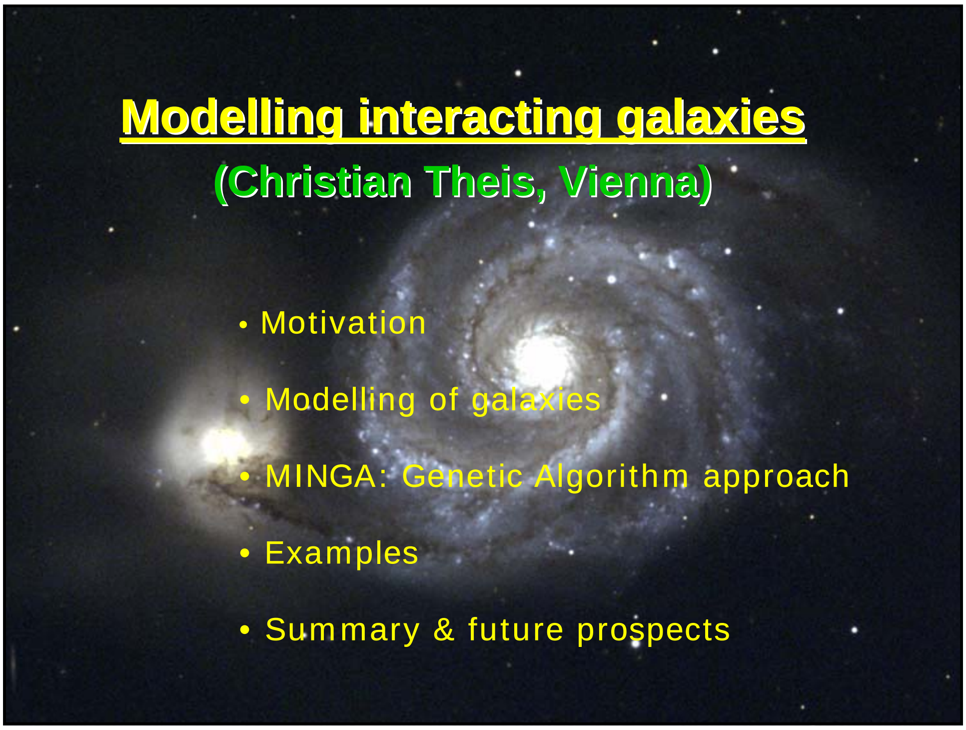
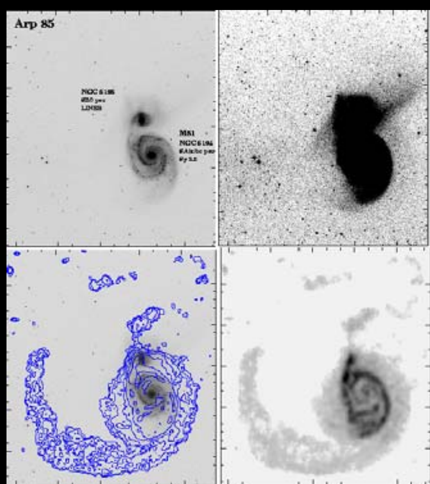


M51: a prototype for an interaction



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

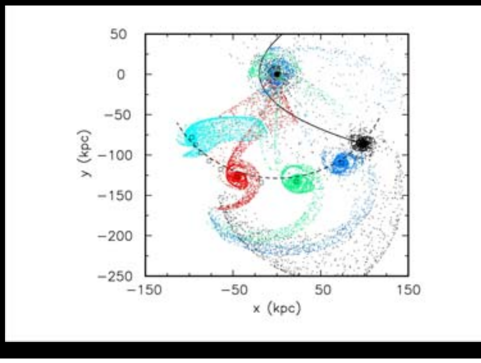
What can we learn from galaxy interactions?

- kinematical history of galaxies
- 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

Influence of dark matter halos on galaxy interactions

- Why interacting systems?
  - Tidal tails can trace outer galaxy
  - Tidal tails can probe off-plane regions
  - Tidal features sensitive to DM halo properties (Dubinski et al. 1999, Springel & White 1999)
- Halo parameters:
  - Mass
  - Extension
  - Flattening (?)
  - (Rotation)

Influence of a variable halo size



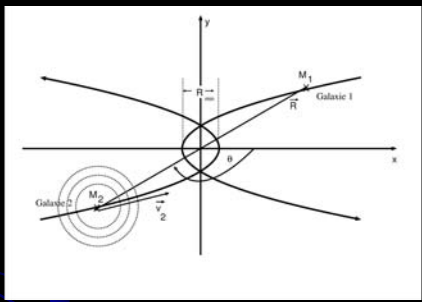
halos act like softened gravitational forces

