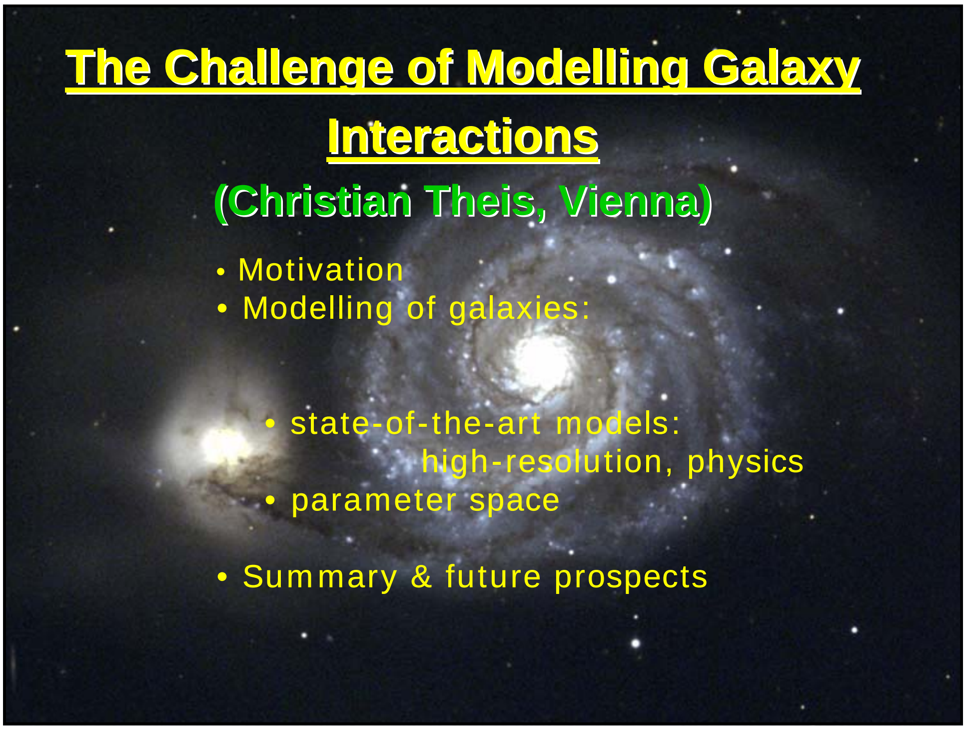
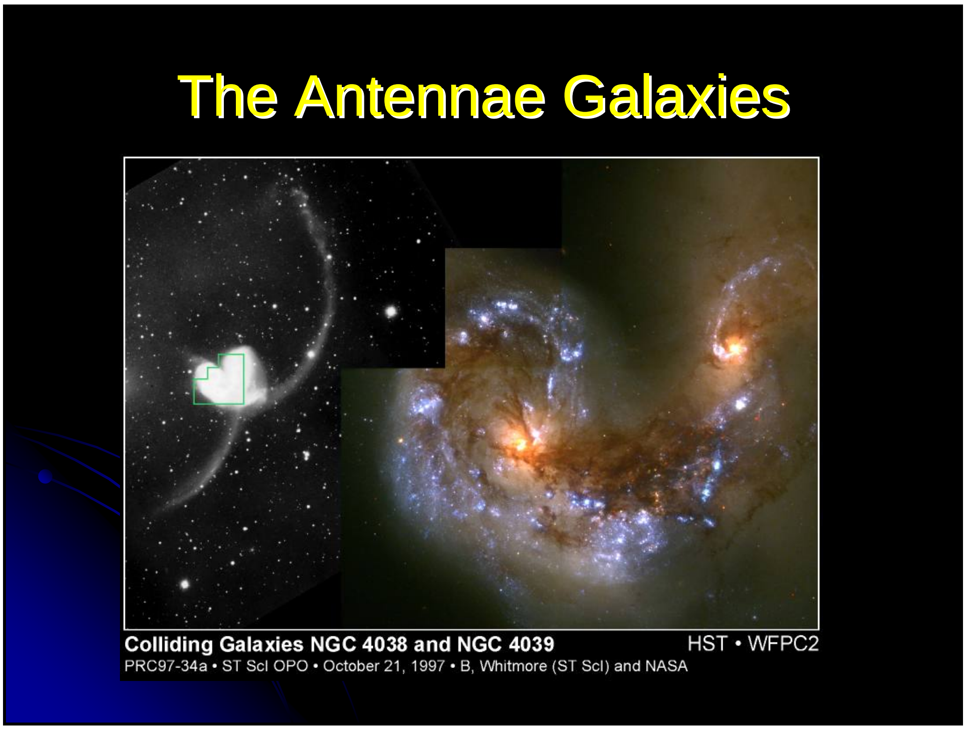
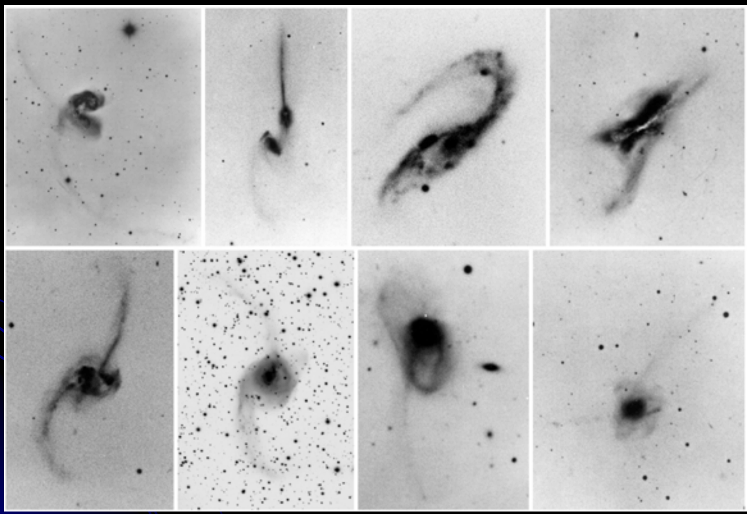

