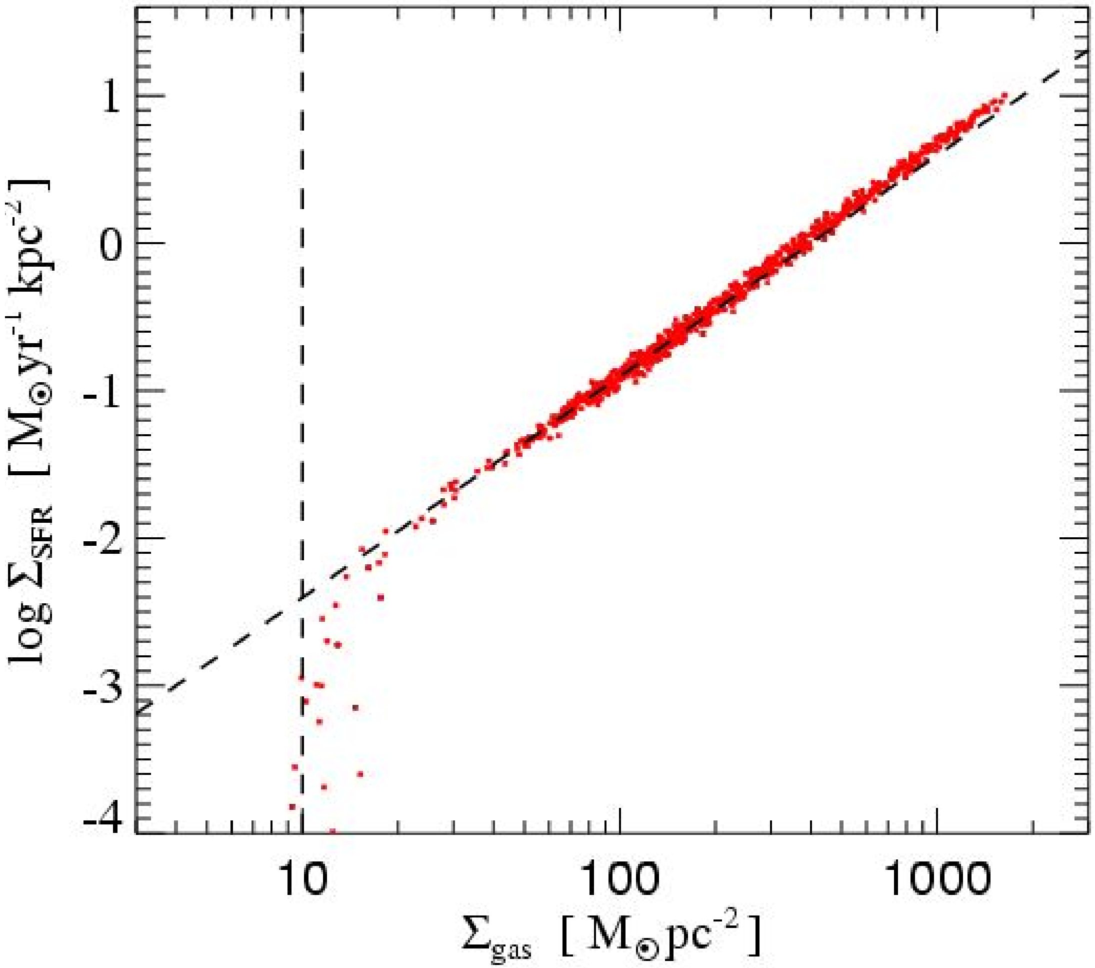
Global "Kennicutt-law" (Kennicutt 1998)

$$\Sigma_{\rm SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{\rm M_\odot pc^{-2}} \right)^{1.4\pm0.15} \frac{\rm M_\odot}{\rm yr\,kpc^2}$$

Simulations of isolated disk galaxies are used to check the normalization of the multi-phase model