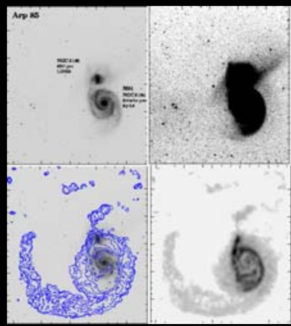
Modelling Galaxies

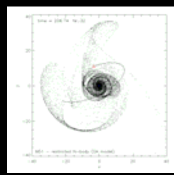
- Components:
  - Stars and stellar remnants
  - Interstellar medium (molecular clouds, diffuse gas, dust)
  - Dark matter
  - Black Holes
- Processes:
  - Dynamics:
    - Gravitational N-body problem
    - Hydrodynamics
  - Galactic „microphysics“:
    - Phase transitions (star formation, stellar death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

Restricted N-body simulations

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







- **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)

(Theis & Spinneker 2003)

Self-consistent simulations

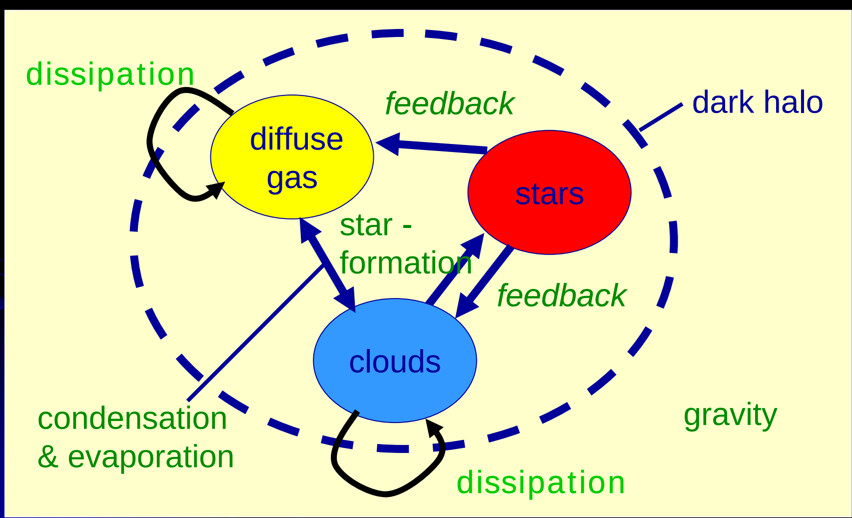
- include self-gravity of stars, gas and dark matter
- main problem: N^2-bottleneck
- simulation methods:
  1. TREE-codes (~N logN, ~N) (e.g. Barnes & Hut 1986, Dehnen 2000)
  2. grid-based schemes (~N) (e.g. Sellwood 1982)
  3. expansion methods, (~N) (e.g. SCF Hernquist & Ostriker 1992)
  4. special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

     (Tokyo group [Makino, Sugimoto et al.] since 1990)
- **BUT:**
  - no trivial stable initial configurations
  - low resolution in low-density regions
  - computationally expensive

Gas dynamics in galaxy models…

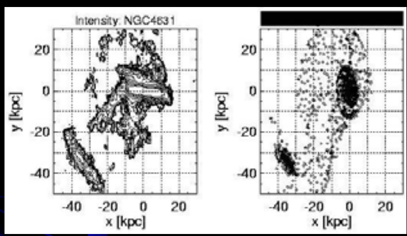
- Single component ISM
  - hydrodynamical models:
    - grid codes
    - smoothed particle hydrodynamics (SPH)
  - phenomenological models:
    - sticky particles (for gas clumps, clouds)
- Multi-component ISM
  - often: sub-grid models
  - high-resolution hydrodynamical models (SPH, grid)
  - hybrid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

Chemo-dynamics: towards a complete model...



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:

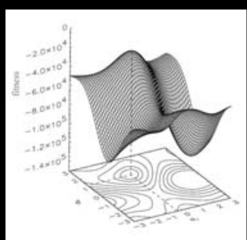
- Finding a solution
- Uniqueness of a solution

Problems:

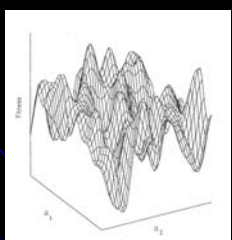
- Extended parameter space
- Trapping by local optima

Fitness landscapes

smooth landscape:



multi-peaked landscape:



Parameter space

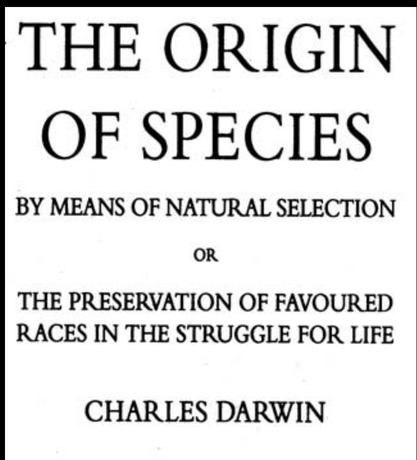
- **Parameters:**
  - two-body parameters (orbital plane, eccentricity, pericenter, masses...)
  - characteristics of galaxies (orientation of disk, scalelength,...,halo...)
- **Example:**
  - Disk+point-like perturber: 7 parameters
  - grid with 5 pts./dimension: 78125 models or ~ 3.5 years GRAPE6 CPU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