The Challenge of Modelling Galaxy Interactions
(Christian Theis, Vienna)
• Motivation
• Modelling of galaxies:
• state-of-the-art models: high-resolution, physics
• parameter space
• Summary & future prospects


The Antennae Galaxies
Colliding Galaxies NGC 4038 and NGC 4039
HST • WFPC2
PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

Toomre´s merger sequence



(Toomre 1977)

What can we learn from nearby galaxy interactions?

- test bed for galactic dynamics:
  - kinematical history of galaxies
  - physics of merging process (dynamical friction, timescales, galactic structure)
- test bed for galaxy evolution:
  - strength, mode and timing of perturbation
  - dynamical stability of galaxies
  - induced structural changes (mass flows, bars and spiral structure, mergers)
  - reaction of ISM ➔
    - star formation
    - chemical evolution
    - nuclear activity and mass loss
- properties of the dark matter halo

Modelling Galaxies

- Components:
  - Stars and stellar remnants
  - Interstellar medium (molecular clouds, diffuse gas, dust)
  - Dark matter
  - Black Holes
- Processes:
  - Dynamics:
    - Gravitational N-body problem
    - Hydrodynamics
  - Galactic „microphysics“:
    - Phase transitions (star formation, stellar death etc.)
    - Processes within a phase (e.g. cooling)
    - Interactions between phases (e.g. stellar feedback)

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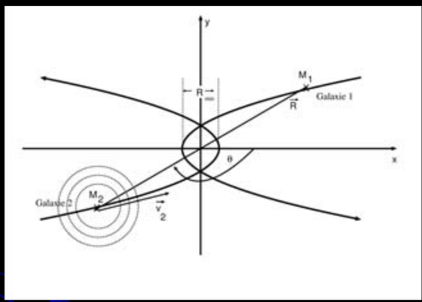
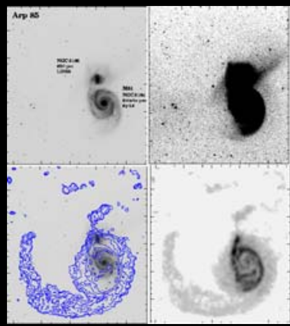
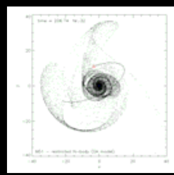
Restricted N-body simulations

- Idea (Pfleiderer & Siedentopf 1961, Toomre & Toomre 1972)







(Theis & Spinneker 2003)

- **Basic assumption:**
  Galaxies follow Keplerian orbits
  - Stars are treated as test particles
  - Fast integration (~ 1 CPU sec on modern PC)
  - High spatial resolution in regions of interest
- **BUT:** not self-consistent (e.g. no merging)

Self-consistent simulations

- include self-gravity of stars, gas and dark matter
- main problem: N^2-bottleneck
- simulation methods:
  1. TREE-codes (~N logN, ~N) (e.g. Barnes & Hut 1986, Dehnen 2000 [gyrfalcon], Springel 2005 [Gadget2], Wetzstein 2005 [VINE])
  2. grid-based schemes (~N) (e.g. Sellwood 1982, Couchman et al. [HYDRA])
  3. expansion methods, (~N) (e.g. SCF Hernquist & Ostriker 1992)
  4. special purpose computer, GRAPE (~N^2)

     (Tokyo group [Makino, Sugimoto et al.] since 1990)

GRAPE-project

- **IDEA:** hardwire the law of gravity on a chip
  (Sugimoto, Makino et al., since 1989)
  - use standard components/technology (cheap)
  - extension card for a workstation/PC (e.g. PCI)
- Concept of a GRAPE simulation:
  - GRAPE-card does the N^2-operations (gravitational force)
  - Remaining computations are performed on a host computer/cluster
  - Recent variation: GRACE-Cluster (Spurzem, Heidelberg): remaining CPU intensive operation on host are done by FPGA card