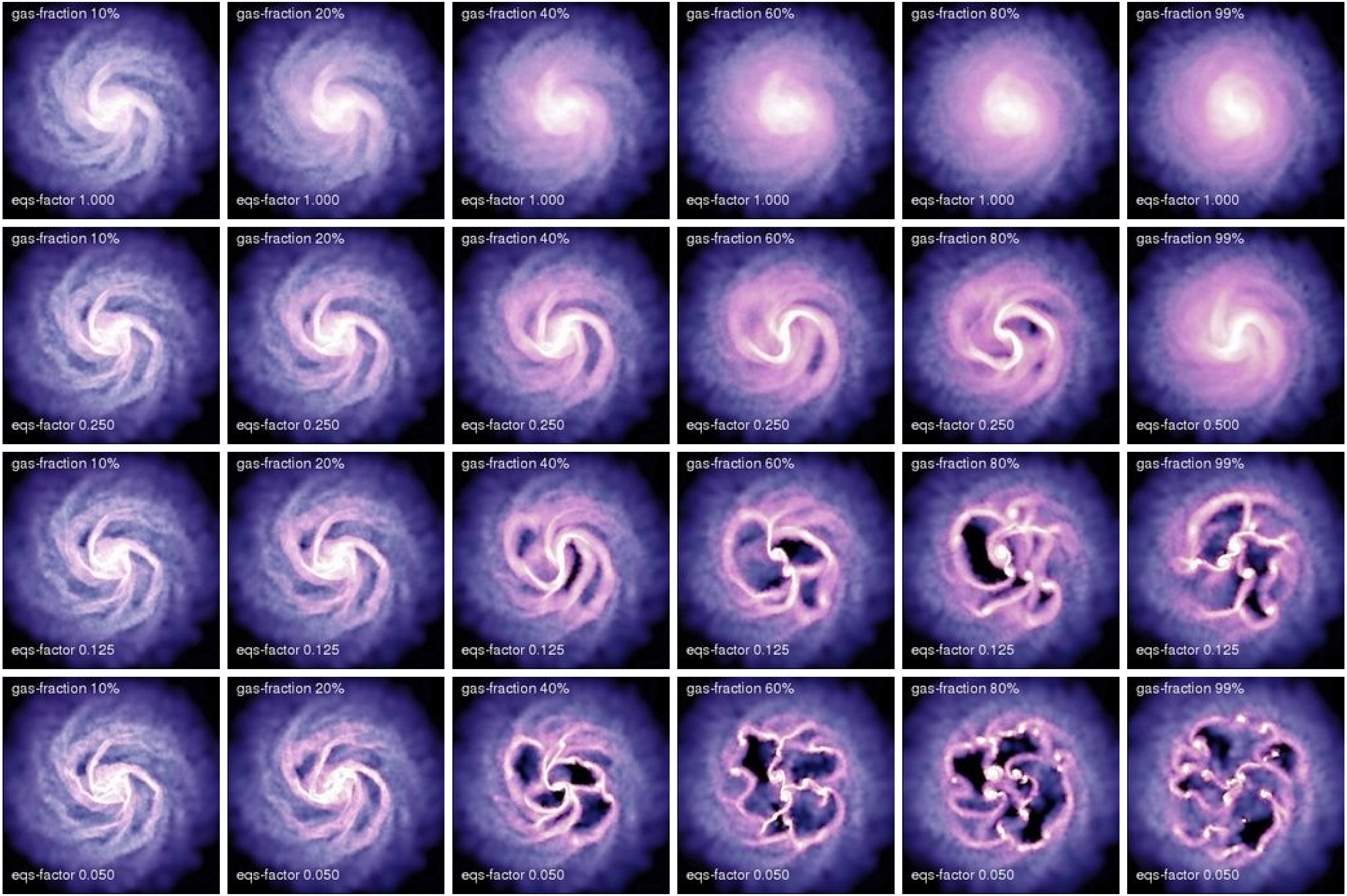
MEASURED KENNICUTT LAW





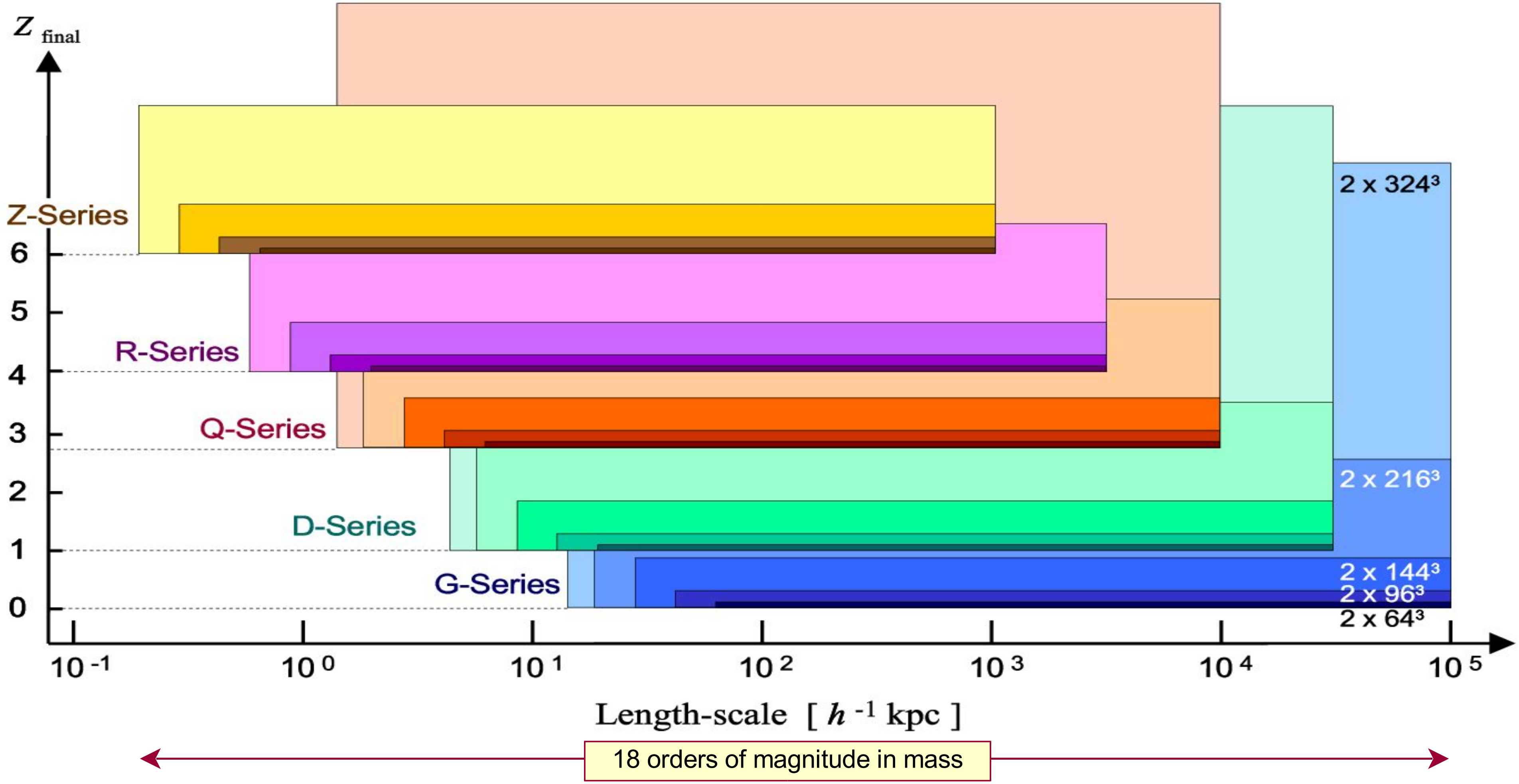
The multiphase-model allows stable disk galaxies even for very high gas surface densities

STABILITY OF DISKS AS A FUNCTION OF GAS FRACTION AND EQUATION OF STATE



We have run a program of simulations on a set of interlocking scales and resolutions

SIMULATION PROGRAM



Run on **Mako**, Harvard - CfA

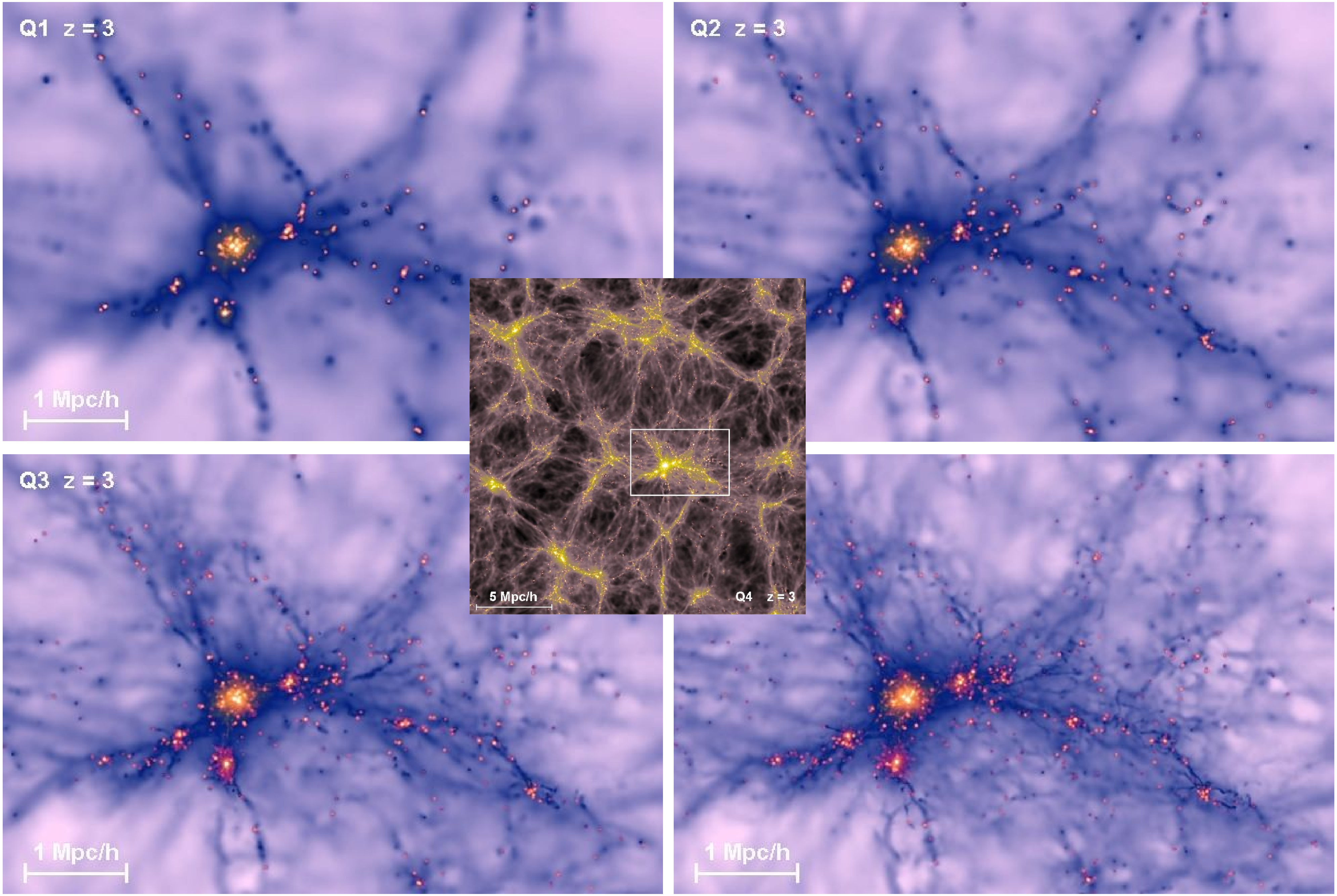
Beowulf-class computer

Configuration:

256 Athlon MP (1.6 GHz) arranged in 128 double-processor SMP nodes with 1 GB RAM each, 100 Base-T switched Ethernet, Linux