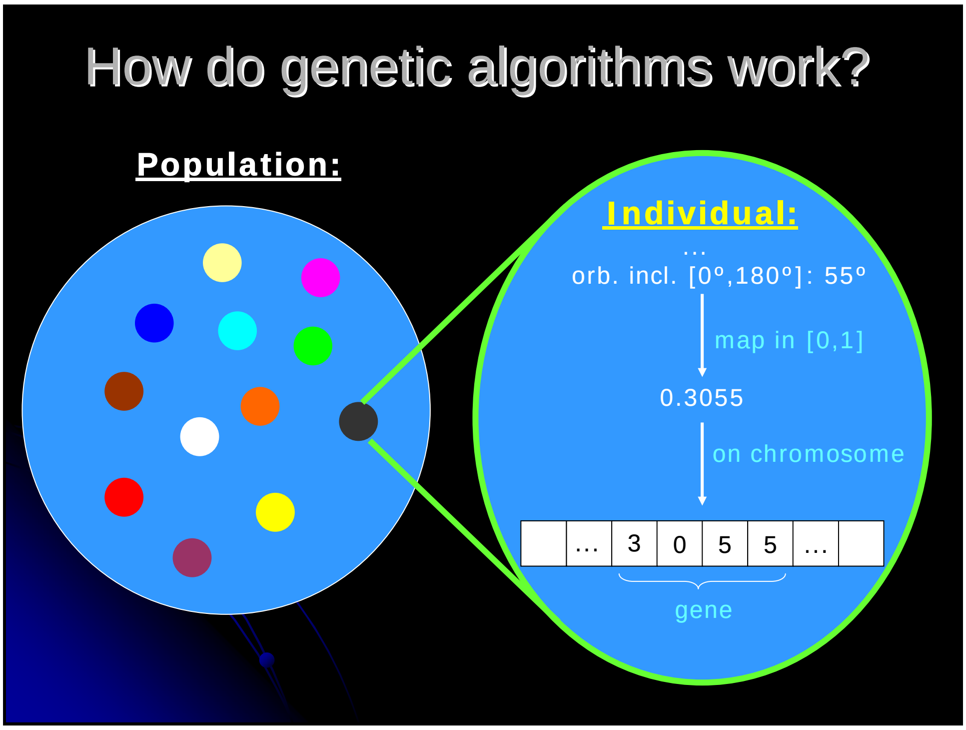

THE ORIGIN OF SPECIES

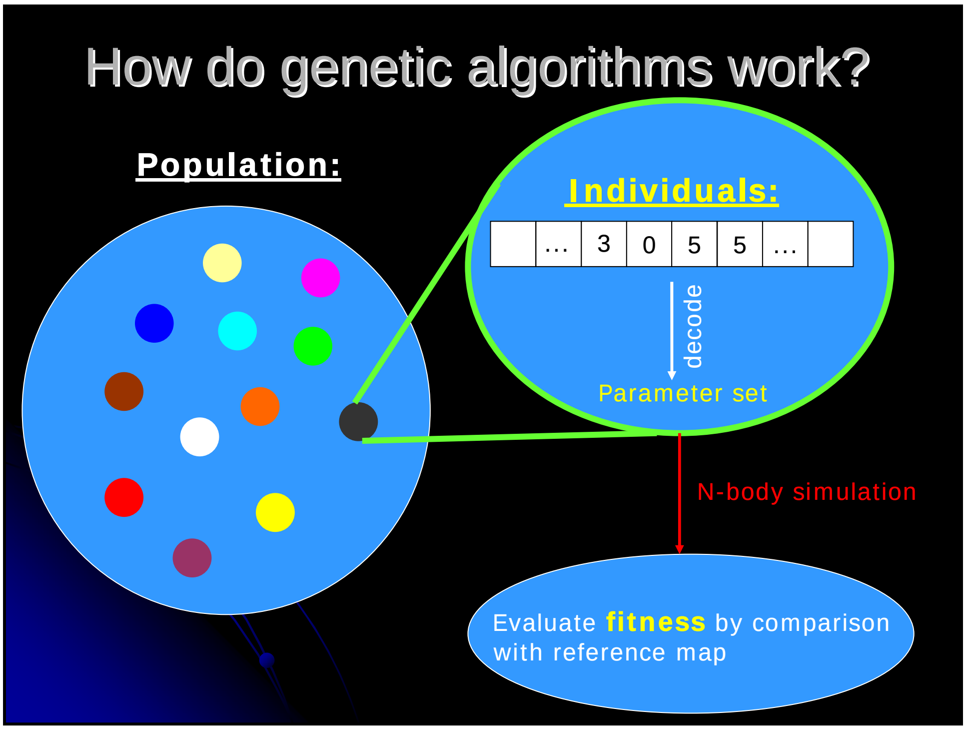
BY MEANS OF NATURAL SELECTION