GRAPE-project

GRAPE clusters

RIT's gravitySimulator is operational since Feb 2005

- 32 dual 3GHz-Xeon nodes
- 32 GRAPE-6A's
- 14 TByte RAID
- low-latency Infiniband interconnects (10Gbps)
- Speed: nom. 4 TFlops (pract. 2 TF)
- *N* up to 4 Million particles
- Cost: $0.5x10^6$
- Funding: NSF/NASA/RIT
- Similar clusters:
  - 24(?) nodes (University of Tokyo)
  - 32 nodes (Heidelberg)
  - Vienna (soon): 10 nodes

(Rochester Institute of Technology)

(kindly prov. by S. Harfst)

Modelling Galaxies

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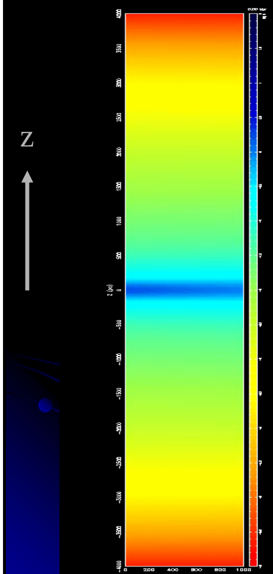
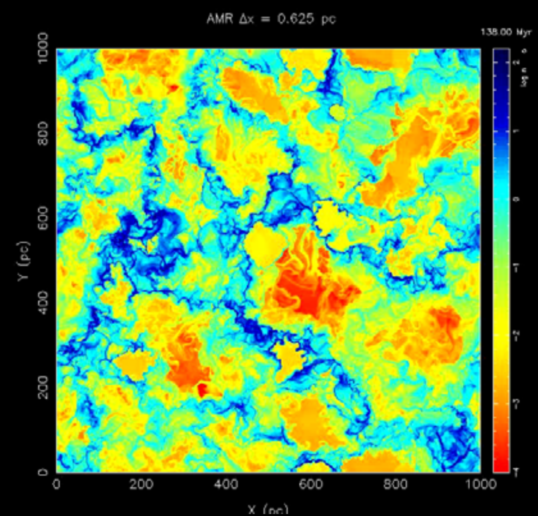
Gas dynamics in galaxy models…

- Single component ISM
  - hydrodynamical models:
    - grid codes
    - smoothed particle hydrodynamics (SPH)
  - phenomenological models:
    - sticky particles (for gas clumps, clouds)
- Multi-component ISM

HD Evolution of large/small scale structures of the ISM





(Avillez & Breitschwerdt 2005)

- Simulation of SN driven ISM over 400 Myr
- Grid: 1kpc x 1 kpc x ± 10 kpc
- max. resolution: 0.625 pc

Multiphase ISM models

- high-resolution simulations: SPH, grid approaches (e.g. Heitsch et al. 2006; de Avillez & Breitschwerdt 2006)
  problem: model only a small fraction of a galaxy
- SPH-models + subgrid physics
  - single particle consists of stars, clouds and hot gas (Springel & Hernquist 2003); coupled dynamics of stars, clouds & gas
  - H_2 formation in a radiation field, sub-resolution cloud mass spectrum (Pelupessy et al. 2006)
- hybrid-codes: SPH + sticky particles
  - SPH: diffuse gas & sticky particles: molecular clouds (Semelin & Combes 2002; Berczik et al. 2003; Harfst, Theis & Hensler 2006; Booth, Theuns & Okamoto 2007)
- problem for all subgrid AND hybrid codes: treatment of small-scale physics depends strongly on the adopted ISM model

CD-model of interacting galaxies

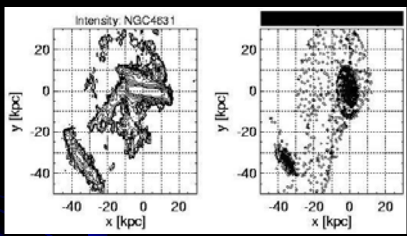
- TREE-SPH (gyrfalcon, Dehnen 2000)
  - alternatively: GRAPE-SPH
- *life DM halo* with
  - TREE or GRAPE
- additional features
  - star formation and stellar *feedback*
  - (radiative) cooling
  - cloud collisions
  - multi-phase ISM (evaporation/condensation)

simulation based on code developed by S. Harfst and Ch. Theis (Harfst et al. 2006)

(Harfst, Theis, Hensler, Kroupa, in progress 2007)

How can we learn from interactions: parameter space

- Optimization problem:



Fitness function:

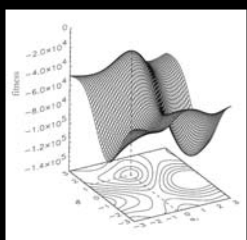
$$f = \frac{1}{1+\delta}; \ \delta \equiv \sum_{cells} \frac{|I_{ref,i} - I_{sim,i}|}{\max(I_{ref,i}, I_{sim,i})}$$

Goals:
- Finding a solution
- Uniqueness of a solution

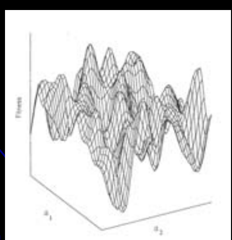
Problems:
- Extended parameter space
- Trapping by local optima