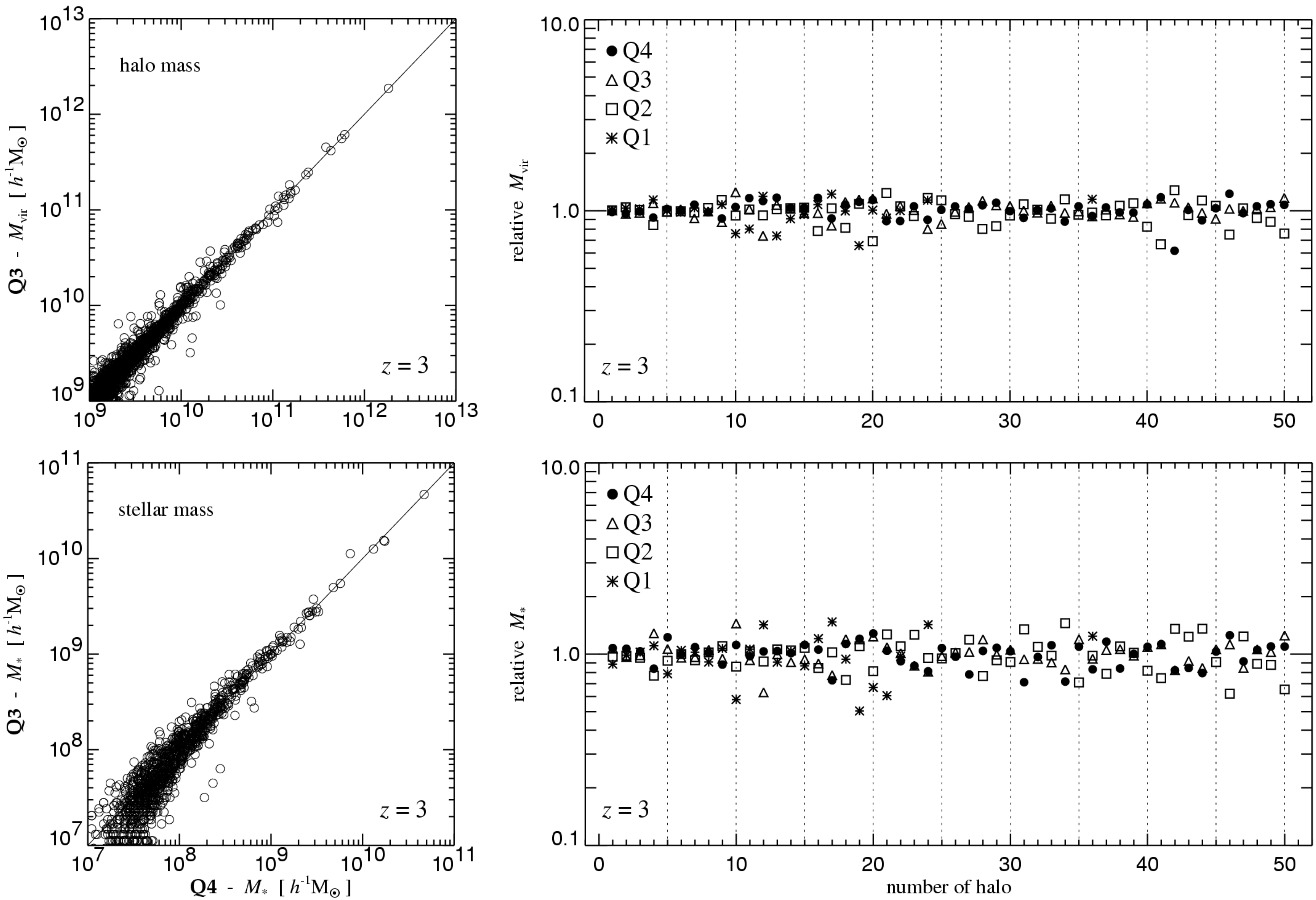
Separate Frontend and 2 big Fileservers

Higher mass resolution can resolve smaller galaxies



The star formation rate of individual galaxies converges well for sufficient mass resolution

OBJECT-BY-OBJECT RESOLUTION STUDY



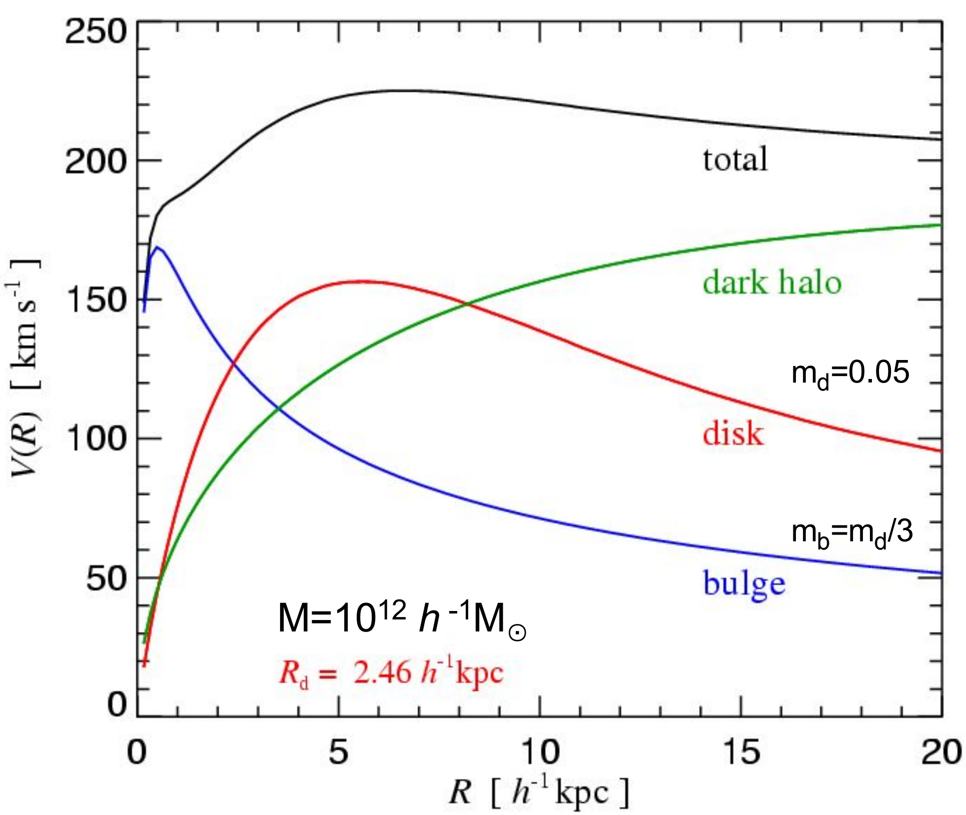
We construct compound disk galaxies that are in dynamical equilibrium

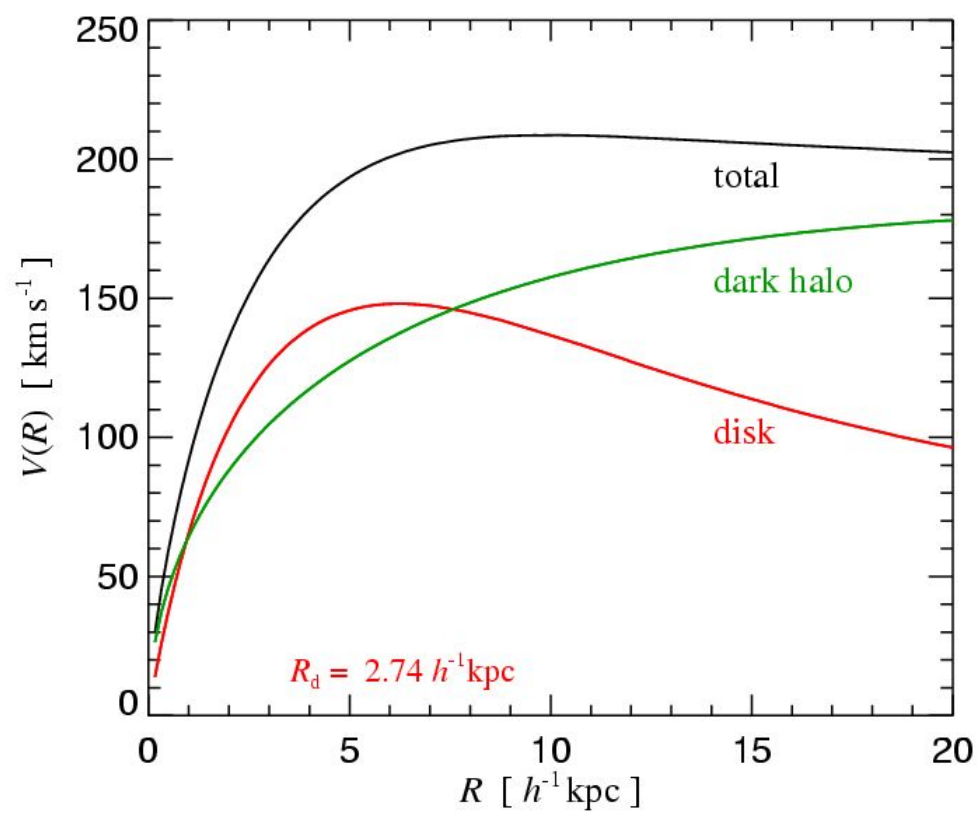
STRUCTURAL PROPERTIES OF MODEL GALAXIES

Components:

- Dark halo (Hernquist profile matched to NFW halo)
- Stellar disk (expontial)
- Stellar bulge
- Gaseous disk (expontial)
- Central supermassive black hole (small seed mass)

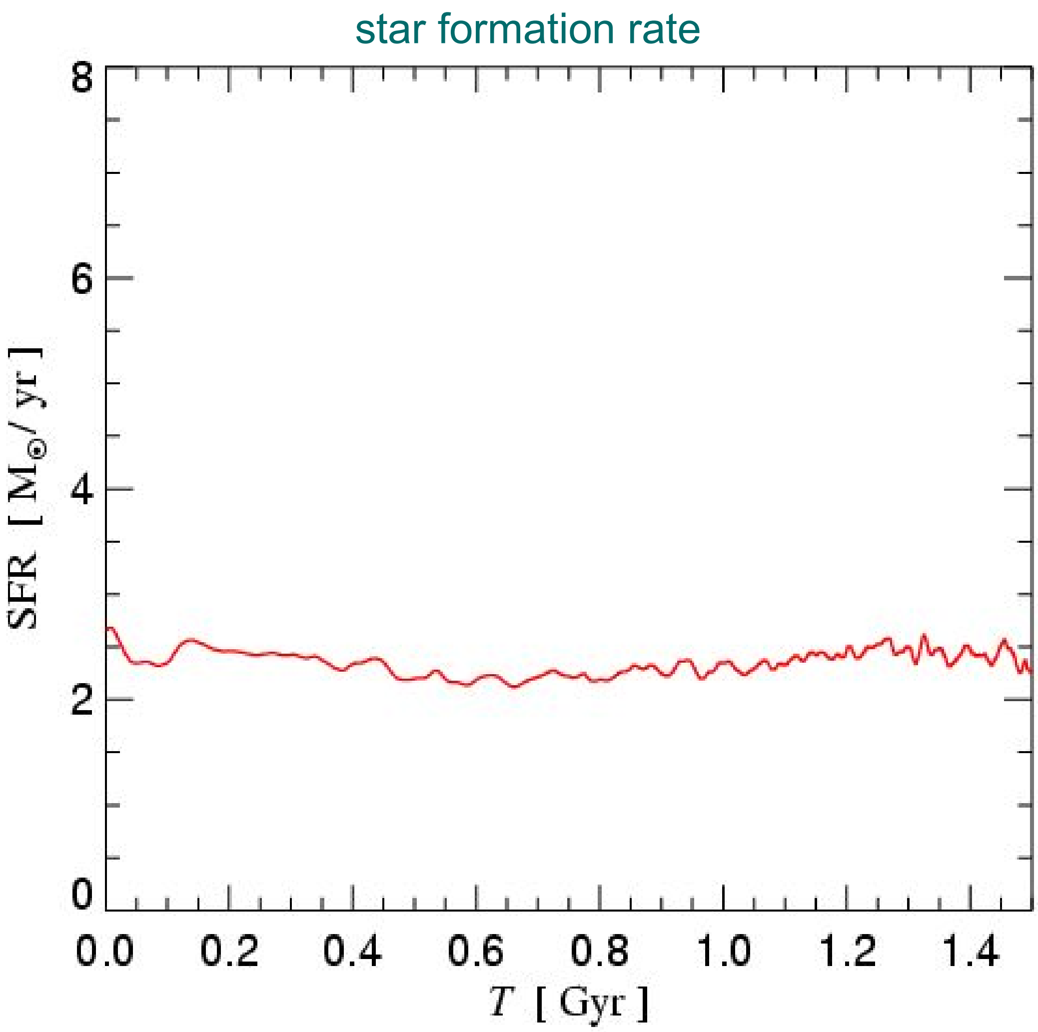
- We compute the exact gravitational potential for the axisymmetric mass distribution and solve the Jeans equations
- Gas pressure effects are included
- The gaseous scale-height is allowed to vary with radius