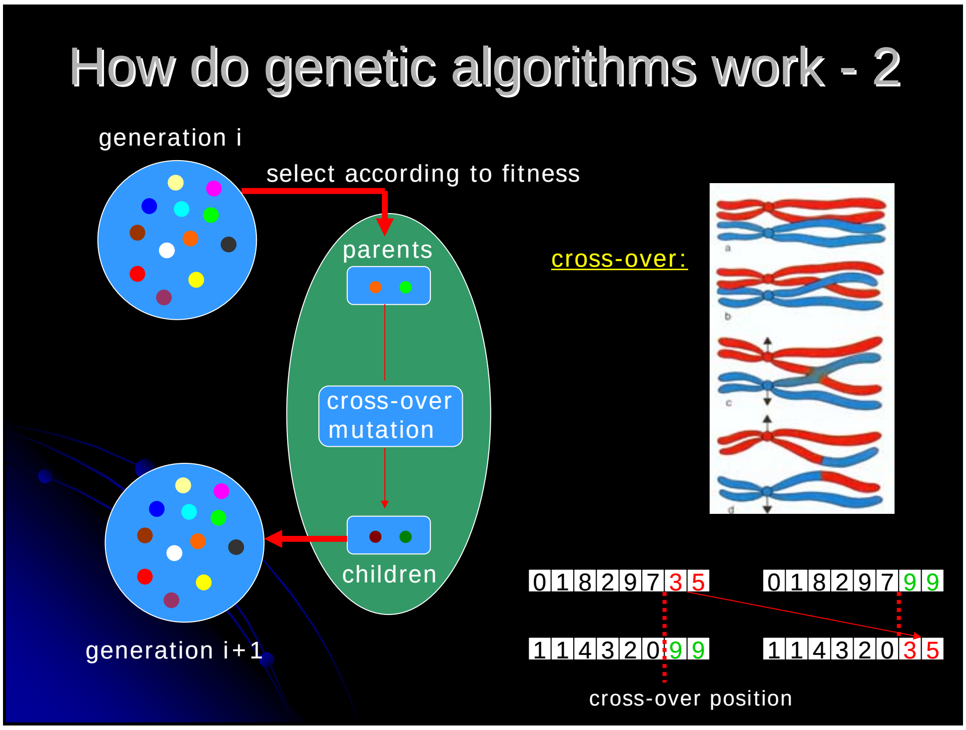
OR

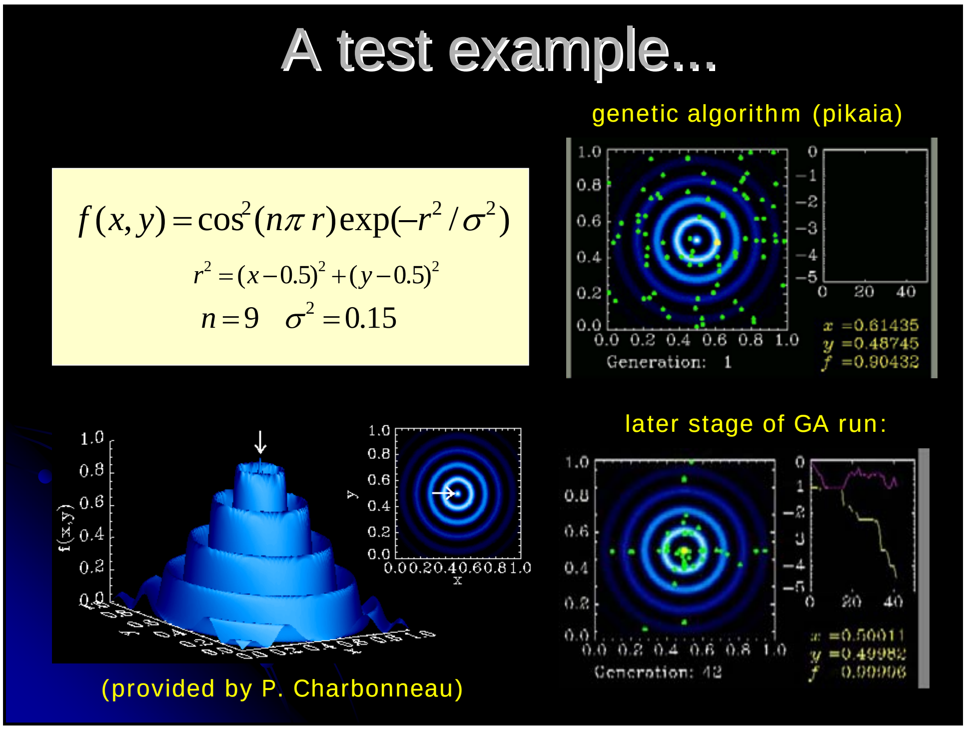
THE PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE

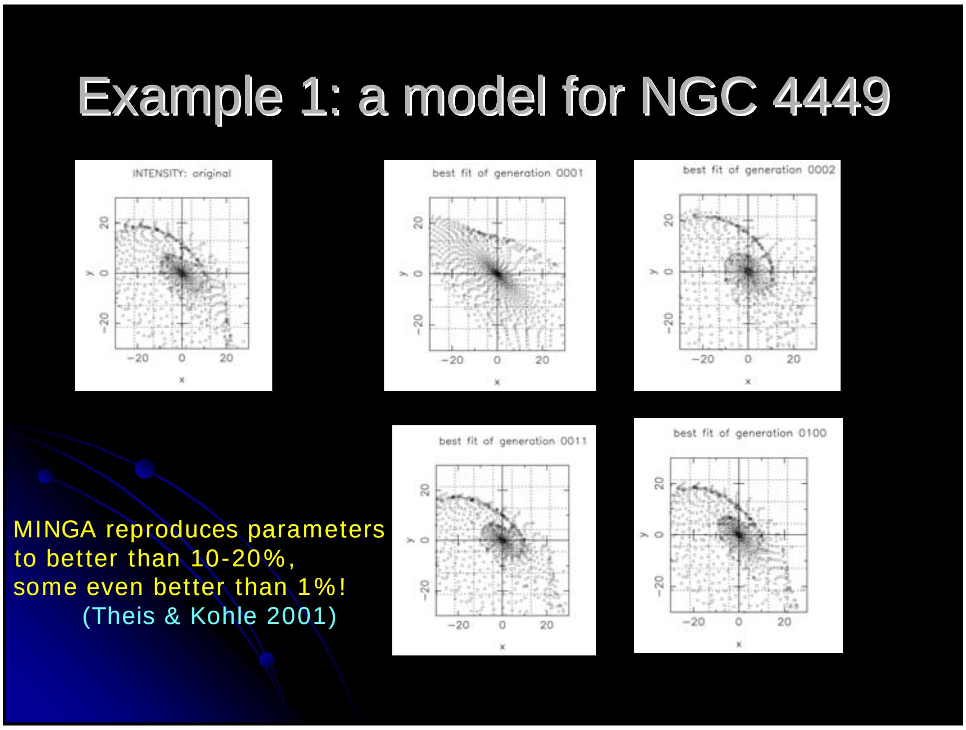
CHARLES DARWIN

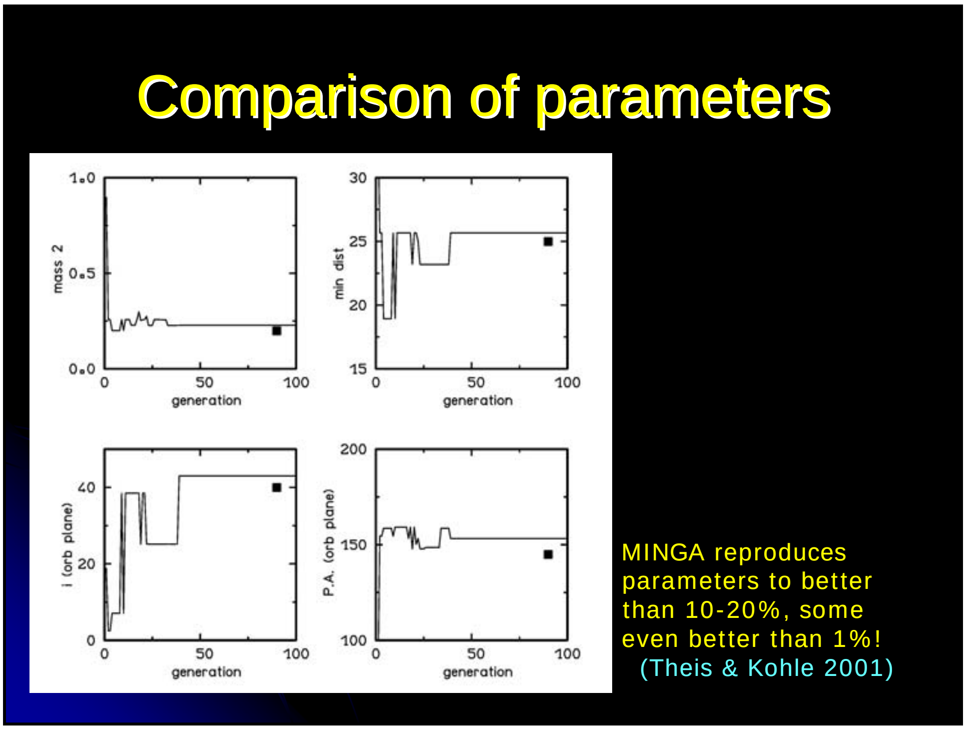

How do genetic algorithms work?
Population:
Individual:
...
orb. incl. [0°,180°]: 55°
map in [0,1]
0.3055
on chromosome
... 3 0 5 5 ...
gene


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

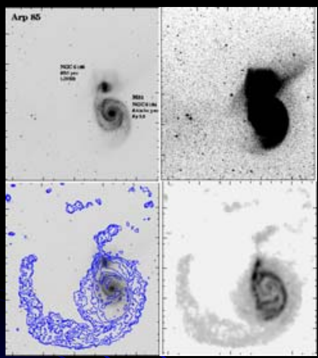

How do genetic algorithms work - 2
generation i
select according to fitness
parents
cross-over
mutation
children
generation i+1
cross-over:
0 1 8 2 9 7 3 5
0 1 8 2 9 7 9 9
1 1 4 3 2 0 9 9
1 1 4 3 2 0 3 5
cross-over position