Fitness landscapes

smooth landscape:



multi-peaked landscape:



Parameter space

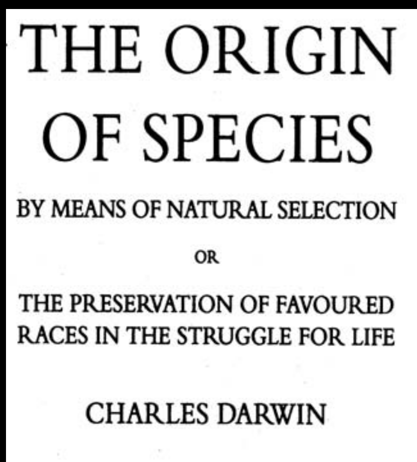
- Parameters:
  - two-body parameters (orbital plane, eccentricity, pericenter, masses...)
  - characteristics of galaxies (orientation of disk, scalelength,...,halo...)
- Example:
  - disk+point-like perturber: 7 parameters
  - grid with 5 pts./dimension: 78125 models or ~ 3.5 years GRAPE6 CPU time

Fast N-body technique and efficient search strategy required!

Genetic algorithm

- IDEA: imitate evolutionary optimization, i.e. adaptation of a population by „survival" of the fittest solution (Holland 1975, Goldberg 1989)