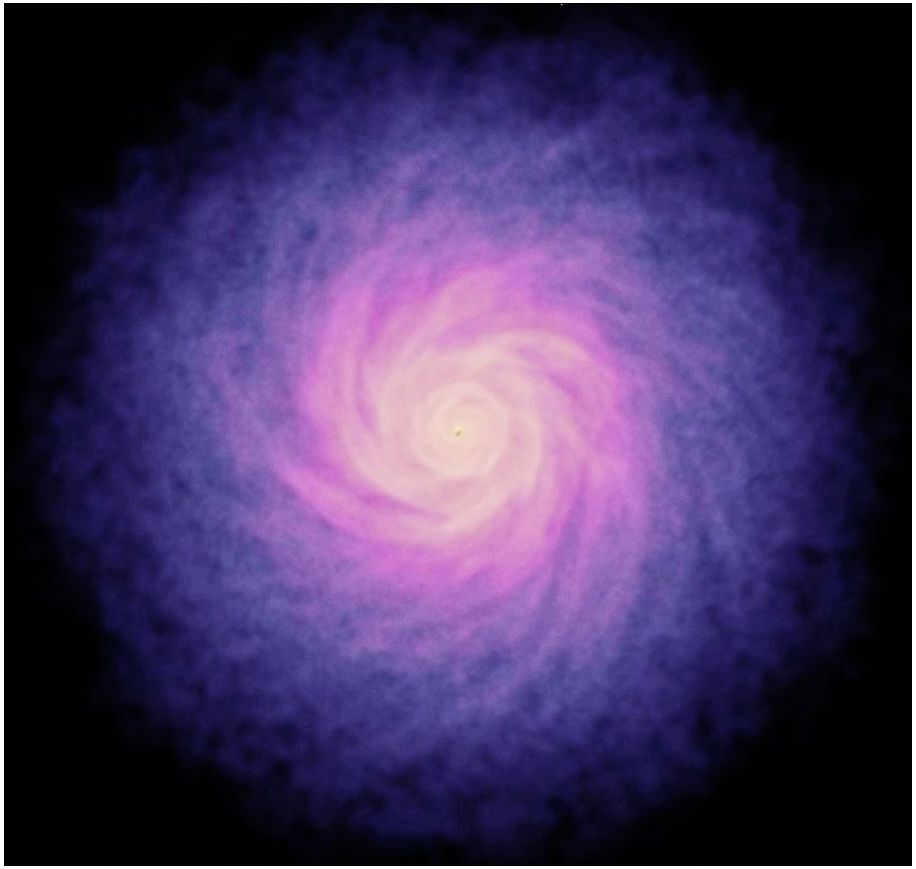




Carefully constructed compound galaxies are stable when evolved in isolation

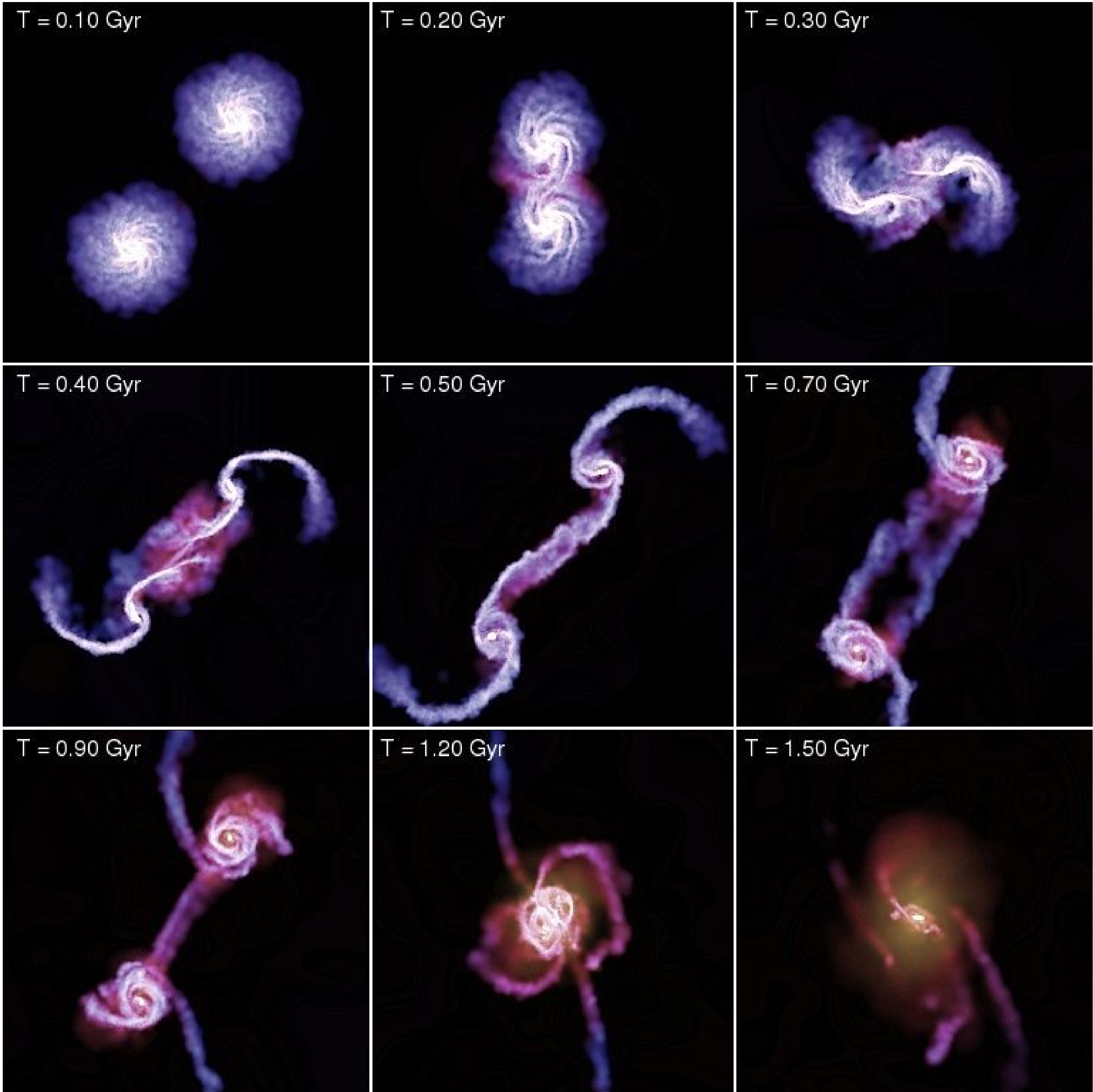
TIME EVOLUTION OF AN ISOLATED GALAXY WITH A CENTRAL BLACK HOLE





In major-mergers between two disk galaxies, tidal torques extract angular momentum from cold gas, providing fuel for nuclear starbursts

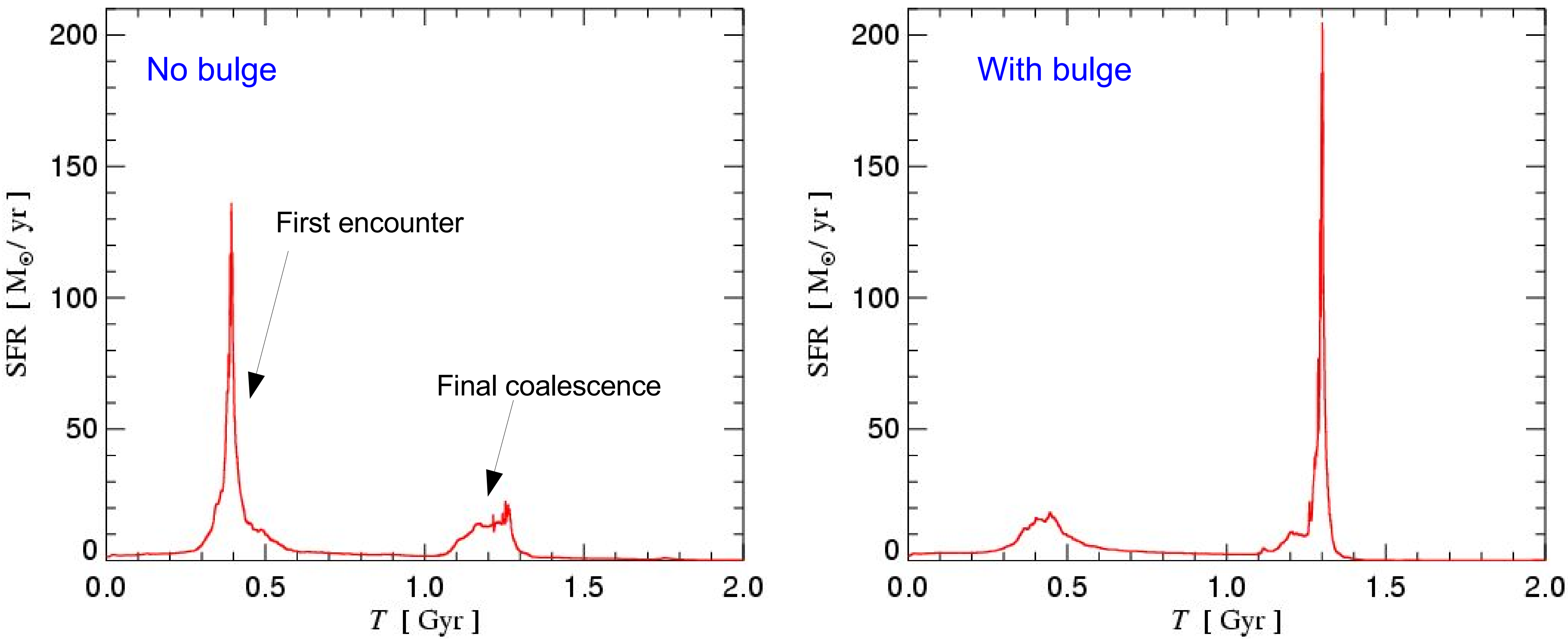
TIME EVOLUTION OF A PROGRADE MAJOR MERGER



This may also fuel a central AGN !

The strength and morphology of the starburts depends on the structural stability of the disks, and on the collision orbit