A test example...
$f(x,y) = \cos^2(n\pi r)\exp(-r^2/\sigma^2)$
$r^2 = (x-0.5)^2 + (y-0.5)^2$
$n = 9 \quad \sigma^2 = 0.15$
genetic algorithm (pikaia)
Generation: 1
x =0.61435
y =0.48745
f =0.90432
later stage of GA run:
Generation: 42
x =0.50011
y =0.49982
(provided by P. Charbonneau)

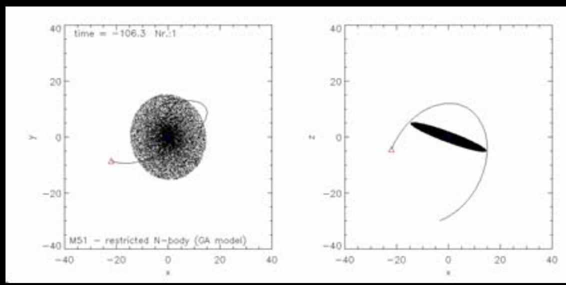

Example 1: a model for NGC 4449
INTENSITY: original
best fit of generation 0001
best fit of generation 0002
best fit of generation 0011
best fit of generation 0100
MINGA reproduces parameters
to better than 10-20%,
some even better than 1%!
(Theis & Kohle 2001)

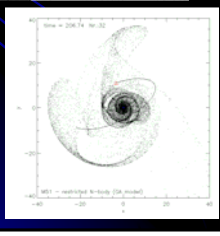

Comparison of parameters
mass 2
min dist
i (orb plane)
P.A. (orb plane)
generation
MINGA reproduces
parameters to better
than 10-20%, some
even better than 1%!
(Theis & Kohle 2001)