1. Start with a random population, i.e. N_p points in parameter space
2. Apply iteratively reproduction operators

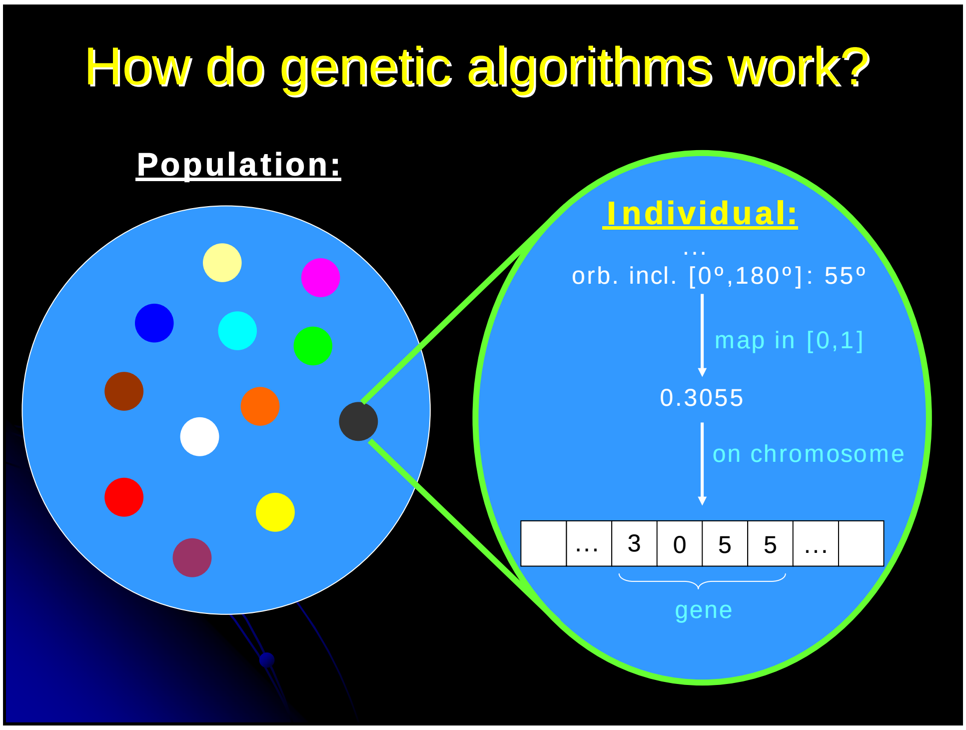

THE ORIGIN OF SPECIES