STARBURSTS IN MODELS WITH ISOTHERMAL EQUATION OF STATE

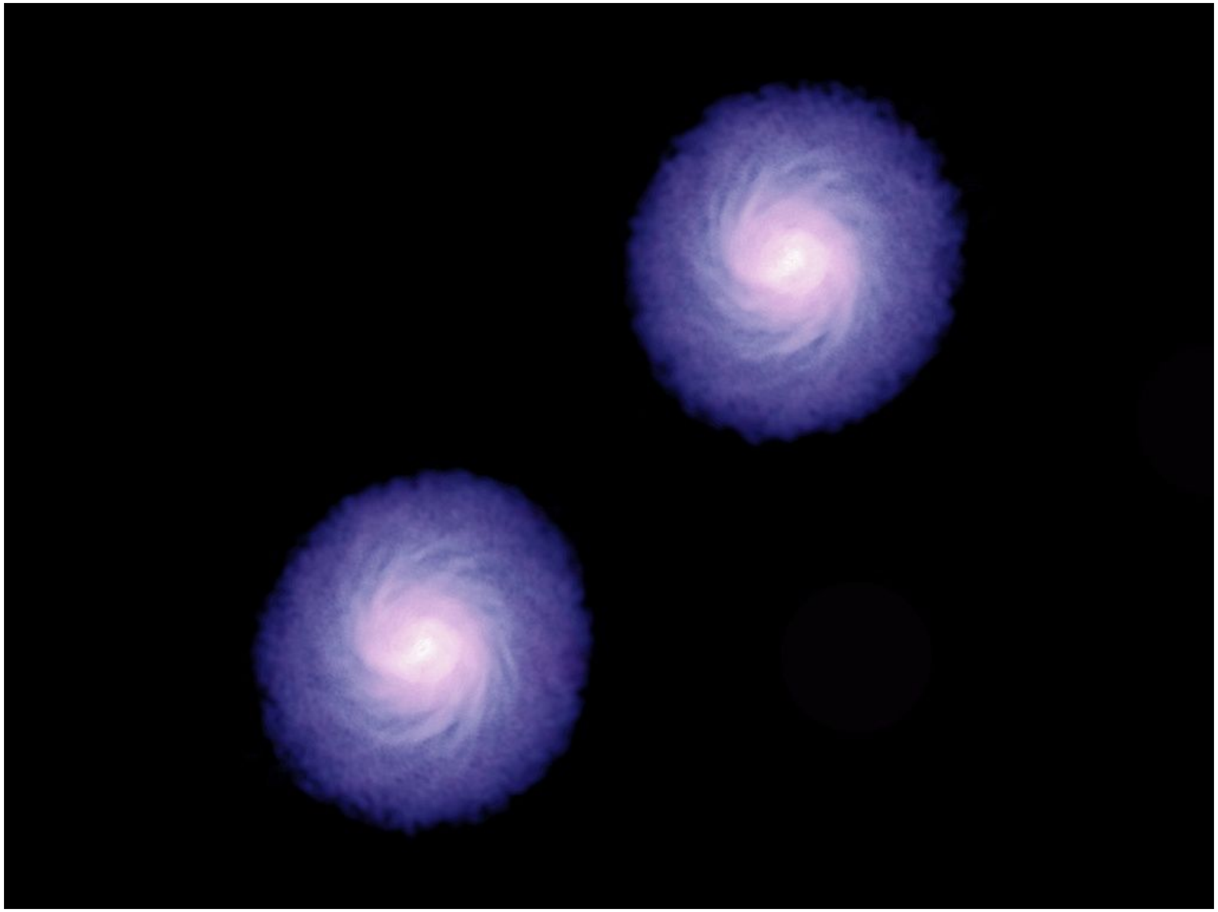


Same behaviour as in: Mihos & Hernquist (1994)
Springel (2000)

In mergers with supermassive black holes, simultaneous feeding of nuclear starbursts and central AGN activity occurs

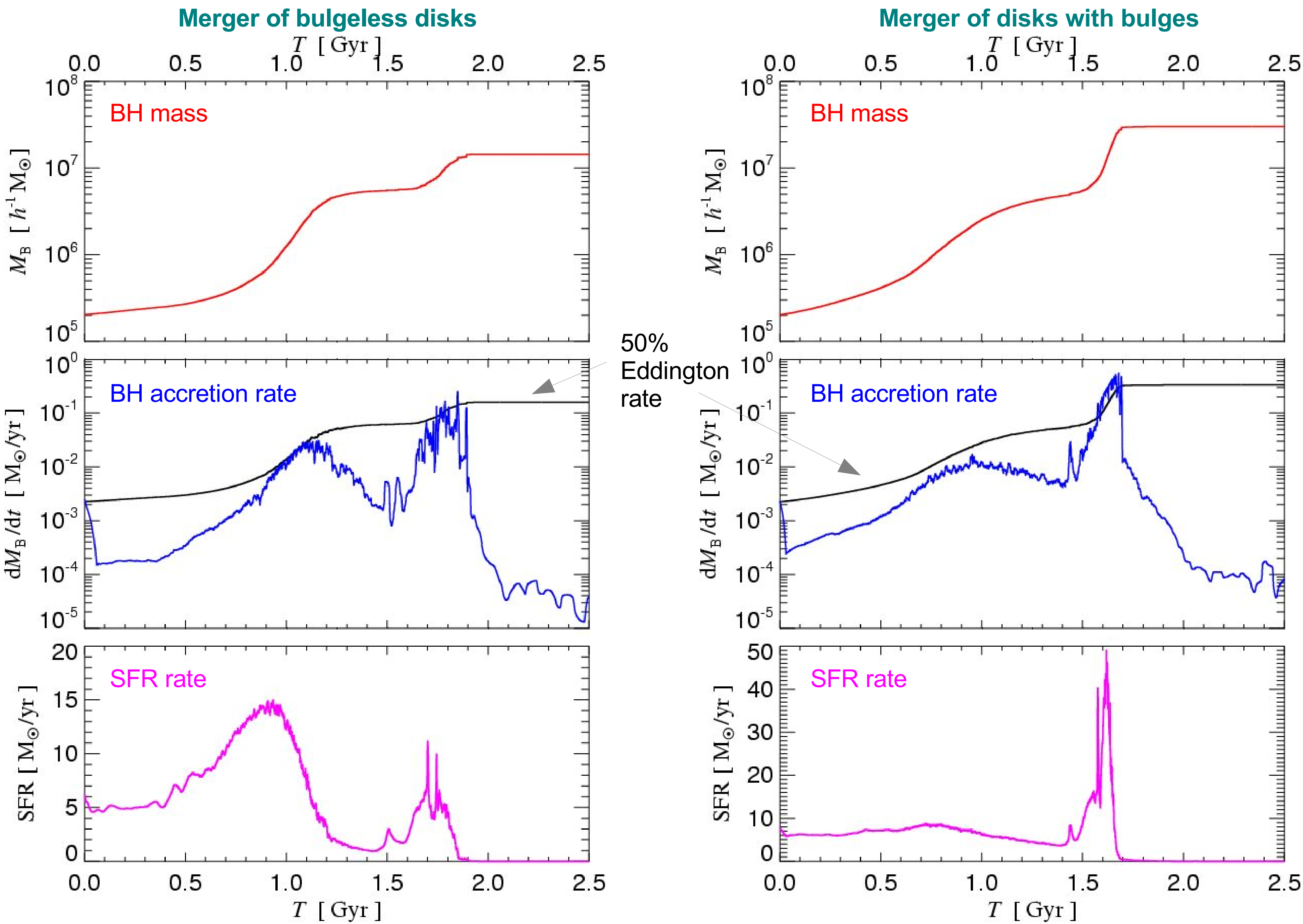
TIME EVOLUTION OF A MERGER WITH CENTRAL BLACK HOLE ACCRETION

The movie...



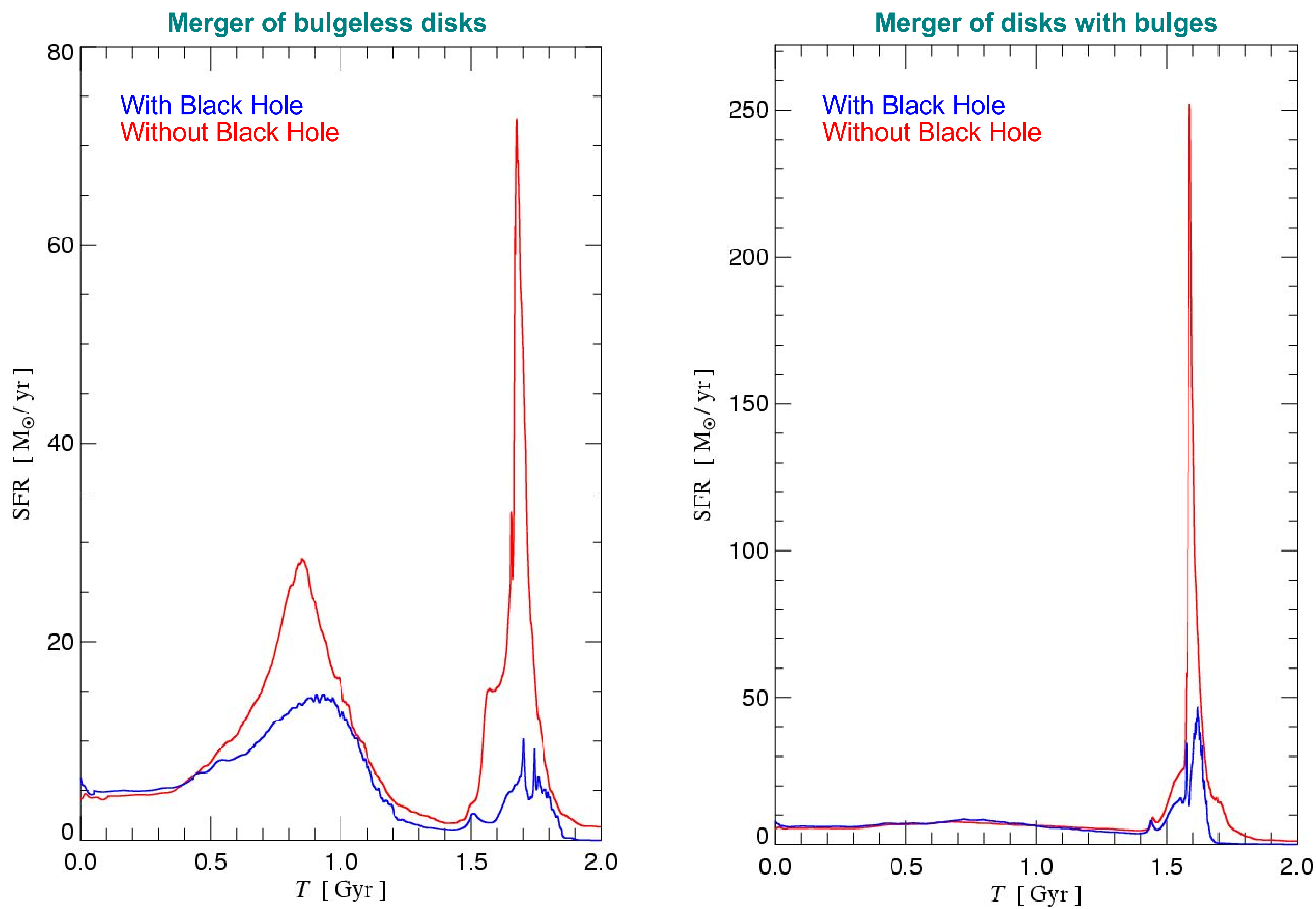
Mergers of disk galaxies trigger starburts and ignite central AGN activity