Example 2: M51



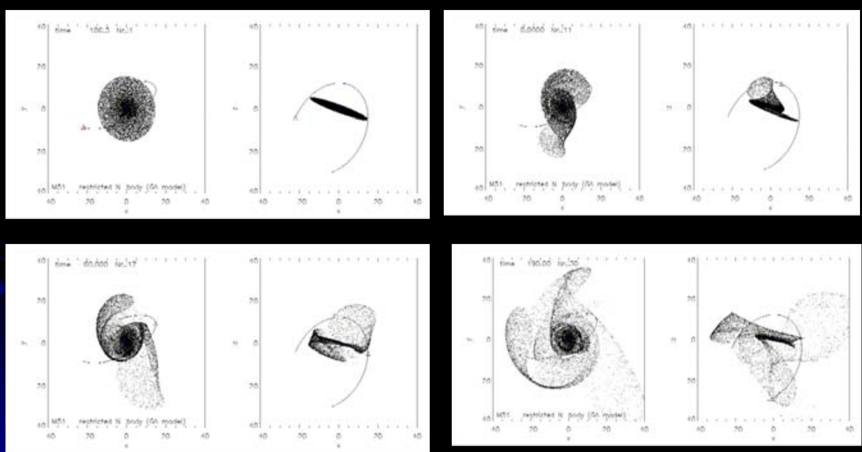
- M51 restricted N-body simulation

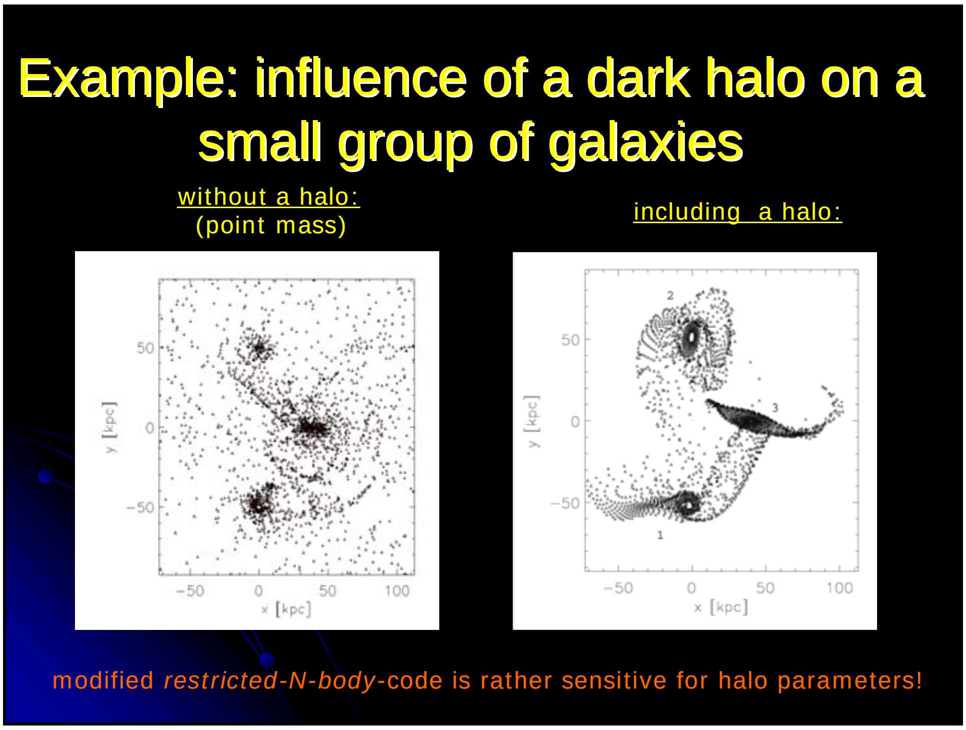


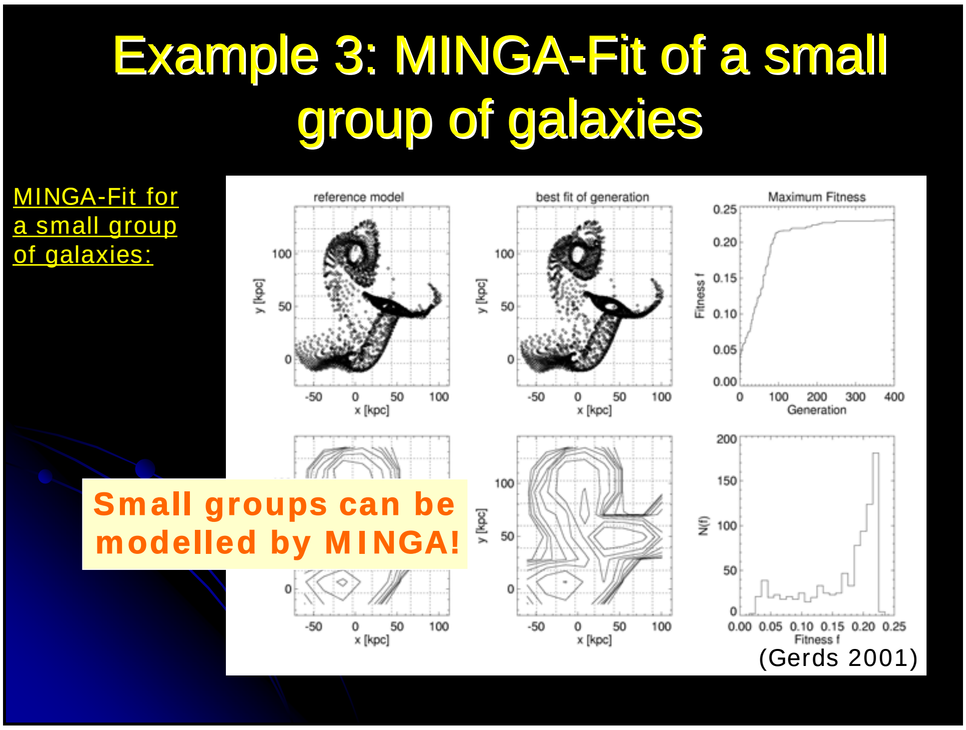


- GA models fits intensity map
- parameter are close to Salo & Laurikainen´s (2000) „two disk passages"-model
- (interaction induced grand design spiral)

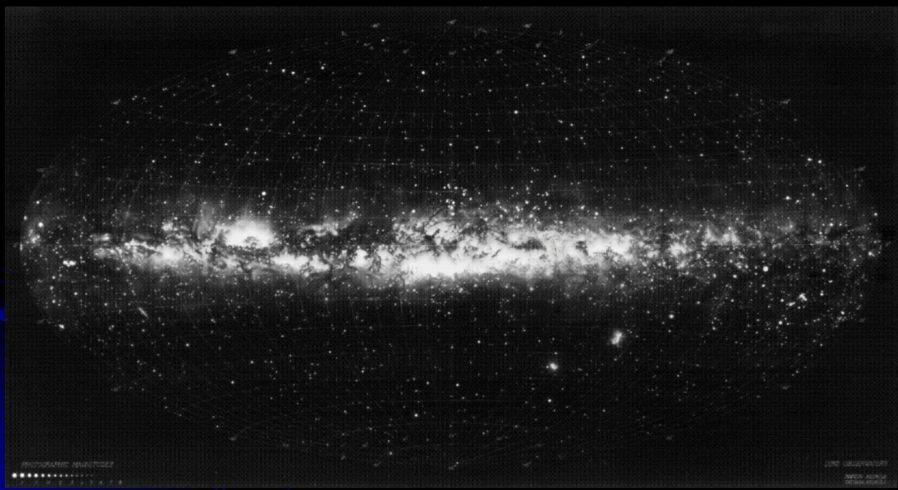
Example 2: snapshots of the GA model for M51




Example: influence of a dark halo on a small group of galaxies
without a halo:
(point mass)
including a halo:
y [kpc]
x [kpc]
modified restricted-N-body-code is rather sensitive for halo parameters!