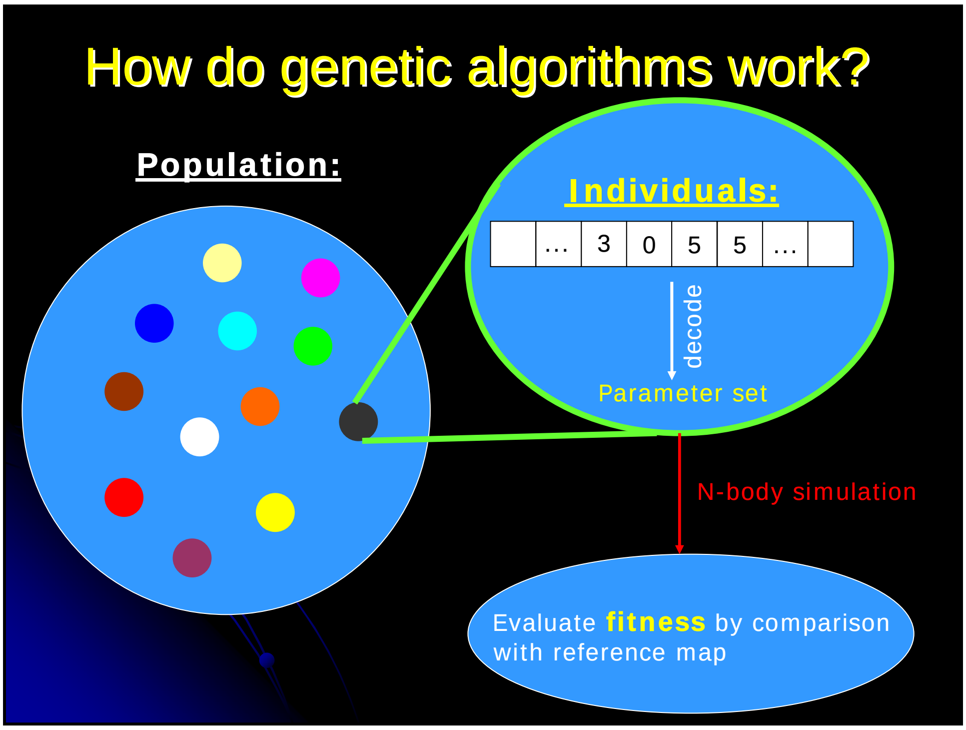
BY MEANS OF NATURAL SELECTION

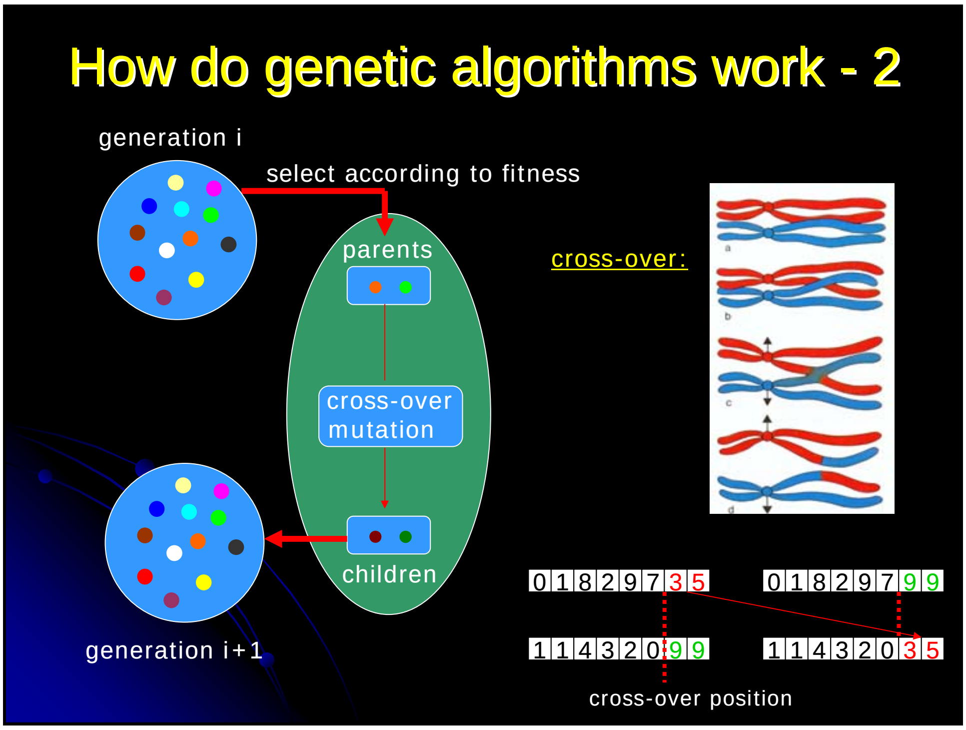
OR

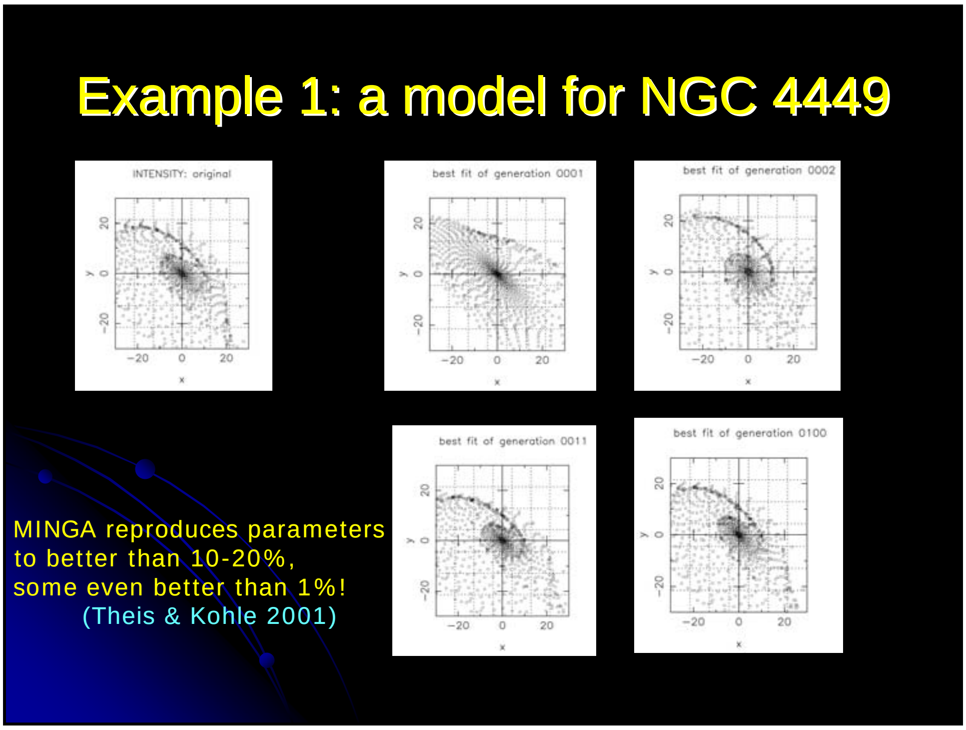
THE PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE

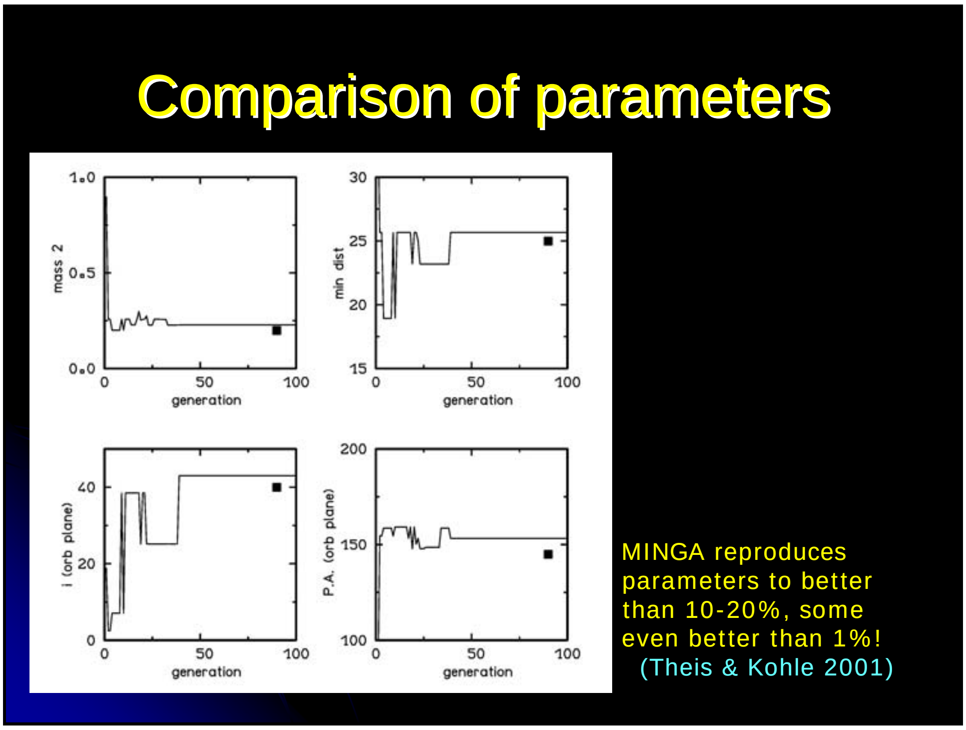
CHARLES DARWIN

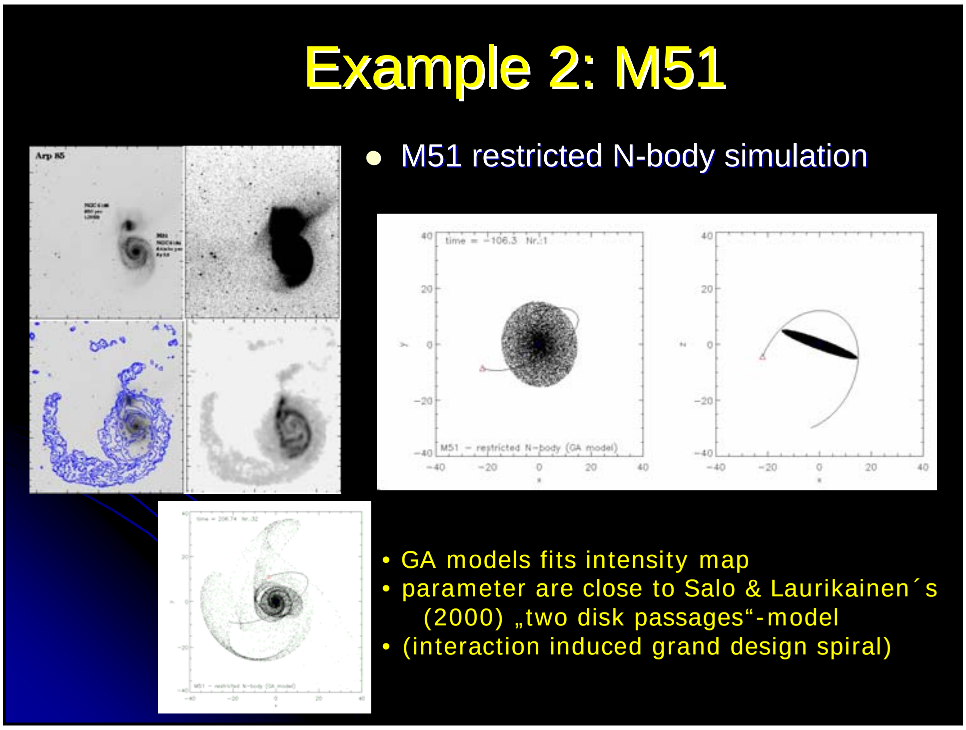

How do genetic algorithms work?
Population:
Individual:
...
orb. incl. [0°,180°]: 55°
map in [0,1]
0.3055
on chromosome
... 3 0 5 5 ...
gene


How do genetic algorithms work?
Population:
Individuals:
... 3 0 5 5 ...
decode
Parameter set
N-body simulation
Evaluate fitness by comparison with reference map


How do genetic algorithms work - 2
generation i
select according to fitness
parents
cross-over
mutation
children
generation i+1
cross-over:
0 1 8 2 9 7 3 5
0 1 8 2 9 7 9 9
1 1 4 3 2 0 9 9
1 1 4 3 2 0 3 5
cross-over position

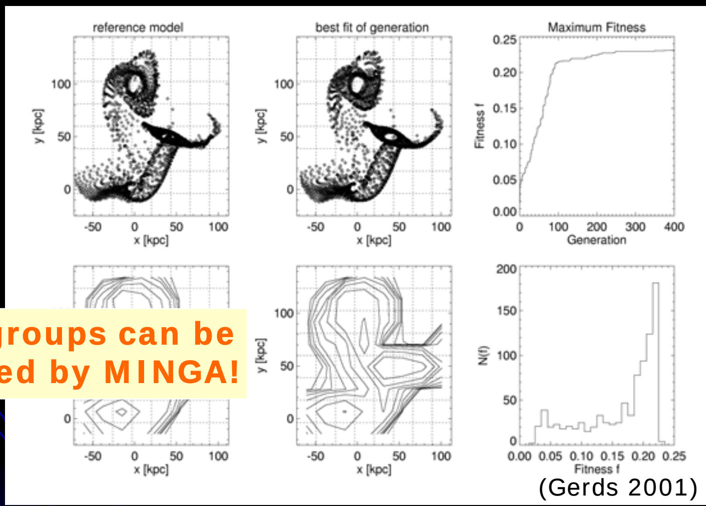

Example 1: a model for NGC 4449
INTENSITY: original
best fit of generation 0001
best fit of generation 0002
best fit of generation 0011
best fit of generation 0100
MINGA reproduces parameters
to better than 10-20%,
some even better than 1%!
(Theis & Kohle 2001)


Comparison of parameters
mass 2
min dist
i (orb plane)
P.A. (orb plane)
generation
MINGA reproduces parameters to better than 10-20%, some even better than 1%!
(Theis & Kohle 2001)


Example 2: M51
• M51 restricted N-body simulation
Arp 85
• GA models fits intensity map
• parameter are close to Salo & Laurikainen´s (2000) „two disk passages“-model
• (interaction induced grand design spiral)

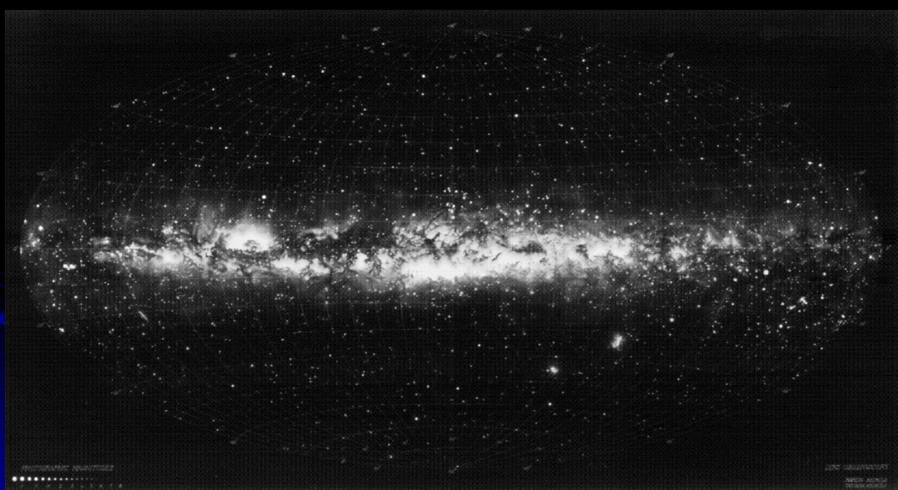
Example 3: MINGA-Fit of a small group of galaxies