TIME EVOLUTION OF STAR FORMATION RATE AND BLACK HOLE GROWTH IN A MERGER



The feedback by the AGN can reduce the strength of the starburst

COMPARISON OF STAR FORMATION IN MERGERS WITH AND WITHOUT BLACK HOLE



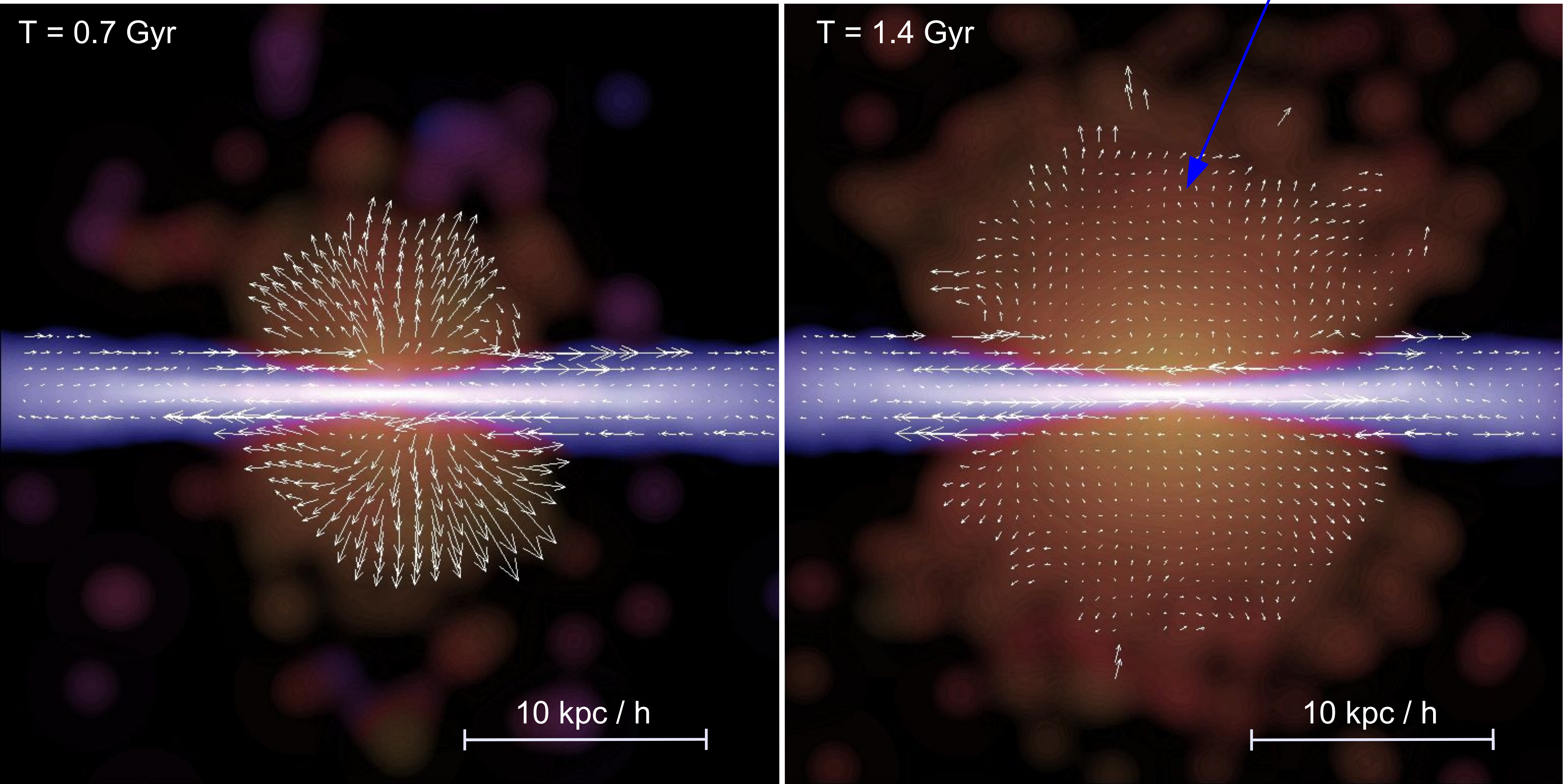
At low accretion rates, feedback by the central black hole activity may blow a weak wind into the halo

GAS FLOW INTO THE HALO

Isolated disk galaxy with bulge

Generated hot halos holds 1-2% of the gas

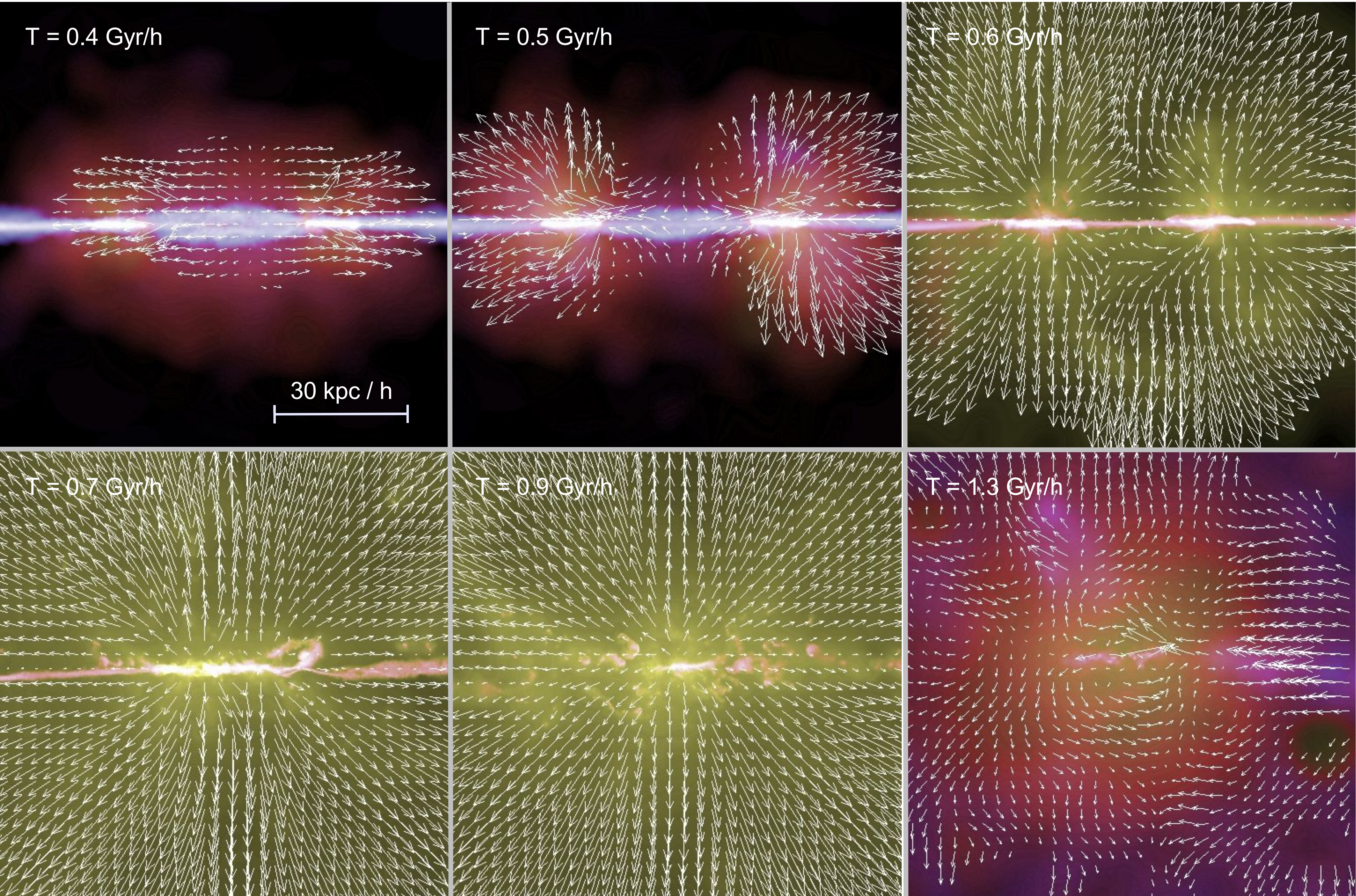
(dynamic range in gas surface density ~10^6)