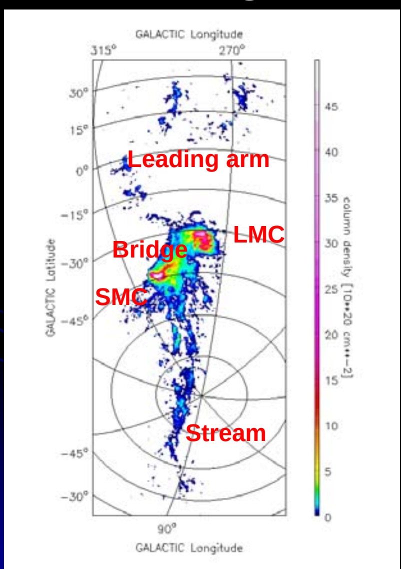

Example 3: MINGA-Fit of a small group of galaxies
MINGA-Fit for a small group of galaxies:
reference model
best fit of generation
Maximum Fitness
y [kpc]
x [kpc]
Fitness f
Generation
N(f)
Small groups can be modelled by MINGA!
(Gerds 2001)

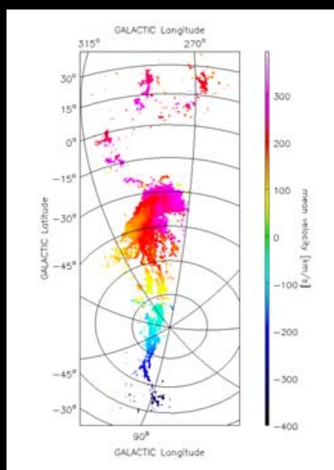
Example 4: The Magellanic System



(Lund observatory)

The Magellanic System in HI



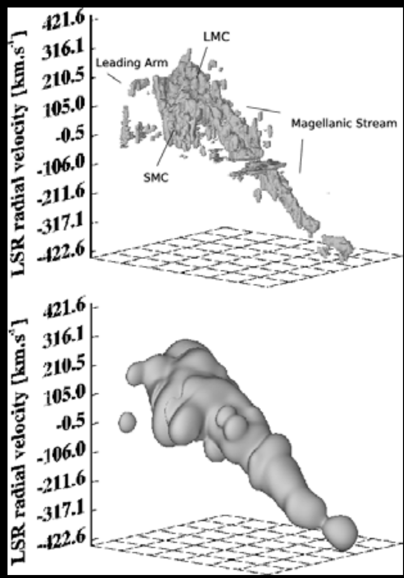


(Brüns et al. 2005)

A Genetic Algorithm model…

Observational data cube:

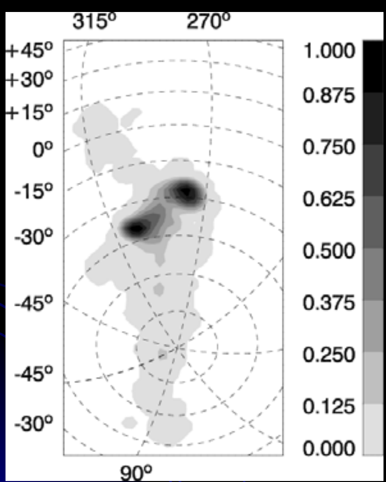
Smoothed data cube:
(used in GA)



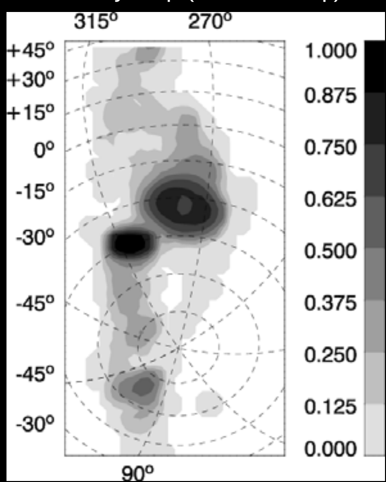
(Ruzicka, Palous & Theis 2007)

A Genetic Algorithm model…

Observed intensity map



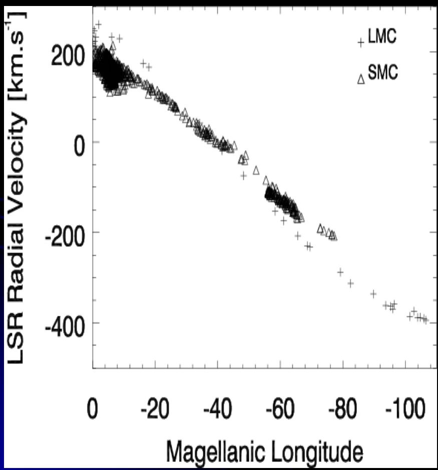
Intensity map (model A seq.)

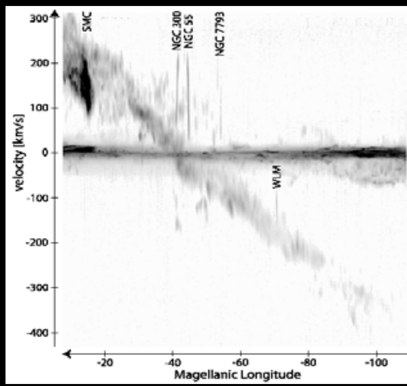


(Ruzicka, Palous & Theis 2007)

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)

A GA model…

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

Summary

- MINGA can model interacting galaxies:
  - Automatic analysis of observational data
  - Uniqueness tests
- Included Features:
  - Spherical DM halos consistently included
  - Extended to small galaxy groups
  - Applied to Magellanic System
- Easy to parallelize
- Remark: GA models are just a first step, further detailed self-consistent models necessary

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.)

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 (Wien)