MINGA-Fit for a small group of galaxies:

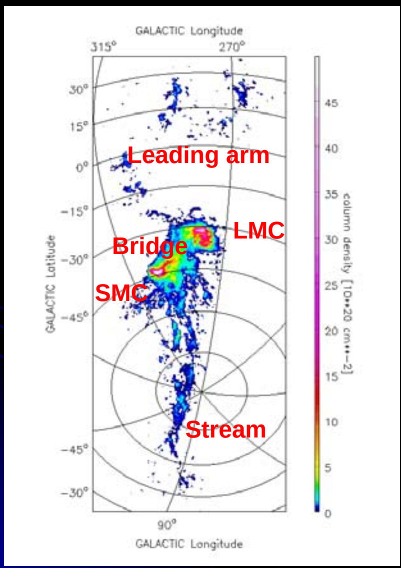


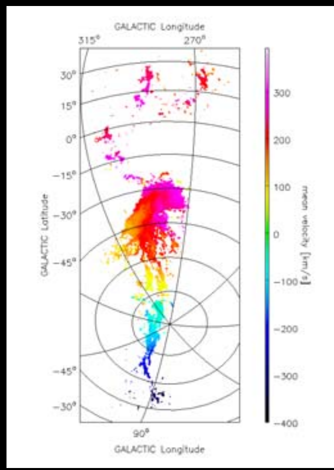
(Gerds 2001)

Example 4: The Magellanic System


(Lund observatory)

The Magellanic System in HI

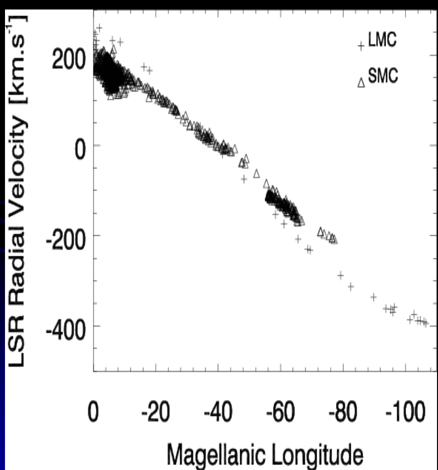


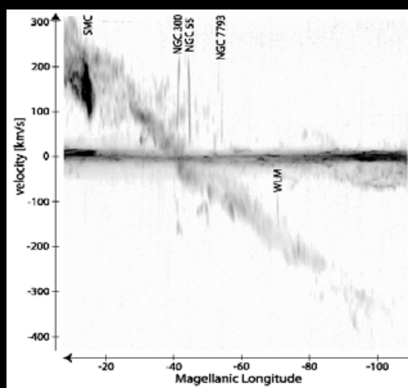


(Brüns et al. 2005)

A Genetic Algorithm model…

- 3D LMC-SMC column density data-cube used
- actual resolution of 16” x 16” x 7km/s





(Ruzicka, Palous & Theis 2007)

GA model for Magellanic Stream…

Results:

- MW dark matter halo close to spherical, probably slightly oblate
- Preferred model class A:
  - MW halo flattening: q~0.84
  - Clouds only recently close together
  - Material in the Stream stems from both Clouds

Near Future of MINGA…

- **Work in progress:**
  - merging galaxies:
    - dynamical friction in restricted N-body models
  - flattened halos
  - full data cubes (HI) as input data
- **Work in preparation:**
  - ram pressure effects
  - improved treatment of galaxy groups
  - GRAPE-MINGA: modelling with self-consistent models

Multimethod Modelling

- Step 1: GA-based analysis of parameter space
- Step 2: Dynamically self-consistent modelling
  - Pure stellar dynamics
  - Gas dynamics
- Step 3: Self-consistent multi-component modelling, i.e. chemo-dynamical modelling (including SF, feedback, etc.)

Summary

- State-of-the-art simulations:
  - Stellar-dynamics: ++ (still difficult: collisional stellar dynamics near massive BH)
  - ISM treatment:
    - dynamics: + -
    - phase transitions (SF, feedback): (+) -
- Parameter space handling/modelling individual galaxies:
  - overall dynamics: + -
  - microphysics: - -

Collaborators

- Stefan Harfst (Rochester)
- Simone Recchi (Trieste), Gerhard Hensler (Vienna), Pavel Kroupa (Bonn)
- Christian Boily (Strasbourg), Thorsten Naab (Munich)
- Lia Athanassoula, Albert Bosma (Marseille)
- Christian Brüns, Nikolaus Neininger, Uli Klein, Sven Kohle (Bonn)
- Adam Ruzicka, Jan Palous (Praha)
- Helmut Meusinger (Tautenburg)
- Jay Gallagher, Linda Sparke (Madison)
- Werner Zeilinger (Vienna), Giovanna Temporin (Milano)
- Christoph Gerds, Christian Spinneker (Kiel)
- Gerald Jungwirth, Harald Leibinger, Armin Liebhart, Hanns Petsch, Julia Weniger (Vienna)