The feedback by the central black activity may drive a strong quasar wind

GAS OUTFLOW BY AGN FEEDBACK

(outflow reaches speeds of up to ~1800 km/sec)



The properties of merger remnants are altered by the AGN activity

THE FATE OF THE GAS IN A MERGER WITH AND WITHOUT BLACK HOLES

Merger without black hole:

initial gas mass: 1.56 x 10^{10} $h^{-1}M_\odot$

- 89.0% turned into stars
- 0.05% expelled from halo
- 1.2% cold, star forming gas
- 9.8% diffuse gas in halo

X-ray luminosity

~ 9.5 x 10^{39} erg s^{-1}

Residual star formation rate

~ 0.13 $M_\odot yr^{-1}$

(1 Gyr after galaxy coalesence)

Merger with black hole:

initial gas mass: 1.56 x 10^{10} $h^{-1}M_\odot$

- 51.9% turned into stars
- 35.3% expelled from halo
- 0% cold, star forming gas
- 11.1% diffuse gas in halo
- 1.6% swallowed by BH(s)

X-ray luminosity

~ 4.8 x 10^{38} erg s^{-1}

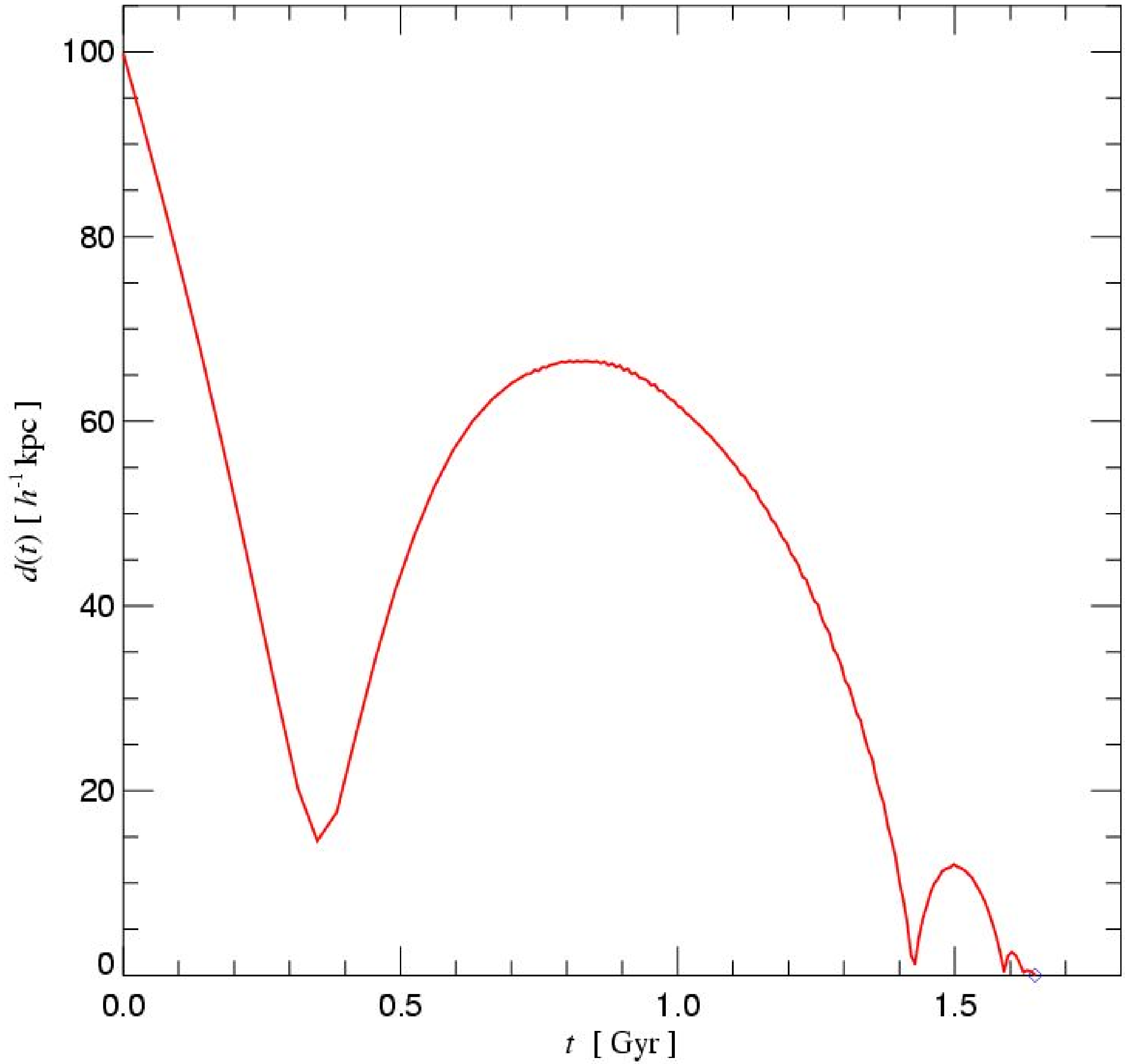
Residual star formation rate

0 $M_\odot yr^{-1}$

(1 Gyr after galaxy coalesence)

Galaxy mergers bring their central supermassive black holes quickly to separations less than ~100 pc

APPROACH OF THE BLACK HOLES IN MERGER SIMULATIONS



Note: The actual formation of a black hole binary, and the hardening of it, cannot presently be addressed by our simulations in an adequate way, due to lack of spatial dynamic range.

Conclusions

- We have implemented new numerical methods which allow us to carry out unprecedently large, high-resolution cosmological N-body simulations.
  We achieve $N>10^{10}$, with a formal dynamic range of 10^5 in 3D.

- A suite of advanced analysis software has been developed. It will allow the construction of theoretical mock galaxy catalogues, describing the history of 25 million galaxies. This will form one of the backbones of an emerging *Theoretical Virtual Observatory*.

- We have implemented new numerical methods which allow us to carry out large, high-resolution cosmological simulations of galaxy formation that track the growth of galactic supermassive black holes. The growth of black holes is self-regulated by AGN feedback.

- Mergers of galaxies exhibit a complex interplay between starbursts and nuclear AGN activity. In a major merger, star formation and accretion can be terminated on very short timescales, with the black hole driving a strong quasar outflow. As a result, the merger left behind is a comparatively gas-poor, “dead” elliptical, which quickly develops a red stellar color.